energies

MDPI

Review

Status of Deep Borehole Disposal of High-Level Radioactive Waste in Germany

Guido Bracke [1,*], Wolfram Kudla [2] and Tino Rosenzweig [2]

1 GRS gGmbH, Schwertnergasse 1, 50968 Cologne, Germany
2 Technische Universität Bergakademie Freiberg, Institut für Bergbau und Spezialtiefbau, 09599 Freiberg, Germany
* Correspondence: guido.bracke@grs.de; Tel.: +49-221-2068608

Received: 17 May 2019; Accepted: 1 July 2019; Published: 4 July 2019

check for updates

Abstract: The phase-out of nuclear energy in Germany will take place in 2022. A site for final disposal of high-level radioactive waste (HLRW) has not yet been chosen, but a site selection process was restarted by the Site Selection Act in 2017. This Act was based on a recommendation by a commission which also advised to follow up the development of deep borehole disposal (DBD) as a possible option for final disposal of HLRW. This paper describes briefly the status of DBD in Germany and if this option is to be pursued in Germany. Although DBD has some merits, it can only be a real option if supported by research and development. The technical equipment for larger boreholes of the required size will only be developed if there is funding and a feasibility test. Furthermore, any DBD concept must be detailed further, and some requirements of the Act must be reconsidered. Therefore, the support of DBD will likely remain at a low level if there are no political changes.

Keywords: deep borehole disposal; Germany; high-level radioactive waste; Site Selection Act

1. Introduction

The geological disposal of radioactive waste is well established at an international level with deep borehole disposal (DBD) being one of the long known options [1–3]. It is referred by the IAEA as well [4,5]. DBD for larger volumes of high-level radioactive waste (HLRW) has not yet been applied and is a controversial topic. Some authors are supportive of this technology [6–9], whereas others are reluctant to accept this idea for Germany [10]. It is obvious that the idea of disposal of HLRW in deep boreholes has some geological disposal merits, but it also has disadvantages which need to be discussed and weighed. Only after a thorough look at it, can one form an opinion of whether or not there is a possible use of a concept and technology for DBD for the specific type and amount of waste to be disposed of. The radioactive waste inventory, technology and a concept, which may be applicable to Germany, have already been presented in [11–13]. This paper wants to give an update and overview of the status of; DBD for HLRW, discussions and recent developments in Germany as DBD could be part of the concept of geological disposal of HLRW within the site selection process. The disposal of LLW and ILW is not considered here.

2. Regulatory Framework in Germany as of 2019

2.1. General

Nuclear power has a long history in Germany. The first nuclear power plant was put into operation in 1962. The Atomic Act has been updated several times since then. In the year 2000 an update included the phase-out from nuclear energy [14]. The last reactor will cease operation in 2022. Therefore, the question of disposal of high-level radioactive waste has been becoming more and more urgent. In 2002 a commission was set up to make a proposal for a site selection process [15]. Their proposal was not implemented for political reasons. After a long political debate, an act on site selection was issued in 2013 [16], foreseeing a commission to define a detailed site selection process. Subsequently, a new commission was set up in 2015 to develop a site selection process. The proposed process is laid down in [17] and was issued as a revised site selection act in 2017 [18]. As the regulatory framework and funding [19] was revised in parallel, the institutions (implementer and regulator) were founded and could commence their activities in 2017. The site selection process and the actors are described briefly in the following.

2.2. Site Selection Act

The Site Selection Act [18] aims to find the best possible site for final disposal high-radioactive waste in the geological formation of rock salt, clay or crystalline rock in Germany. It foresees actors, phases for the site selection process and several criteria for the site selection. A short description of the process is given below. This is needed for understanding the status and possibility of DBD in Germany.

2.2.1. Actors in the Site Selection

The main actors of the site selection procedure include:

- German Parliament
- Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
- Federal Office for the Safety of Nuclear Waste Management (BfE)
- Federal Company for Radioactive Waste Disposal (BGE)
- National Accompanying Body (NBG)

These actors have different roles (Figure 1). The BGE being implementer performs the site selection and hands over the results of each phase (see below) with proposals to the BfE. The BfE as regulatory authority ensures participation of the public and approves a final proposal for each phase. The BMU submits this proposal to the German Parliament for a final decision and issuance of an act. During the site selection process, the NBG has the right to insight and to act as mediator. The NBG is composed of members of the public selected by the German parliament.

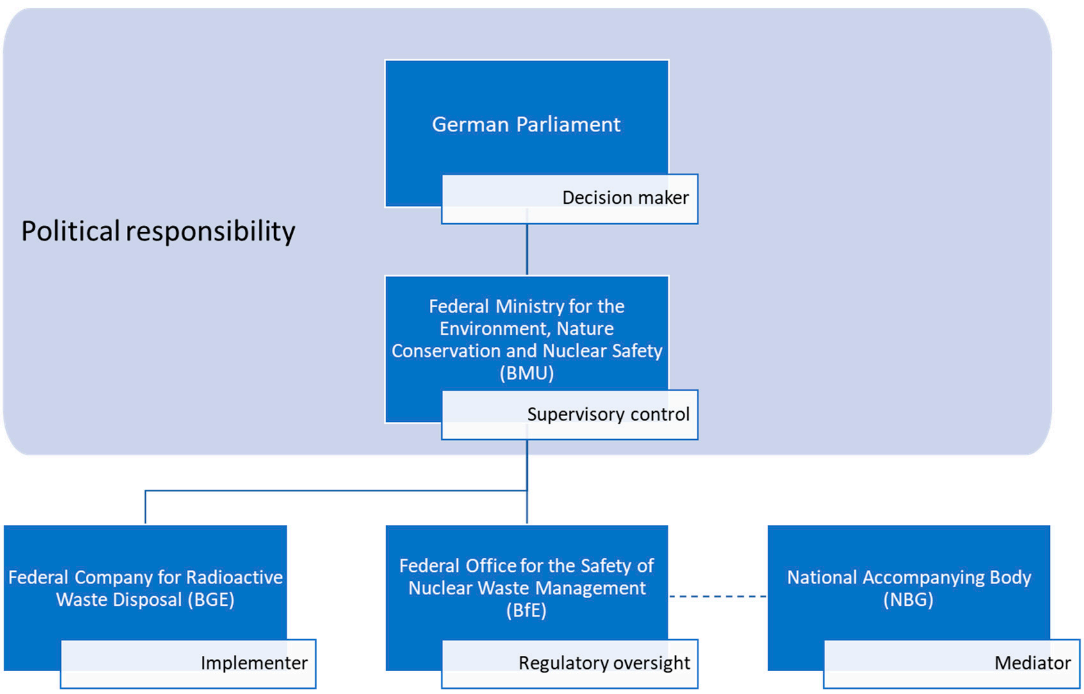

Figure 1. Roles of main actors in the site selection procedure.

2.2.2. Phases of the Site Selection Process

The site selection process was divided into three main phases as shown in the Figure 2:

Phase 1: Identification of possible regions
Phase 2: Exploration from the surface
Phase 3: Underground explorations and decision for a site

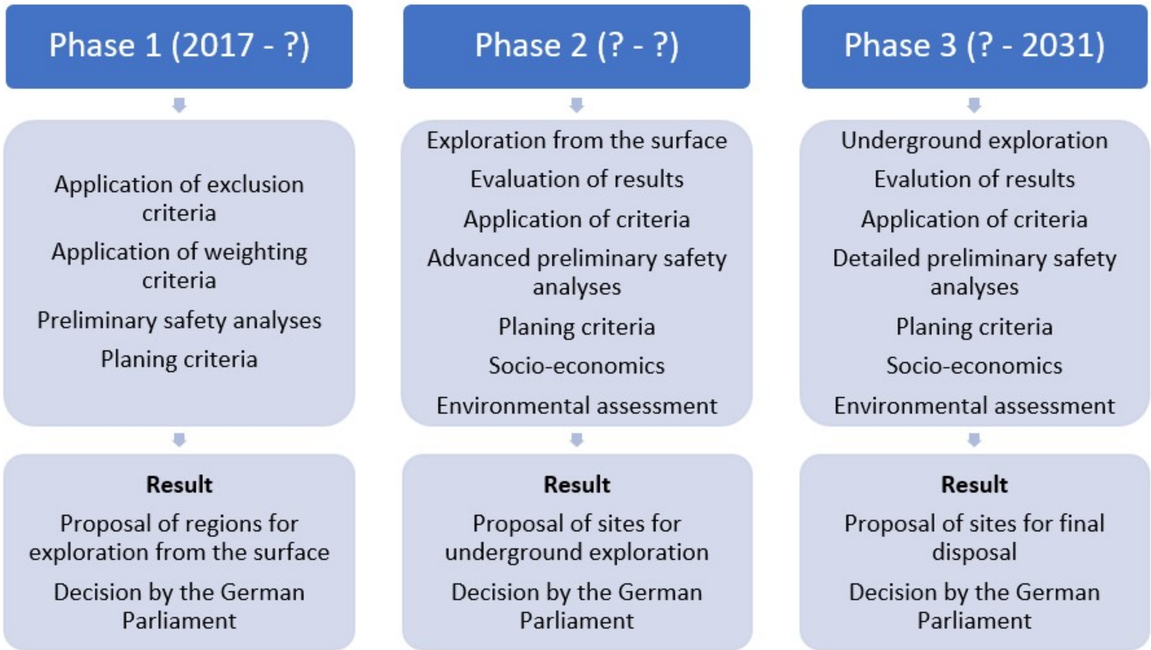

Figure 2. Phases within the site selection process.

The site selection process started in 2017 with phase 1 and shall be finalized in 2031 with phase 3 according to [18]. As the "Decide/Declare/Defend" approach failed for the former intended repository in Gorleben in Germany, a public participation and debates are foreseen for all phases. This is to be organized by the BfE according to the site selection act. Phase 1 shall find regions for exploration from the surface applying exclusion and weighing criteria set in the act. After performing preliminary safety analyses on concepts to be developed, planning criteria may be assessed. Once the regions have been decided by the German parliament, phase 2 will start with an exploration from the surface to find sites for underground exploration. After application of geo-scientific criteria, advanced preliminary safety analyses, consideration of secondary planning criteria, socio-economics and an environmental assessment, the sites for underground exploration can be decided by the German parliament. Phase 3 shall be finished with a proposal of sites based on the results of underground exploration, application of criteria and detailed preliminary safety analyses and again considering in second order planning criteria, socio-economics and an environmental assessment. The German parliament will decide on the site based on the proposal of two sites, which are the result of phase 3.

2.2.3. Containment Providing Rock Zone and Deep Borehole Disposal

The containment providing rock zone (CPRZ) is an important term by the German site selection act [18] describing the part of a rock formation in which disposal systems, which are mainly based on geological barriers, ensure the safe containment of radioactive waste in a disposal facility in coaction with the technical and geotechnical seals. Minimum and weighing requirements and criteria have been set for the CPRZ in [18]. Some possible configurations of a CPRZ are shown in Figure 3.

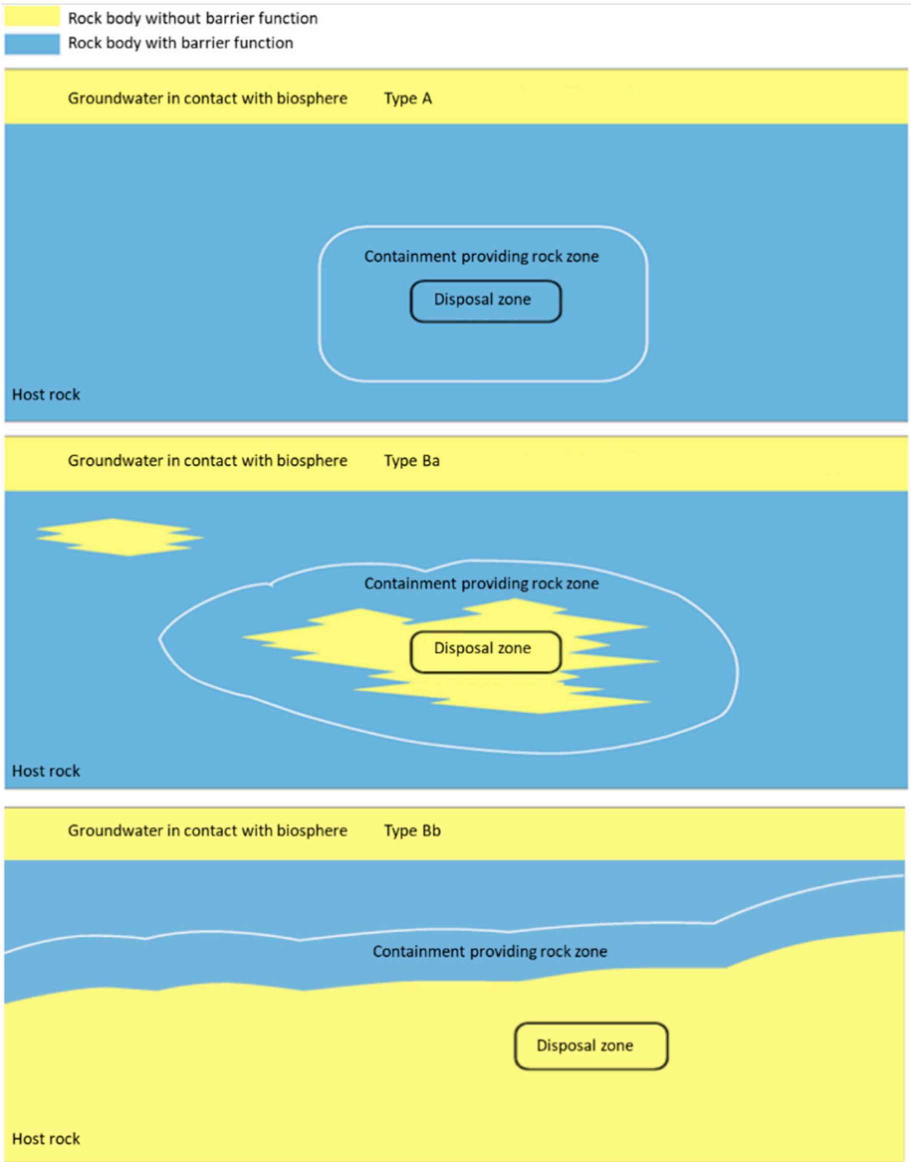

Figure 3. Types of containment providing rock zones (not to scale).

A containment, which imposes significantly more stringent requirements regarding the long-term integrity of the container, is permissible for crystalline rock as given in §23 (1) of [18].

2.2.4. Requirements, Criteria, Indicators

The site selection must consider clay rock, crystalline rock and rock salt as possible host rocks in all phases. Exclusion criteria are applied in the first step. To further narrow down regions (phase 1) to subareas or specific sites, a preliminary safety and disposal concept is obviously needed. These concepts will consider either a containment providing rock zone and/or technical barriers for containment. If these concepts are not available, suitable subareas may not be assessed. The discussion on safety concepts or disposal concepts has not currently been started in detail.

The site selection act foresees geo-scientific criteria for exclusion (large scale vertical movements, active faults, impact from mining, seismic and volcanic activity, age of groundwater), which can be applied directly to any site in a geological formation even without a disposal concept.

The minimum geo-scientific criteria provided (permeability of formation, thickness of the possible containment providing rock zone (CPRZ), depth of possible CPRZ) are to be applied to rock salt and clay rock in order to narrow down regions with suitable geological formations. Since a CPRZ is not required for crystalline rock and technical barriers are favored in the site selection act, not all minimum geo-scientific criteria apply to crystalline rock. This leads to an inequality for the different host rocks concerning the criteria and complicates the development and comparison of concepts.

The site selection act lists eleven weighting geo-scientific requirements in three groups based on [17]: quality of containment and reliability of its evidence; validation of containment, and; additional safety-relevant features (see Tables 1–3).

Table 1. Requirements of the weighting group 1: Quality of containment and reliability of its evidence.

	Requirement	Comments by the Authors Regarding DBD
1.	No or slow transport with groundwater in the CPRZ	Achievable
2.	Favorable configuration of rock body, host rock and CPRZ	Achievable
3.	Good spatial characterization	Tools to characterize host rock properties are available for greater depths but may pose a larger effort compared to lower depth. The volume of rock to be characterized for a CPRZ for DBD may be lower than for a repository depending on the concept.
4.	Good predictability of the long-term stability of favorable conditions	Achievable

Table 2. Requirements of weighting group 2: Validation of containment.

	Requirement	Comment by the Author Regarding DBD
1.	Favorable rock mechanics	Achievable
2.	Low tendency to generation of groundwater flows in host rock and CPRZ	Achievable

Table 3. Weighting group 3: Further safety relevant features.

	Requirement	Comment Regarding DBD
1.	Protective composition of overlying rocks	Achievable
2.	Good conditions to avoid or minimize gas generation	The draft concept for container and casing is using steel, which will inevitably lead to gas generation. Gas generation may be minimized or slowed down by choice of suitable borehole fluid or cementation of containers. A future concept may also minimize the use of steel or may provide physical gas traps. Gas generation cannot be completely avoided.
3.	Good temperature compatibility	The temperature in the disposal zone will be higher than 100 °C due to the depth. Any safety analyses must consider the temperatures and its compatibility for DBD.
4.	High radionuclide retention capability of CPRZ	Achievable
5.	Favorable hydrochemistry	Achievable

These criteria may be used the compare the different sites and their quality but might not be decisive in detail as the overall safety is assessed in preliminary safety analyses.

The requirement “Good temperature compatibility” has been discussed intensely. Since there is a dedicated §26 in [18], a maximum temperature of 100 °C at the outer surface of the containers must be considered in preliminary safety analyses. A strict application of 100 °C as a requirement would render many safety and disposal concepts as obsolete. However, there is the clause, that further research may yield other results. A recent study concluded that setting a regulatory temperature limit prior to the assessment of safety and disposal concepts would hamper optimization of safety and disposal concepts [20].

2.3. Safety Requirements and Safety Analyses

Furthermore, any disposal site must comply with the upcoming ordinances for preliminary safety analyses (see §27 of [18]) and for safety requirements on final disposal [21], which are under revision and will be published as drafts in 2019. The ordinance will outline how to consider the requirements and criteria within a site selection for geological disposal. It is almost certain that this ordinance is drawn up against the background, even mind-set, of a mined repository and so will be inapplicable in some respects to other forms of geological disposal (like DBD). An additional ordinance will outline requirements on preliminary safety analyses.

The authors think that most requirements to be expected in these ordinances can be met by a concept for DBD if confinement of radionuclides, integrity and criticality are concerned. The requirement to provide retrievability of the waste container may also be complied with. The requirement for a possible recovery of the disposed waste for 500 years after closure may not be reasonably achievable in larger depths even with corrosion resistant containers. This permanence can be one of the advantages of DBD for safeguards etc. but is a contradiction to this requirement.

If there were a requirement for a maximum temperature of 100 °C or for a preset assumption in safety analyses to be applied, this would be nonsense for DBD since the ambient temperatures at the depths involved can be much higher than this. The capacity to cope with elevated temperatures, including waste-generated ones, is one of the advantages of the DBD concept.

3. Geology in Germany

Several studies [22–26], have been done to find geological formations in Germany which could be considered suitable for the final disposal of HLRW. The study on crystalline rocks for final disposal showed only the outcrops of crystalline rocks on the surface [22]. Recently an update for concepts in crystalline rocks was created referring to the crystalline basement in Germany [23]. A disposal concept for crystalline rock could be based on the containment by technical and geotechnical barriers like the Swedish KBS-3 concept [27].

Previous concepts considered mainly domal rock salt for final disposal in Germany [28]. Recently a study was done which considered layered rock salt [24]. Also, concepts for clay rock have been developed in the past [25]. Only one study considered layered rock salt as a confining rock zone above a mine [26]. One study considered alternative concepts below rock salt formations [26].

Although different requirements have been set, all studies have one thing in common—that a disposal mine is foreseen for disposal. None of the studies considered disposal deeper than 1500 m depth due to the technological challenges of mining.

4. Inventory of High Level Radioactive Waste (HLRW) in Germany

The HLRW consists mainly of spent fuel elements, currently stored in CASTOR containers, canisters with vitrified waste and spent fuel pebbles. These waste types are shown in Figure 4. These waste types must fit into a container for deep borehole disposal as they cannot be handled or disposed of as they are.

The volume of HLRW is limited in Germany due to the phase-out of nuclear energy in 2022 [17,29–31]. The waste forms are mainly spent fuel elements from power reactors (approximately 35,000 pieces with about 10,500 Mg spent fuel or approximately 7600 m^3 if considered as fuel rods only), canisters with vitrified waste from reprocessing (approximately 8000 pieces, approximately 2000 m^3) and some spent fuel elements from research reactors (approximately 2000 m^3).

The total volume of high-level radioactive waste in POLLUX containers and canisters is projected to be around 27,000 m^3 in 2080 [30].

The vitrified waste canisters are unlikely to be changed or reconditioned. This means that a disposal container must have a minimum diameter to accommodate vitrified waste canisters or another disposal option must be found for the vitrified waste canisters.

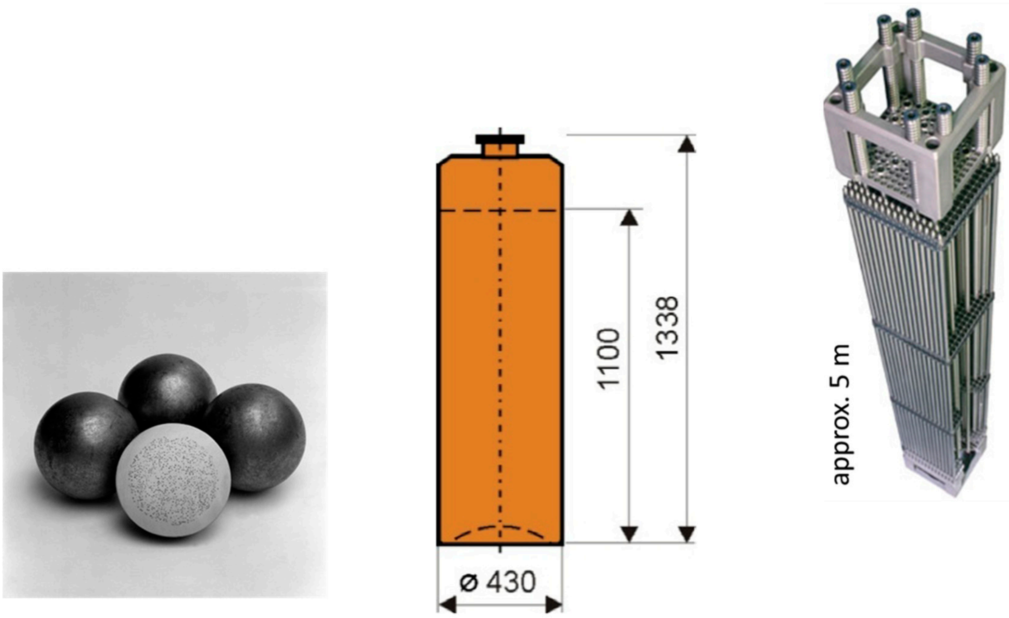

Figure 4. Types of high-level radioactive waste in Germany.

The reconditioning and repackaging of the spent fuel elements are necessary as the direct disposal of CASTOR container in boreholes is considered practically impossible and would require shaft sinking. To minimize the effort for reconditioning and repackaging the spent fuel rods should remain intact. This is considered possible. Therefore, the container to accommodate the intact spent fuel rods must have minimum length of about 5 m. The spent fuel pebbles can be repacked easily because of their size in any container type. For all containers subcriticality must be ensured.

5. Drilling Technology and Its Consequences on the Disposal Concepts

The drilling technology in the field of conventional deep drilling in the oil and gas industry is well advanced. This led to several proposals to use deep boreholes for disposal for radioactive waste (see e.g., [6,7,32,33] were considered [34]. These tests were aborted for political reasons [35].

The actual maximum borehole diameter that can be drilled depends on the rock type. The state-of-the-art deep drilling technology allows for the drilling of depths of 5000 m in crystalline rock with diameters of up to 17.5″ (44.5 cm). This can be ordered off-the-shelf. For larger boreholes, larger roller bits must be developed. Alternatively, drilling techniques in hard rock (e.g., the electric impulse method) would have to be developed or further developed. However, larger borehole diameters cannot currently be drilled using state-of-the-art deep drilling technology at 5000 m. Adapting deep drilling equipment for drilling into hard rock and for diameters considerably larger than 17.5″ (44.5 cm) would require considerable developmental and testing work. The particular challenges are; to provide the large-sized part with the necessary contact pressure (drill rod design); to continuously clean the cuttings from the borehole (capacity of the pumps); to manage the heavy drill string (development and engineering of a special deep drilling rig); and to develop a well design that can cope with a minimal drilling diameter in the first drilling section (lean casing or mono bore method). Drilling and disposal technologies are presented and discussed in detail in [10,36].

Some concepts have been considered for DBD in Germany in these studies. They vary in the size of the container and the depth of disposal [10,36,37]. Three concepts with the approximate technical data are summarized below which differ mainly in borehole diameter and depth of the borehole (Table 4).

Table 4. Technical data for different concepts in Germany ([10,36,37]).

Concept #	1 * [10]	2 [10]	3 [36,37]
Diameter of borehole	17.5″/44.5 cm	35.4″/90 cm	29.5″/75 cm
Maximum depth of borehole	5000 m	5000 m	3500 m
Disposal zone	3000–5000 m	3000–5000 m	1500–3500 m
Space for cementation	44.5 mm	44 mm	25 mm
Outer diameter of casing	14″/356 mm	32″/812 mm	27.6″/700 mm
Wall thickness of casing	21.6 mm	63.5 mm	62.5 mm
Space between casing and container	24 mm	25 mm	25 mm
Outer diameter of container	265 mm	635 mm	525 mm
Inner diameter of container	175 mm	435 mm	435 mm
Wall thickness of container	45 mm	100 mm	45 mm
Length of container	5.6 m	5.6 m	5.6 m
Number of containers	27,000	11,000	11,000
Number of containers per borehole	180	356	356
Minimum number of boreholes	150	31	31

* Spent fuel rods and pebbles only.

The first concept is limited by the biggest possible borehole diameter at 5000 m according to the state-of-the-art deep drilling technology. The second and third concept for 5000 m and 3500 m depth is based on the minimum diameter needed to be able to dispose of the vitrified waste canisters, which are unlikely to be changed or reconditioned as stated before. All three concepts consider a container length of 5.6 m so that the length of the spent fuel rods of approx. 5 m fits into the container.

The pressure on the container results from the load of the stacked containers and the hydrostatic pressure of the liquid column (during operation, the borehole must be filled with fluid for stability reasons). The rock pressure is not considered, as it is assumed that the borehole casing, together with the fluid-filled borehole, will withstand the rock pressure until the borehole seal is fully functional. To withstand the loads at a maximum burial depth taking into consideration the fluid and the casing in the borehole but not the bridge plugs, the steel containers would need a wall thickness of about 4.5 cm to 10 cm depending on the concept.

The advantage of the first concept of smaller borehole diameter of 44.5 cm is that a further development of the drilling technology is not necessary and that the state-of-the-art deep drilling technology can be used. However, the first concept has the disadvantage that a relatively large number of boreholes is required. Furthermore, this concept cannot accommodate the radioactive waste, which is already vitrified, from reprocessing as this would require the containers to have an inner diameter of at least 43 cm. Thus, only the fuel rods of spent fuel elements from power reactors could be emplaced. If one borehole is filled with 180 containers, approx. 150 boreholes would be required for about 27,000 containers. There is still potential for optimization.

The advantage of the second and third concept is that with 31 boreholes (11,000 containers), the number of boreholes is considerably lower than in the first concept. The disadvantage is that without considerable further developments in the deep drilling equipment, these concepts cannot be implemented.

Furthermore, the additional advantage of third concept is that if a lower depth for disposal is selected, the necessary diameter of the borehole can be reduced significantly. This is due to the lower hydrostatic pressure of the liquid column on the container. Therefore, a lower wall thickness of container is needed.

A proposed container for the second and third concept is shown in Figure 5. This container would fit the pebbles, the vitrified waste canisters and the spent fuel rods from the disassembled fuel bundles.

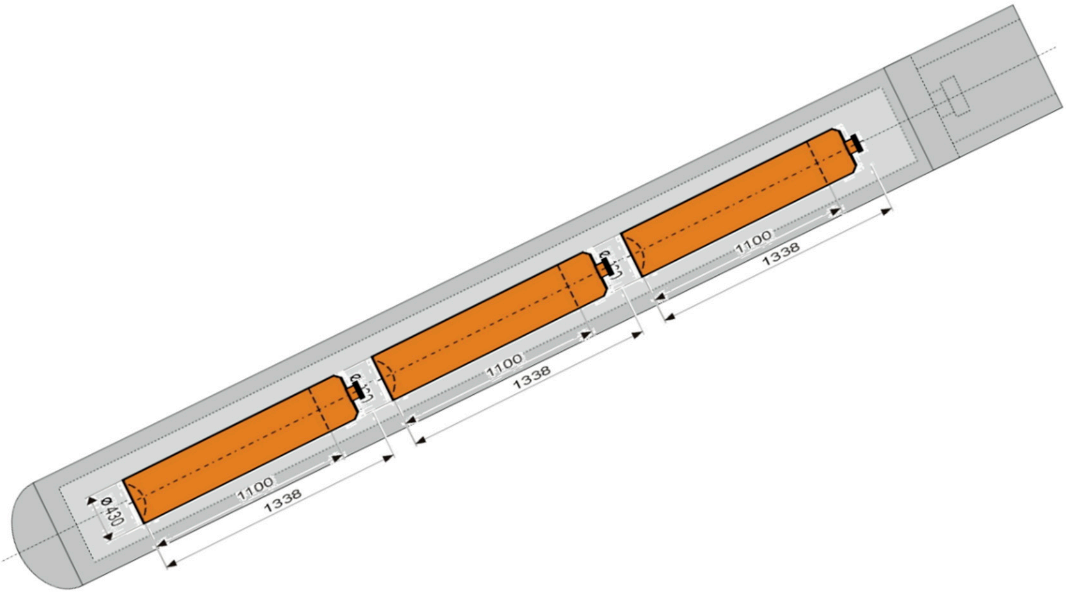

Figure 5. Sketch of the proposed container for deep borehole disposal.

Drilling technology using fluids and a casing for stability for boreholes going down to 5000 m with a diameter of 37.5 cm can be ordered off-the-shelf. This would cost about 30 million Euro [13]. A diameter of 70 cm to 3500 m depth or even 90 cm to 5000 m depth would require special equipment which is not currently available off-the-shelf but can be developed, according to drilling engineers. The price has not yet been calculated but will be less than a dry borehole with a diameter of 111 cm down to 5000 m. A dry borehole of that size would be considered shaft sinking instead of drilling a borehole. A cost estimate yielded more than 500 million Euro [13]. It seems to be out of the question because costs alone are too high, without even considering its feasibility.

Table 5 shows a cost estimate if the HLRW of Germany were to be disposed in about 35 boreholes for about 11,000 containers based on the concept outlined in Section 6. Clearly, such cost estimates have a high level of uncertainty and are hypothetical, but it would be less than the 24.1 billion € which has been paid by the utilities to a fund for disposal of HLRW [38].

Table 5. Cost estimate.

Task	Number	Costs	Sum
Feasibility Demonstration	1	500 Mio €/each	0.50 billion €
Site Selection and Exploration	5	200 Mio €/each	1.00 billion €
Borehole	35	50 Mio €/each	1.75 billion €
Containers	11,000	0.1 Mio €/each	1.10 billion €
Reconditioning	1	1 Billion €	1.00 billion €
Installation and Operating Costs	35/2 years	50 Mio €/each	3.50 billion €
Licensing/safety analyses	35	5 Mio € /each	0.175 billion €
Total	**-**	**-**	**9.025 billion €**

Initially, a feasibility demonstration is considered mandatory. The effort for site selection and explorations could be limited if several boreholes were installed at one site. Not every borehole will be successfully installed, therefore 35 boreholes are assumed. The steel containers are relatively simple in their design and should not be as costly as CASTOR or POLLUX containers (each approx. up to 1 million €). This figure may change, if the concept is modified.

Reconditioning of the HLRW is necessary, but similar costs would also apply for any other disposal concept. Since the disposal must be performed complying with operational safety requirements and radiological protection, installation and operational costs are relatively high, but the operating time is only 2 years per borehole.

The total costs could be less than 10 billion €.

6. Outline of a Concept for Deep Borehole Disposal in Germany

6.1. Safety Concept

A proposed concept for DBD should comply with the site selection act, which foresees a CPRZ. Disposal using boreholes in rock salt or clay rock could be type A, whereas, disposal using boreholes in crystalline rock would be at least type Bb if overlaying rock salt or clay rock formations are considered as CPRZ. If exploration can characterize crystalline rock well enough the assignment of type A could be possible. The disposal technology, whether using mines or deep boreholes should not be relevant for the assignment of these types. overlaying of rock salt and clay rock formations are available in Germany [26], it seems possible to have a redundant and diverse multiple geological barriers system of type Bb when using DBD. A containment, which imposes significantly more stringent requirements regarding the long-term integrity of the container and which is permissible for crystalline rock as given in §23 (1) of [18] could come in addition.

Therefore, the use of multiple, independent geological barriers formed by e.g., clay and salt layers together with seals, should provide the main safety functions of a generic concept for DBD. This means that boreholes must be sealed effectively to restore the functionality of the geological barriers.

The study [10] outlined that it may be possible to install borehole seals into a dry borehole. The borehole will be stable while lowering the liquid column in a way that the area to be sealed is dry. This allows the use of different materials to create redundant and diverse borehole seals. Some materials were considered as possible backfilling or sealing materials like bentonite, bitumen/asphalt, and cement as well as salt suspensions and eutectic molten salt and barite [10]. First considerations about how to feed the material into the boreholes or voids have also been presented in [10]. However, all these technologies still need to be developed and tested with regard to the special conditions of DBD.

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 acting as CPRZ. Ideally, an additional geological feature could act as gas trap below these barriers.

The minimum depth for DBD is selected at 1500 m to allow a suitable geological setting with barriers [37] to be found. Furthermore, at lesser depths technical features of a mine could outweigh DBD features. The greater depth of DBD compared to disposal in a mine will facilitate the finding of sites with several independent geological barriers and exclude glacial impacts on barriers and waste with greater certainty. The maximum depth for DBD is set at 3500 m. This is due to the large diameter of the borehole. The technical challenge and costs increase greatly with depth. A disposal length of 2000 m seems to be sufficient for an outline of a concept. Inclined, deviated or horizontal boreholes are not considered at that stage.

The minimum and maximum depth should be optimized by considering geological setting, state-of-the art drilling, disposal technology and the outcome of safety analyses. A vertical borehole is preferred over inclined boreholes but multiple and deviating boreholes are possible.

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

- Clay rock: bedded clay which can ensure retardation and containment.

- Salt rock: bedded salt with high sealing capacity and self-sealing ability based on its visco-plastic characteristics.

These barriers should ideally 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. Such settings occur naturally in Germany and can be found undisturbed. A schematic figure is shown in [37].

An alternative concept of DBD was proposed in [10] considering a disposal in boreholes in salt rock (domal salt) at depths of 2500 to 4000 m. This would take advantage of some features of rock salt. For example, the self-sealing features of rock salt are useful as it creeps under stress. This process becomes even faster with increasing temperatures. Therefore, it is possible to seal the boreholes very quickly by using the creeping feature of the salt rock. This is not possible in any other host rock.

6.2. Other Aspects for Concepts in Germany

Besides challenges such as drilling large boreholes in great depth, borehole stability, operational safety on disposal and retrieval technology are important when disposing high-level radioactive waste. Incidents such as the sticking of containers and leakage of radionuclides from containers must be discussed and managed. Considering the concept for containment, three rock zones can be defined:

- Disposal zone where containers are supposed to be disposed of
- Retention zone, which is the containment providing rock zone (CPRZ)
- Transfer zone to which the container must pass.

If a container becomes stuck in the designated disposal zone and cannot be recovered, the container may stay in place and the borehole is abandoned and sealed.

If a container becomes stuck in the transfer zone, a removable liner should have been foreseen. The liner including the container is recovered.

If a container leaks, the contaminated fluid must be dealt with. Contamination in the designated or retention zone alone would imply abandonment and sealing of the borehole without handling of the fluid.

If a container leaks within the transfer zone, the liner with container and the fluid can be recovered and treated. A gate/valve using a hydraulic control pipe to separate the fluid in the liner from the remaining borehole fluid must be foreseen.

This implies monitoring of fluids for radioactivity at any time to detect leakage and to provide enough storage and treatment facilities.

This concept is supposed to show that technical solutions are available to handle such incidents. A schematic figure is shown in [37].

7. Discussion

A detailed safety analysis and assessment of a general concept for DBD in Germany has not been performed. Studies on DBD in the U.S. considered a radionuclide transport around the borehole [39,40]. The radionuclide transport from that depth would exhibit an extremely low release of radionuclides to the biosphere. Still, it must be shown for a generic concept or site with CPRZ for DBD in Germany.

The commission handed over their report [17] to the German government recommending preferably a geological disposal with a mined repository. They also recommend following up on developments in DBD as the only alternative option as other options (e.g., partitioning and transmutation) were excluded. Based on this report, the German Parliament updated the site selection act in 2017 and restructured the duties of the different new actors. The act provided many requirements which must be fulfilled in each phase prior to the selection of regions, areas or sites.

There are exclusion and minimum criteria which must be fulfilled by any region, area or site. These criteria can also be met by a site using DBD. Furthermore, the site selection act does not limit the depth.

Weighting criteria are applied if there are several possible sites. Only three aspects of about 12 criteria must be considered more specifically in detail for DBD.

The first one is the gas compatibility. There is a lot of steel put underground using containers and casings which may generate gas. This can be addressed in a concept.

The second one concerns the temperature. The site selection act requires that a safety analysis should be done for temperatures of 100 °C on the outside of the container. If the temperature is higher, further research must show that it is also safe and feasible. At depths of more than 1500 m, the temperature underground is already high and will raise beyond 100 °C when disposing HLRW. Therefore, detailed safety analyses on this are needed for DBD compared to disposal in a mine.

The third aspect refers to the requirement of geochemistry of the disposal zone and CPRZ. These zones do not coincide in the configuration of type Bb. Therefore, an interpretation is needed, and how it can apply to DBD must be discussed in detail.

Apart from these weighting requirements, recovery of radioactive waste for up to 500 years after sealing of the boreholes is required in the Site Selection Act. This will remain a challenge once the waste is disposed of in deep boreholes and the boreholes are sealed. This requirement could be changed as it can been seen to be in contradiction to safeguards and possible proliferation.

The requirements stipulated by the relevant legal regulations in Germany are listed and analyzed also in [10]. It was concluded that applying current legal provisions and requirements to DBD would cause an impediment as these provisions refer to disposal in mines. Thus, some legal requirements can and should be revised or redrafted in such a way that they also apply to DBD. This is a political and not a technical issue.

Apart from this, research and development is needed for DBD if it should ever become a feasible option for Germany. This concerns the conceptual design and safety concept as the former studies were general. Moreover, a technical feasibility study with practical demonstration is required. The container design can be further improved and optimized. It is still necessary to discuss the requirement of recovery.

Further open issues are: Is long-term monitoring needed and how can it be done? Also, there is a need for an operational safety analysis.

Some advantages of DBD are; a multiple barrier system due to its great depth; the fact that no man must go underground as it is man-less disposal technology; several sites being possible provided that the geology is suitable; proliferation not being likely once the waste is disposed of; the cost possibly being less, and the implementation possibly being quicker.

However, the biggest issue for DBD in Germany is that no major actor (which are BGE and BfE) is currently interested in following up developments in DBD nor in supporting further research on it. All actors intend to stick to the exact wording of the Site Selection Act. Although it is not foreseen in the Site Selection Act to follow or support developments of DBD, it is also not forbidden to do so. Any work on DBD could rely only on the recommendation of the commission [17]. Therefore, it will be difficult for any organization to get enough funds for further research, development or feasibility studies on DBD in Germany.

Furthermore, disposal of high-level radioactive waste remains a very political topic. The political agreement, which has been made when issuing the Site Selection Act, seems to be stable. If the site selection procedure performs successfully in the next few years, no one will seek an alternative option. Therefore, it is expected by the authors that politics will change details (e.g., requirement on recovery, temperature issue) to facilitate pursuing DBD only, when issues are coming up which prolong significantly the site selection procedure.

8. Summary and Conclusions

The present article summarizes the background and status of DBD in Germany as it can be concluded from two studies [10,36], final report of the commission [17] and the Site Selection Act [18]. Supporting ordinances to site selection act are to be issued soon in 2019. These regulations will not likely prescribe the follow-up of other options such as DBD, which has been mentioned in [17].

As no major actor (BGE, BfE) in Germany is currently interested in following up developments in DBD or in supporting further research on it, DBD is likely to only be followed up at a very low-level in Germany. That is, if there are significant developments or progress in other countries. Even then, active support in DBD by research, development or feasibility studies is not expected in Germany as skepticism is high, especially when considering the requirement of recovery and the discussion of maximum container temperatures. Nevertheless, the German oil and gas industry has a lot of know-how and the appropriate specialists to carry out developments of DBD if asked.

Only if the site selection procedure is going to fail for whatever reason by 2031 or prolonged significantly beyond, may DBD become an interesting option. Results of the site selection procedure from later phases will hardly apply fully to this option, as the geological settings have not been considered in the concepts which are needed to perform a site selection for DBD.

9. Outlook

There is still a chance that DBD to be followed up on at a very low level in Germany.

Author Contributions: Conceptualization, G.B.; Methodology, G.B.; Data Curation, T.R. and W.K.; Writing-Original Draft Preparation, G.B.; Writing-Review & Editing, G.B., T.R., W.K.

Funding: This article received no external funding.

Acknowledgments: The authors wish to thank two anonymous reviewers and those who were not able to join as authors for different reasons but supported the writing.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chapman, N.; McCombie, C. *Principles and Standards for the Disposal of Long-lived Radioactive Wastes*; Elsevier Science Limited: Oxford, UK, 2003; ISBN 0080441920.
2. Ojovan, M.I.; Lee, W.E. *An Introduction to Nuclear Waste Immobilisation*, 2nd ed.; Elsevier: Kidlington, UK; Oxford, UK; Waltham, MA, USA, 2014; ISBN 9780080993928.
3. *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and radioactive Waste*, 2nd ed.; Apted, M.J.; Ahn, J. (Eds.) Woodhead Publishing: Cambridge, UK, 2017; ISBN 9780081006528.
4. International Atomic Energy Agency (IAEA). *Scientific and Technical Basis for the Geological Disposal of Radioactive Waste*; IAEA: Vienna, Austria, 2003; Technical Report Series STI/DOC/010/413.
5. International Atomic Energy Agency. *Selection of Technical Solutions for the Management of Radioactive Waste*; IAEA: Vienna, Austria, 2017; ISBN 9789201047175.
6. Beswick, A.J. Borehole Construction and Operation for Disposal in Crystalline Rocks. *Radwaste Solut.* **2017**, *24*, 28–32.
7. Gibb, F.G.; Beswick, A.J.; Travis, K.P. Deep borehole disposal of nuclear waste: Engineering challenges. *Proc. Inst. Civ. Eng.-Energy* **2014**, *167*, 47–66. [CrossRef]
8. Arnold, B.W.; Brady, P.V.; Sutton, M.; Travis, K.P.; MacKinnon, R.; Gibb, F.G.F.; Greenberg, H. *Deep Borehole Disposal Research: Geological Evaluation, Alternative Wasteforms, and Borehole Seals*; SAND2014-17430R; Sandia National Laboratorie: Albuquerque, NM, USA, 2014.
9. Deep Isolation Technical Team. Technology—Deep Isolation. Available online: https://www.deepisolation.com/technology/ (accessed on 22 March 2019).
10. Bollingerfehr, W.; Dieterichs, C.; Herold, M.; Kudla, W.; Reich, M.; Rosenzweig, T. Untersuchungen zu Chancen und Risiken der Endlagerung wärmeentwickelnder radioaktiver Abfälle und ausgedienter Brennelemente in Tiefen Bohrlöchern (CREATIEF). Abschlussbericht. 2018. Available online: https://www.tib.eu/suchen/download/?tx_tibsearch_search%5Bdocid%5D=TIBKAT%3A1039255396&cHash=0c55080f07884c822286779dc663cd81#download-mark (accessed on 3 July 2019).
11. Bracke, G.; Hurst, S.; Merkel, B.; Müller, B.; Schilling, F. Final disposal in deep boreholes using multiple geological barriers. Digging deeper for safety. In Proceedings of the Workshop Final Disposal in Deep Boreholes Using Multiple Geological Barriers: Digging Deeper for Safety, Berlin, Germany, 5–6 June 2015;

Bracke, G., Hurst, S., Merkel, B., Müller, B., Schilling, F., Eds.; Gesellschaft fuer Anlagen-und Reaktorsicherheit mbH: Köln, Germany, 2016. ISBN 978-3-944161-87-7.
12. Bracke, G. Endlagerkonzept einer tiefen Bohrlochlagerung (Deutschland). In *Anforderungen an aktuelle Endlagerkonzepte für unterschiedliche Wirtsgesteinsformationen*; Bericht zum Arbeitspaket 1 GRS-471 Anhang 7; Gesellschaft fuer Anlagen-und Reaktorsicherheit mbH: Cologne, Germany, 2017.
13. Bracke, G.; Charlier, F.; Liebscher, A.; Schilling, F.; Röckel, T. Does Deep Borehole Disposal of HLRW has a Chance in Germany? *Atw—Int. Z. für Kernenerg.* **2017**, *62*, 46–53.
14. Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren: AtG. In *Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren: Atomgesetz—AtG*; Bundesgesetzblatt Teil I: Bonn, Germany, 2018; pp. 1122–1124.
15. Arbeitskreis Auswahlverfahren Endlagerstandorte (AkEnd). *Auswahlverfahren für Endlagerstandorte. Empfehlungen des AkEnd*; Abschlussbericht; Bundesamt für Strahlenschutz (BfS): Köln, Germany, 2002; Available online: https://doris.bfs.de/jspui/handle/urn:nbn:de:0221-201111176633 (accessed on 3 July 2019).
16. Gesetz zur Suche und Auswahl eines Standortes für ein Endlager für Wärme entwickelnde radioaktive Abfälle: Standortauswahlgesetz—StandAG. In *Gesetz zur Suche und Auswahl eines Standortes für ein Endlager für Wärme entwickelnde radioaktive Abfälle: Standortauswahlgesetz—StandAG*; Bundesgesetzblatt Teil I: Bonn, Germany, 2013; pp. 2553–2561.
17. Kommission Lagerung hoch radioaktiver Abfallstoffe. *Abschlussbericht. Verantwortung für Die Zukunft—Ein Faires und Transparentes Verfahren für Die Auswahl Eines Nationalen Endlagerstandortes*; Drucksache der Kommission Lagerung hoch radioaktiver Abfallstoffe K-Drs. 268, 2016. Available online: https://www.bundestag.de/blob/434430/bb37b21b8e1e7e049ace5db6b2f949b2/drs_268-data.pdf (accessed on 24 January 2019).
18. Gesetz zur Suche und Auswahl eines Standortes für ein Endlager für hochradioaktive Abfälle: Standortauswahlgesetz—StandAG. In *Gesetz zur Suche und Auswahl eines Standortes für ein Endlager für hochradioaktive Abfälle: Standortauswahlgesetz—StandAG*; Bundesgesetzblatt Teil I: Bonn, Germany, 2017; pp. 2808–2838.
19. *Gesetz zur Errichtung eines Fonds zur Finanzierung der kerntechnischen Entsorgung (Entsorgungsfondsgesetz-EntsorgFondsG). EntsorgFondsG*; Bundesgesetzblatt Teil I: Bonn, Germany, 2017; pp. 114–129.
20. Bracke, G.; Weyand, T.; Hartwig-Thurat, E.; Meleshyn, A.; Larue, J.; Fischer-Appelt, K. *Untersuchungen zu den "maximalen physikalisch möglichen Temperaturen" gemäß § 27 StandAG im Hinblick auf die Grenztemperatur an der Außenfläche von Abfallbehältern*. 1. Statuskonferenz Endlagerung von hochradioaktiven Abfällen, 2018. Available online: https://www.bfe.bund.de/SharedDocs/Downloads/BfE/DE/fachinfo/soa/18110809_Statuskonferenz_Poster_Forschungsvorhaben_BfE.pdf?__blob=publicationFile&v=3 (accessed on 25 June 2019).
21. Federal Ministry for the Environment, Nature Conversation and Nuclear Safety (BMU). *Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste*; Federal Ministry for the Environment, Nature Conversation and Nuclear Safety (BMU): Bonn, Germany, 2010.
22. Bräuer, V.; Reh, M.; Schulz, P.; Schuster, P.; Sprado, K.-H. *Endlagerung stark wärmeentwickelnder radioaktiver Abfälle in tiefen geologischen Formationen Deutschlands.-Untersuchung und Bewertung von Regionen in nichtsalinaren Formationen*; Bundesanstalt für Geowissenschaften und Rohstoffe (BGR): Hannover, Germany, 1994; Archiv-Nr.: 112642; 2025039; Tgb.-Nr.: 12437/91.
23. Jobmann, M.; Becker, D.-A.; Hammer, J.; Jahn, S.; Lommerzheim, A.; Müller-Hoeppe, N.; Noseck, U.; Krone, J.; Weber, J.R.; Weitkamp, A.; et al. *Projekt CHRISTA: Machbarkeitsuntersuchung zur Entwicklung einer Sicherheits- und Nachweismethodik für ein Endlager für Wärme entwickelnde radioaktive Abfälle im Kristallingestein in Deutschland* TEC-20-2016-AB, 2016. Available online: https://www.dbe-technology.de/fileadmin/user_upload/unterlagen/f_e_berichte/CHRISTA-Projekt_Abschlussbericht.pdf (accessed on 27 March 2018).
24. Reinhold, K.; Hammer, J.; Pusch, M. *Verbreitung und Eigenschaften flach lagernder Salzschichten in Deutschland (BASAL). Verbreitung, Zusammensetzung und geologische Lagerungsverhältnisse flach lagernder Steinsalzfolgen in Deutschland—Zwischenbericht* 9Y2013030000, 2014. Available online: https://www.bgr.bund.de/DE/Themen/Endlagerung/Downloads/Charakterisierung_Wirtsgesteine_geotech_Barrieren/2_Steinsalz/2014-12-10_BGR_Basal_ZB_Verbreitung_Eigenschaften.pdf?__blob=publicationFile&v=3 (accessed on 25 June 2019).
25. Hoth, P.; Wirth, H.; Reinhold, K.; Bräuer, V.; Krull, P.; Feldrappe, H. *Endlagerung radioaktiver Abfälle in tiefen geologischen Formationen Deutschlands. Untersuchung und Bewertung von Tongesteinsformationen*. 2007. Available online: https://www.bgr.bund.de/DE/Themen/Endlagerung/Downloads/Charakterisierung_Wirtsgesteine_

geotech_Barrieren/1_Tongestein/2007-04-00_BGR_Tonstudie2007.pdf?__blob=publicationFile&v=6 (accessed on 3 July 2019).
26. Schreiber, U.; Jentzsch, G.; Ewert, T. *Geologische Potentiale zur Einlagerung von radioaktiven Abfallstoffen unterhalb von stratiformen Salzformationen. Konzeptstudie für ein alternatives Endlagermodell*. Material für die Kommission Lagerung hoch radioaktiver Abfallstoffe K-MAT 42, 2015. Available online: https://www.bundestag.de/endlager-archiv/blob/395402/f31ce26e4e7fc8528c956bd5986fce75/kmat_42-data.pdf (accessed on 23 June 2019).
27. Birgersson, L. *The barriers in the KBS-3 repository in Forsmark*. SKB Public Report No. 1520261, 2015. Available online: http://www.skb.se/wp-content/uploads/2016/01/D-The-barriers-in-the-KBS-3-repository-in-Forsmark.pdf (accessed on 16 November 2017).
28. Bracke, G.; Fischer-Appelt, K. Methodological approach to a safety analysis of radioactive waste disposal in rock salt: An example. *Prog. Nucl. Energy* **2015**, *84*, 79–88. [CrossRef]
29. Peiffer, F.; McStocker, B.; Gründler, D.; Ewig, F.; Thomauske, B.; Havenith, A.; Kettler, J. Abfallspezifikation und Mengengerüst. In *Basis Ausstieg aus der Kernenergienutzung (Juli 2011). Bericht zum Arbeitspaket 3, Vorläufige Sicherheitsanalyse für den Standort Gorleben*; Gesellschaft für Anlagen—und Reaktorsicherheit (GRS) mbH: Köln, Germany, 2011; ISBN 978-3-939355-54-0.
30. Federal Ministry for the Environment, Nature Conversation, Building and Nuclear Safety (BMUB). Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. In *Report of the Federal Republic of Germany for the Sixth Review Meeting*; Federal Ministry for the Environment, Nature Conversation, Building and Nuclear Safety (BMUB): Bonn, Germany, 2018.
31. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB). *Verzeichnis radioaktiver Abfälle. Bestand zum 31. Dezember 2017 und Prognose*; Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB): Bonn, Germany, 2018.
32. Ewing, R.C.; Bahr, J.M.; Becker, S.M.; Brantley, S.L.; Croff, A.G.; Foufoula-Georgiou, E.; Frankel, G.S.; Nozick, L.K.; Peddicord, K.L.; Turinsky, P.J.; et al. Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program. A Report to the U.S. Congress and the Secretary of Energy, 2016. Available online: https://www.nwtrb.gov/docs/default-source/reports/dbd_final.pdf?sfvrsn=7 (accessed on 25 June 2019).
33. Hardin, E.L. *Deep Borehole Field Test. Requirements and Controlled Assumptions*; SANDIA Report SAND2015-6009, 2015. Available online: https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2015/156009.pdf (accessed on 24 June 2019).
34. Rigali, M.J.; Hardin, E.L.; Stein, E.R.; Su, J.C. Large Diameter Deep Borehole Disposal Concept for HLW Glass. In Proceedings of the International High-Level Radioactive Waste Management Conference, Charlotte, NC, USA, 9–13 April 2017; pp. 536–546.
35. Heidelberger, C.A. Energy Dept. Cancels Deep Borehole Field Test. Available online: https://dakotafreepress.com/2017/05/23/energy-dept-cancels-deep-borehole-field-test/ (accessed on 24 June 2019).
36. Bracke, G.; Charlier, F.; Geckeis, H.; Harms, U.; Heidbach, O.; Kienzler, B.; Liebscher, A.; Müller, B.; Prevedel, B.; Röckel, T. *Tiefe Bohrlöcher*; Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH: Köln, Germany, 2016; ISBN 9783946607052.
37. Bracke, G.; Charlier, F.; Liebscher, A.; Schilling, F.; Röckel, T. About the Possibility of Disposal of HLRW in Deep Boreholes in Germany. *Geosciences* **2017**, *7*, 58. [CrossRef]
38. Fonds zur Finanzierung der kerntechnischen Entsorgung. Available online: http://www.entsorgungsfonds.de/ (accessed on 23 June 2019).
39. Arnold, B.W.; Brady, P.V.; Bauer, S.J.; Herrick, C.; Pye, S.; Finger, J. *Reference Design and Operations for Deep Borehole Disposal of High.-Level Radioactive Waste* SAND2011-6749, 2011. Available online: https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2011/116749.pdf (accessed on 25 June 2019).
40. Freeze, G.A.; Stein, E.; Brady, P.V. Post-Closure Performance Assessment for Deep Borehole Disposal of Cs/Sr Capsules. *Energies* **2019**, *12*, 1980. [CrossRef]