Does Deep Borehole Disposal of HLRW have a Chance in Germany?

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1 Introduction

The disposal of high-level radioactive waste (HLRW) using deep boreholes in geological formations (salt rock) previously has been considered in Germany a long time ago [GOM 82] but was not pursued then. Furthermore, safety requirements [BMU 10] were identified for a geological underground mine.

Deep borehole disposal (DBD) may offer some advantages such as a better containment due to greater depth, faster disposal and lower costs. It is under discussion currently by the Department of Energy in the USA [NWTRB 16], in the UK [GIB 14] and in Germany [BRA 15].

Therefore, the German Commission “Storage of high-level radioactive waste”, which was active from 2014 to 2016 [KOM 16], discussed deep borehole disposal as an alternative disposal option and requested a study addressing several questions [BRA 16].

In the following, an overview is presented of the concept of HLRW disposal in deep boreholes based on results of [BRA 16]. Furthermore, the DBD concept is discussed with regard to its compatibility with recommendations of the Commission and the safety requirements of the BMUB [BMU 10].

2 Waste volume in Germany

The volume of high-level radioactive waste is limited in Germany due to the phase-out from nuclear energy. The waste forms are mainly spent fuel elements from power reactors (approx. 35,000 pieces), cans with vitrified waste from reprocessing (approx. 8,000 pieces) and some spent fuel elements from research reactors (approx. 2,000 m³) [see e.g. KOM 16].

3 Concept for deep borehole disposal

A concept for deep borehole disposal (DBD) should show containment of the high-level radioactive waste in the long-term from the biosphere (subject of protection). Technical feasibility and operational safety have to be demonstrated.

3.1 Safety requirements and the disposal concept

The great depth which can be reached by boreholes can contribute to a safe containment if overlying sedimentary rocks provide additional geological barriers (multiple geological barrier concept). The large distance of the disposed waste from the surface is also expected to ensure long migration times for radionuclides released from the waste form to human beings and the subject of protection (e.g. groundwater, biosphere). The expected time period for keeping a borehole open for waste emplacement is considerably shorter than for a mined geological repository, so proliferation risks can be assumed to be much lower.

The general requirements for the presented generic concept for DBD are:

- The disposal of vitrified waste containers and spent fuel should be technically feasible. Other waste is not considered here.
- The concept should provide a multi-barrier concept.
- The retrieval of waste should be possible.
- The concept should also allow monitoring during the operational and post-closure phases
- The appropriate lithology should be available in Germany and characterisable.

The use of multiple, independent geological barriers formed by e.g. clay and salt layers together with seals, provide the main safety functions of the generic concept. This means that boreholes have to be sealed effectively within these barriers to restore the functionality of the barriers. Furthermore, only very slow groundwater movement should be probable at great depths which ideally restricts radionuclide migration to diffusion alone.

The generalized concept foresees disposal in the geological bed-rock (which is most likely a crystalline rock) which should be overlain by at least two redundant or diverse geological barriers. Ideally, an additional geological feature can act as gas trap below these barriers. The minimum depth for DBD is set at 1,500 m with a maximum depth of 3,500 m. This will facilitate location of sites with several independent geological barriers and exclude with greater certainty glacial impacts on barriers and waste.

The maximum depth should be optimized by assessing state-of-the-art drilling, disposal technology and the outcome of safety analyses. A vertical borehole this generic concept is preferred over inclined boreholes but multiple and deviating boreholes are possible [DEA 15, TIS 06]. The concept is depicted schematically in Figure 1.

Possible geological barriers overlying the disposal zone (designated zone) are:

- Clay rock: bedded clay which can ensure retardation and containment. Fig. 1 shows an alternating sequence of clay and sandstone.
- Salt rock: bedded salt with high sealing capacity and self-sealing ability based on its visco-plastic characteristics. Fig. 1 shows bedded and domal salt.

These barriers should be combined. At least two independent barriers should be available.

A further possible feature would be porous rock (e.g. sandstone) acting as a trap for gases which could be released from the disposal zone. Fig. 1 shows a sandstone formation below the salt layer acting as a gas trap. Such settings are naturally occurring in Germany and can be found undisturbed.

3.2 Exploration

Geological exploration is necessary to find and characterize the site. This can be performed using a number of standard technologies which also include exploration boreholes with logging and coring. Exploration boreholes may be used at later stages for monitoring or can be developed as boreholes for disposal.
3.3 Container and casing
Containers have to withstand the geomechanical and geochemical conditions experienced during disposal operations. If recovery of containers is foreseen for a certain period of time beyond disposal operations, the container should also be able to withstand conditions in the disposal zone. The latter is a design requirement for the canisters which may be achieved by wall thickness allowance or by material selection.

A Deep Borehole Container – Retrievable (DBC-R) was designed using austenitic steel (Figure 2). The size of the container was derived from the diameter of the canisters with vitrified waste (0.435 m), which are not pressure resistant due to a head space, and the length of the fuel rods from spent fuel elements (approx. 4.5 m) assuming that one container should suit all waste types. The length of the container is about 5.6 m. The container can fit three canisters or an assembly of rods from spent fuel elements.

The thickness of the of the DBC-R (and therefore the diameter) increases with vertical stacking and disposal depth. (Table 1). The diameter of the DBC-R is a minimum of about 55 cm for disposal from 3,000 m to 3,600 m depth with allowance for temperature and some corrosion.

The total outer diameter of the casing is 70 cm considering a wall thickness of approx. 6 cm and play. Therefore a borehole diameter of 75 cm including some allowance for uncertainties could suffice for 3,600 m depth (Figure 3). The depth of 5,000 m was included at the request of the Commission [BRA 16].

Further optimization of the canister’s design and material is expected. By varying the thickness or material of the wall, corrosion or other degradation mechanisms can be countered.

4 Boreholes and drilling technology
Technical feasibility and costs of drilling are important factors for disposal in geological formations. Classical drilling technologies are used in conventional and unconventional oil and gas production, in geothermics and mining. Experience is also available from experimental drilling and research.

The diameter of boreholes ranges from cm to m (shaft sinking) in drilling technology. Since DBD of waste containers with diameters of 55 cm and more is envisaged, the borehole diameter must be large (Tab. 1). Physical constraints have to be considered, as boreholes become wider and deeper.

The difference between the pressure of overburden of the rock and the pressure inside the boreholes increases with depth. The differential stresses can be so high that boreholes may collapse. This differential stress can be lowered if the boreholes are filled with a fluid. The hydrostatic pressure of the fluid reduces the effective rock pressure on the walls of the borehole or the casing.

Thus, geomechanical stability is a limiting factor for the diameter and the depth of boreholes. This is relevant during site selection. The in-situ stress field has to be observed when setting the orientation of the borehole and avoiding the failure of the wall of the borehole.
Using drilling fluids (drill mud), boreholes can be drilled safely to great depths as shown by the status of technology and experience from more than 100,000 boreholes for oil and gas in different geological formations. Larger diameters were realized in research drillings (see e.g. [ENG 96]) than in the oil and gas industry. Segmental logging of boreholes gives information on lithology, porosity, conductivity, density of the formation, and rock alterations in the vicinity of the wall of each borehole.

Most drilling technologies use a drilling fluid which facilitates drilling and cleaning of the borehole. In addition to stabilization with drilling fluid, boreholes are finished with several steel casings which prevent wall collapse and inflow, and which separate different hydrological layers. The composition of this fluid may vary. After well completion, the drilling fluid is usually replaced by a borehole fluid with different characteristics. Cementation of the casing is usually required.

### 4.1 Borehole design

Boreholes are cased in order to reach the desired depth for disposal safely by drilling. The detailed design of the casing set is based on subsurface data such as formation pressures, rock strengths, wellbore orientation and stress field.

The borehole drilled must be large enough to accept the casing string and to allow room for cement between the outside of the casing and the hole. A wellhead is usually installed on top of the first casing string after it has been cemented in place.

The inside diameter of the casing must be large enough that the next bit fits into it to continue drilling. Thus, each casing string has a progressively smaller diameter.

Casing design (Figure 4) for each size is performed by calculating the worst conditions that may be faced during drilling and production. Mechanical properties of designed pipes such as collapse resistance, burst pressure, and axial tensile strength must be sufficient for the worst conditions.

Casing strings are supported by casing hangers that are set in the wellhead.

The minimum diameter of a borehole with casing for disposal is approx. 75 cm assuming DBC-R-containers with canisters of vitrified waste. A safety margin against collapse and other criteria should be provided by the casing and by the container. The experience of long-term stability and tightness of borehole casings covers more than 100 years. More recent experience is provided by the drillings at the KTB site [ENG 96], Groß-Schönebeck [KW 089], Großbuchholz [KW 08], Urach [TEN 00], Soultz-sous-Forets [TIS 06], Gravberg [JUH 98] and Kola SG 3 [FUC 12], which are publicly documented. These wells have reached greater depths than considered here in the concept for final disposal, but exhibit smaller diameters.

Figure 5 shows the casing set of the KTB site, which had been drilled ca. 25 years ago. The outer diameter of the borehole with 44.5 cm at 3,000 m is near to the outer diameter of approx. 75 cm given in Tab. 1 for a depth of 3,600 m. The red rectangle shows the diameter of the DBC-R of 55 cm.

### 4.2 Drilling and wellbore logging

The most widely used method is rotary drilling. Oil well drilling utilises tri-cone roller, carbide embedded, fixed-cutter diamond, or diamond-impregnated drill bits to wear away at the cutting face. This is preferred because there is no need to return intact samples to the surface for assay as the objective is to reach a formation containing oil or natural gas. Sizable machinery is used, enabling depths of several kilometres to be penetrated. Rotating hollow drill pipes carry down bentonite and barite infused drilling muds to lubricate, cool, and clean the drilling bit, to control downhole pressures, to stabilize the wall of the borehole and to remove drill cuttings. The mud returns back to the surface around the outside of the drill pipe, called the annulus. Examining rock chips extracted from the mud is known as mud logging. Another form of well logging is electronic and is frequently
employed to evaluate the existence of possible oil and gas deposits in the borehole. This can take place while the well is being drilled, using “Measurement While Drilling tools”, or after drilling, by lowering measurement tools into the newly drilled hole.

Deviated boreholes currently reach 10 km distance to the wellhead and are frequently used especially in offshore-drilling.

[ARN 11] concluded that with today’s readily available technology, drillings can be done with a diameter of 43.2 cm (17”) down to 5,000 m. Research and development is necessary to generate drilling technology for standard larger diameters since current drilling technology in the oil and gas industry aims for diameters as small as possible to reduce costs. The expert assessment is that borehole diameters up to 75 cm at 3,500 m are feasible with enhanced technology. Borehole diameters of 100 cm at 5,000 m depth as requested by the Commission [BRA 16] were assessed not to be safely operable with current technology.

4.3 Boreholes and disposal operation
A drilling fluid and a cemented casing are necessary for drilling and operational safety aspects during disposal. The typical diameter of a borehole including casing was assessed to be 75 cm for a disposal depth from 3,000 to 3,600 m and increases with depth and number of stacked containers (Tab. 1). Calculations show that a distance of 50 m between disposal boreholes should be sufficient to exclude mutual thermal and other effects.

Disposal is planned for a zone where all geological barriers are functional. This zone is called the designated zone with a safety distance to the geological barriers. The zone where all of the multiple barriers are fully functional and a containment can be provided is called the retention zone. The retention zone is characterized by having at least one geological barrier. The transfer zone is located above the topmost geological barrier.

4.4 Operational phase
During disposal operations any container is removed from the biosphere and has to pass a transfer zone. Below this zone, at least one geological barrier is functioning and can provide complete containment after backfilling and sealing of the borehole. It is obvious that technical measures have to ensure safety for the biosphere and the transfer zone, as is the case for any other disposal technology.

The complete borehole is cased and cemented. After installation of the cemented casing, the drilling fluid can be replaced by a borehole fluid specifically designed for disposal operations. Solid-free borehole fluids are used in order to allow recovery during the phase of operation for disposal. This borehole fluid should be compatible with the casing and containers to minimize corrosion, have a sufficient density to ensure borehole stability, a suitable viscosity, should inhibit corrosion and have a low complexing ability for radionuclides. After disposal, each individual canister may be cemented replacing the borehole fluid by cement to minimize fluid volumes and to separate the disposed canister from following disposal operations.

4.5 Borehole seals

After completion of disposal and cementation of the well within the designated zone, boreholes should be fully sealed and abandoned. Borehole seals should ensure that there is no intrusion of groundwater into the disposal zone and that no contaminants from the disposal zone are released. The seals will re-establish the characteristics of the geological barriers drilled through. Sealing of the borehole may be achieved in several ways with materials of proven longterm stability (salt, clay, bitumen) and over the entire length of the borehole. A favourable method for sealing a borehole utilises the creep behaviour of salt rock /KRE 09/, which is foreseen in the concept.

Figure 7 shows a cased borehole (1), which is reamed completely including removal of the casing in the salt formation (2). Due to the relatively small diameter of the borehole, the high temperature (above 100 °C)
and high pressure of the salt rock, the salt creeps within hours or days (3.) and the borehole is sealed effectively along its reamed length (4.). The sealing process may be enhanced and supported by filling the reamed section with crushed rock salt. Comparable sealing operations can also be performed in clay formations.

5 Safety of disposal operations

Available disposal technologies are wireline, drill string, coiled tubing, free fall (in the borehole fluid) and liner emplacement modes for instruments of any kind. The main differences to conventional oil and gas industry are the remote, personnel-free operation of the transfer and the huge loads in waste disposal containers compared to probes. A disposal technology for containers in shallower boreholes has already been demonstrated successfully in principle [FIL 10].

The proposed containers are not self-shielding. Therefore measures for radiation protection have to be prepared and a detailed design of such a facility for emplacement in deep boreholes should be developed to comply with radiation protection during operations. The technical concept for an emplacement facility should include completely encased surface facilities and the borehole with its casings. The container should be delivered in a transfer cask through a lock to the disposal facility and connected to the emplacement string for disposal. An additional backup wire serves as a further safety measure. When the container is connected to the string, the lock can be opened to lower the container into the well. The descent of each container is slowed down hydraulically by the borehole fluid. Displaced borehole fluid is collected in a dedicated tub. The fluid is monitored for contaminants and radionuclides. The container is released from the emplacement string when the final disposal position is reached. The emplacement string is removed and monitored for contamination after the disposal of each container. The facility should run in automatic mode so that no personnel are required close to the HLRW. The safe emplacement has to be demonstrated.

The design of the containers need not be self-shielding, but should be aerosol tight for a period of 500 years after emplacement. This is required by [BMU 10] with the objective to facilitate a safe recovery. The present design of the container using steel will inevitably lead to some corrosion due the presence of water and the high temperature in the disposal zone. Therefore, further research and development is necessary on the subject of container design for borehole disposal.

Provided that the borehole exists and is ready for disposal, there is no need for dedicated research on installation of rigs or on transportation of loads for disposal since this is standard technology. If deviating boreholes are foreseen, a high inclination should be planned to minimize friction of containers during emplacement.

6 Site selection criteria and safety assessments

[KOM 16] favours disposal in geological formations using mining technology with retrievability and recoverability. [KOM 16] also mentioned that disposal using boreholes in geological formations is the only realistic alternative option over transmutation or long-term interim storage. If disposal in deep boreholes is to have a chance in Germany, the concept and the selected site have to comply with German safety requirements (currently under revision) [BMU 10] and have to undergo a site selection procedure with (preliminary) safety assessments [KOM 16].

The containment providing rock zone (CPRZ) is a key element of the safety requirements [BMU 10]. The concept for borehole disposal takes advantage of multiple geological barriers. These barriers are clay or salt rock layers, which can be used to define multiple and different possible CPRZ’s of types A (enclosure of waste
by CPRZ in the host rock or Bb (large lateral extension of CPRZ overlying the waste in the host rock) [AKE 02] (Figure 8). If disposal takes place directly in a salt or clay formation, type A is possible. Disposal including a crystalline basement should have at least a CPRZ of type Bb, if no containment is provided by host rock and technical barriers [KOM 16].

A generic concept for disposal in deep boreholes is shown above. The general methodology for safety assessments – which is also discussed in [KOM 16] – should be adapted in some of the technical details (e.g. shaft seals could be seen as equivalent to borehole seals).

Any assessment will be based on the safety requirements [BMU 10] (under revision) and will make analogous use of the requirements and criteria for site selection for geological disposal in a mine given by [KOM 16]. The technically important requirements for site selection have exclusion, minimum and weighting geo-scientific criteria.

Although these requirements and criteria [KOM 16] are intended to be applied to sites in geological formations using a mined repository, they are discussed here for application to a concept using deep boreholes for disposal, or whether, to be applicable, an adaptation of the requirements and criteria should be considered. Specific test criteria for deep borehole disposal are not available currently and planning criteria need not be discussed here.

### 6.1 Geo-scientific requirements and criteria for a mined repository applied to deep borehole disposal

The geo-scientific criteria for exclusion (large scale vertical movements, active faults, impact from mining, seismic and volcanic activity, age of groundwater) can be applied directly to the concept of borehole disposal since it is also disposal in a geological formation.

The minimum geo-scientific criteria (permeability of formation, thickness of the CPRZ, depth of CPRZ, disposal area, period for proof) can be applied to the concept of borehole disposal in the same way as for a mined repository, considering that the location of the CPRZ does not need to coincide with the location of the disposed waste.

Eleven weighting geo-scientific requirements in three groups /KOM 16/ have to be discussed in more detail. The three groups were: quality of containment and reliability of its evidence, validation of containment, and additional safety-relevant features (Table 2, Table 3 and Table 4).

All requirements and criteria are assessed using the generic concept for deep borehole disposal. At a later stage a site specific assessment is required. Due to the disposal in deep boreholes, some weighting criteria can be fulfilled favourably by sticking strictly to the definition of the CPRZ and host rock. Since in the generic concept of the DBD the CPRZ is not part of the host rock (disposal zone), but part of the overlying geological barriers, some criteria for safety relevant features should be applied to different rocks as well (No. 4 of Table 2, Table 3). A favourable weighting seems to be possible, but relative only to the underlying generic concept of DBD.

Two requirements with criteria (No. 2 and 3 of Table 4) have been assessed as not applicable to the concept of borehole disposal.

- Due to disposal depth, the temperature will be above 100 °C even without emplacement of heat generating radioactive waste. The temperature of the rock and container will be in any case significantly above 100 °C. The heat generating waste will further increase the rock temperature, but the relatively small size of the container limits the rise in temperature. The suitability of the rocks for the rise in temperature has to be proven prior to disposal. No general temperature limit can be given here as it seems to be specific to the lithology.
- The present concept for containers and casing foresees use of steel and cast iron which will lead inevitably to some gas generation due to the expected presence of (ground-) water. Even if the gas generation rate may be low, a future concept should minimize the use of steel and cast iron to minimize the potential generation of gas.

Two requirements about criteria (No. 4 and 5 of Table 4) are recommended for reassessment for applicability to DBD.

- The requirement to have a “high retention capability of CPRZ for radionuclides” could be extended to other rock formations available
below the CPRZ in the generic concept.

- The requirement for “favourable hydrochemistry” has to be reassessed for the host rock to be useful in DBD since containment is not provided there.

### 6.2 Safety analysis and assessment

Safety analyses should be done to assess operational safety and the long-term safety of borehole disposal. A recent preliminary safety analysis on a generic concept showed good retention of radionuclides [ARN 13]. However, [ARN 13] did not consider all possibly relevant processes (gas flow, groundwater flow through faults, fractures and the EDZ). Therefore a more detailed operational and long-term safety analysis and assessment of the generic concept of DBD still has to be performed [BRA 16].

### 6.3 Retrievability / Recoverability

The [KOM 16] sets the general requirement for reversibility in the site selection process. On one hand, this concerns the site selection process itself, but on the other, it also has some technical implications which concern retrievability and recoverability of disposed waste.

Retrieval is the planned technical option for removing emplaced radioactive waste containers from the repository facility during its operational phase. This is also required by [BMU 10]. The containers and the borehole must allow retrieval until sealing and closure of the boreholes. It is for decision whether closure means a single borehole, a borehole field or all boreholes. At this stage, the understanding is that disposal can be performed within a few years and the borehole is then sealed and closed. Based on experience in conventional drilling, it was assessed that retrieval of containers should be possible during a timeframe of at least 5 years after closure.

Recovery is the retrieval of radioactive waste from a final repository as an emergency measure after the operational phase is over. This emergency may happen after the borehole is closed. The [BMU 10] requires a time period of 500 years for recovery of waste containers. The understanding is that the container and the casing should be designed to survive this time period without releasing radioactive contaminants or aerosols. Experience on recovery of lost objects in conventional drilling covers 100 years, but does not include recovery of corroded containers with HLW.

Whereas, from the experts’ perspective, retrievability seems to be manageable once the borehole and casing exists, recoverability from deep boreholes needs some research and development to show if it is feasible.

### 6.4 Hazards

Hazardous incidents during the operational phase might cause significant releases of radionuclides. Whereas volcanoes, earthquakes and other hazardous geological events should be excluded as far as possible with the site selection criteria, some operational incidents nevertheless need to be assessed.

An incident might be a crack in the wall or break of a single container during disposal and subsequent the spent fuel or glass might contact the borehole fluid. Dissolution of the glass and an instant release fraction of spent fuel would contaminate the borehole fluid. The amount of released radionuclide would depend on the contact time of fluid and waste and on the composition of the waste package. Measures for retrieval and repair should be provided and comply with radiation protection regulations.

A worst case, which should be unlikely, would be the loss of container within the subject of protection and which cannot be retrieved for some reason. A release of radionuclides takes place in the long- or short-term and has to be assessed taking account of the geochemical and hydrological conditions.

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**Tab. 4.**

Weighting group 3: further safety relevant features.
The long term safety analysis should consider that the containers currently proposed for deep borehole disposal are not corrosion resistant in the long-term with respect to groundwater. Even if corrosion may take place slowly, some hydrogen gas generation and other corrosion processes will occur. This may increase the pressure within the sealed borehole and may impact the transportation of released radionuclides. Heat generation and high temperatures in the disposal zone will speed up chemical processes, which cannot be modelled in detail due to a lack of thermodynamic data.

The total mass of fissile radionuclides in a deep borehole will be above the critical mass. Therefore a possible critical excursion and safety measures have to be assessed. Although preliminary safety analysis excluded critical excursions due to the low solubility and mobility of U(IV), an assessment and optimisation should be performed.

7 Research and development

Boreholes with diameters of 0.75 m at 3,500 m depth are still beyond today’s standard technology, but are considered feasible. Based on this, a concept for disposal of radioactive waste in deep boreholes is drafted. Further development and demonstration of dedicated borehole technology is necessary to demonstrate routine technical feasibility.

The disposal with recoverability according to [BMU 10] also necessitates research and development into the long-term behaviour of the container and casing.

The operational phase for disposal of radioactive waste in deep boreholes requires investigations in detail about its safety and radiation protection. There is a need for development testing and demonstration. This includes the feasibility of retrieval before closure.

If the current proposal of the Commission about recoverability for 500 years remains a prerequisite, it would emphasise the need for research and development on containers and technology.

8 Summary and conclusion

Using deep boreholes for disposal (DBD) of high-level radioactive waste (HLRW) can have advantages for long-term safety due to an ample distance between the HLRW and the biosphere (subject of protection) and may take advantage of multiple geologic barriers as safety features. The great depth and short disposal operation efficiently impedes proliferation. Finally, aside from site selection process, there may be a time related benefit for technical implementation and for costs of implementation.

A generic concept for DBD of HLRW has been developed, applying containment providing rock zones (CPRZ). Although further technical developments are required for HLRW disposal in deep boreholes to address larger than usual diameter and depth of boreholes, DBD seems to be feasible as an alternative option for geological disposal of radioactive waste. Further research and development with feasibility demonstration is necessary. Operational and long-term safety analyses and assessments have to be performed.

On one hand, a major is the requirement for possible recovery of waste for 500 years after closure. On the other hand if disposal is intended to be a permanent and the most safe solution, recovery might not be the main focus of the decision when highest possible safety is desired. During policy decision-making, if there are clear advantages for long-term safety with DBD, these might outweigh the disadvantage with recovery.

The Commission asked initially for borehole diameters of 1 m in 5,000 m based on plans for DBD in the USA [NWTRB 16] which set the initial framework for the generic concept developed, presented and discussed here. Based on the current state of knowledge, it was assessed that this diameter/depth cannot be safely operated. Reducing the depth and therefore necessary borehole and container diameters for disposal lowers the technical challenges without jeopardizing the potential safety benefits of DBD. The favourable depth for DBD ranges from 1,500 to 3,500 m. DBD’s advantages in safety, speed, as well as cost were discussed, and that DBD might be seen as an alternative option for geological disposal in Germany. To have this option available as a proven technology during a policy decision, it seems very sensible to follow up the DBD concept with installation of a real scale demonstration along with a detailed safety analysis. DBD could then provide technical redundancy – if required – in case the siting or implementation of a mined repository fails or cannot be pursued any longer for some reason. Having this in mind, DBD may have a chance in Germany in the long run.

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References


Thermal Margin Comparison Between DAM and Simple Model

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Introduction

Nuclear industry in Korea prefers dry storage system to store spent nuclear fuel (NSF) as an interim storage and demand of adopting relevant technologies is increasing. Safety of dry storage system is to keep integrity of NSF cladding. And the maximum temperature of cladding is the most important factor to keep its integrity in field of thermal analysis. According to Relevant guideline called ISA-11 (Interim Staff Guideline, Cladding Consideration for the Transportation and Storage of Spent Fuel) in USA, the maximum temperature of PWR fuel cladding for normal operating condition and abnormal condition, are 673 K and 843 K, respectively. And USA’s nuclear industry shows thermal safety using CFD, according to ISG-21 (Use of Computational Modeling Software). Corresponding to increasing of computer hardware performance, the industry develop more complex analysis model and expect challenges.

Numerical models and assumptions

The Korea standard PWR spent fuel, which was proposed by KAERI (Korea Atomic Energy Research Institute), is considered in this study. It is assumed that the PWR spent fuel has cooled for 10 years, arrayed 16 by 16 and 938.8 W decay heat (each rod has 3.978 W). The DAM described 1/4 storage numerical model consists of about 7.4 M nodes. The simple model shows the thermal margin comparison for two models.

KOM 16


