Technical Design and Optimization of a HLW-Repository in the Gorleben Salt Dome including Detailed Design of the Sealing System – 13305

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ABSTRACT

The preliminary safety analysis for a HLW repository at Gorleben, the potential repository site in Germany, takes into account an updated set of data on the amounts and types of expected heat-generating waste, the documented results of the exploration of the Gorleben salt dome, and the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" as at 30 September 2010. A repository design was developed for two emplacement concepts (drift disposal and borehole disposal) mainly influenced by the thermal impact of the heat-generating waste on the host rock and taking into account mining constrains. According to the objective to create the conditions for a safe containment of the waste containers in the host rock, a closure concept consisting of backfilling and sealing measures was developed. The repository was designed in such a way that retrievability requirements can be met for all waste containers within the operating phase of the repository. In addition, it could be shown that sufficient measures for ensuring subcriticality are provided both during the operational and the post-closure phases of the repository.

INTRODUCTION

The revised Atomic Energy Act of June 2011 stipulates a phase-out of nuclear energy production in Germany by the end of 2022. Prior to this revision – in summer 2010 – the German Federal Government launched a preliminary safety analysis to assess whether the salt dome at Gorleben is suitable to host all heat-generating radioactive waste generated by German NPPs. This safety assessment includes a repository concept which was optimized to a certain extent during project evolution. The repository design was tailored to the specific geologic environment at the Gorleben site and served as the main technical basis for the site-specific preliminary safety analysis. This preliminary safety analysis took into account the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" as at 30 September 2010 [1] for the very first time.

This paper describes the design approach, the resulting repository designs for the two main emplacement strategies as well as a closure concept and a detailed design of the sealing system. The designs took into account an updated set of fundamental data regarding the amounts and types of expected heat-generating waste and the documented results of the exploration of the Gorleben salt dome. The designs were to transfer a new safety and verification concept [2], i.e. a methodology how to demonstrate operational and long-term safety, into technical solutions for repository components, systems, and processes.

REPOSITORY DESIGN

The primary objective of the preliminary safety assessment for the potential site Gorleben is a traceably documented prognosis of the suitability of the site. This requires, among others, the development of an optimized repository concept. For this purpose, two main repository concepts were considered:

- Variant 1: Emplacement of all heat-generating radioactive waste (spent fuel and vitrified waste) in self-shielding waste containers (POLLUX® casks) in horizontal drifts.

  In addition – for comparison only – the emplacement of all heat-generating radioactive waste in transport und storage casks (CASTOR®) in horizontal boreholes was considered.

- Variant 2: Emplacement of all heat-generating radioactive waste in multi-purpose cylindrical canisters in deep vertical boreholes.

As an option, the emplacement of a certain amount of non-heat-generating radioactive waste was considered (in horizontal emplacement chambers).

For both variants (emplacement in drifts/emplacement in vertical boreholes), the respective final technical design results will be presented.

Technical Design of the Repository Mine

The technical designs comprise first the selection and description of waste-specific (SF/reprocessing waste) waste packages for both strategies. Based on the expected waste inventory (10,445 tonnes of heavy metal resulting from 34,430 spent fuel elements and 8,141 canisters of waste from reprocessing (CSD-V, CSD-B and CSD-C), 3D thermal calculations were carried out to determine canister, drift, and borehole distances. Thus, the results provide suitable design parameters for the layout of emplacement drifts and fields and the entire repository, including infrastructure areas and drifts for the transportation of waste packages and excavated rock salt material. The respective repository design approaches comprise two steps; first a conceptual design was developed, followed by a technical design which includes suggestions for optimization. The final design results for both main variants are as follows:

- Variant 1: Disposal of POLLUX® casks in horizontal drifts of the repository mine.

  The total inventory of heat-generating waste will be disposed of in heavy (weight max. 65 metric tons [Mt]), self-shielding POLLUX® casks containing the fuel rods of disassembled spent fuel elements or waste from reprocessing in horizontal drifts of the salt mine. A minor quantity of remaining structural parts from the conditioning of spent fuel elements will be disposed of in cast iron containers.

The results of the thermal calculations (see the following section) for cask and drift distances, thus guarantying that the temperature limit of 200 °C at the contact between cask and salt will not be exceeded, have been transferred into a repository mine layout which is shown in Figure 1. In total, the north-eastern part of the mine – adjusted to the assumed geologic structure of the Gorleben salt dome at the emplacement level of 870 m below surface – will have a length of approximately 4 km and a width varying between 300 m and 700 m. As mentioned above, a certain amount of non-heat-generating waste was considered as well. As a result, three separate emplacement fields were designed in the south-eastern part of the repository mine (left of shaft 1).

Figure 1 also shows a sketch of the POLLUX© cask and a photograph of the test set-up for full-scale canister emplacement demonstration tests in a drift which were successfully performed in the 1990s.

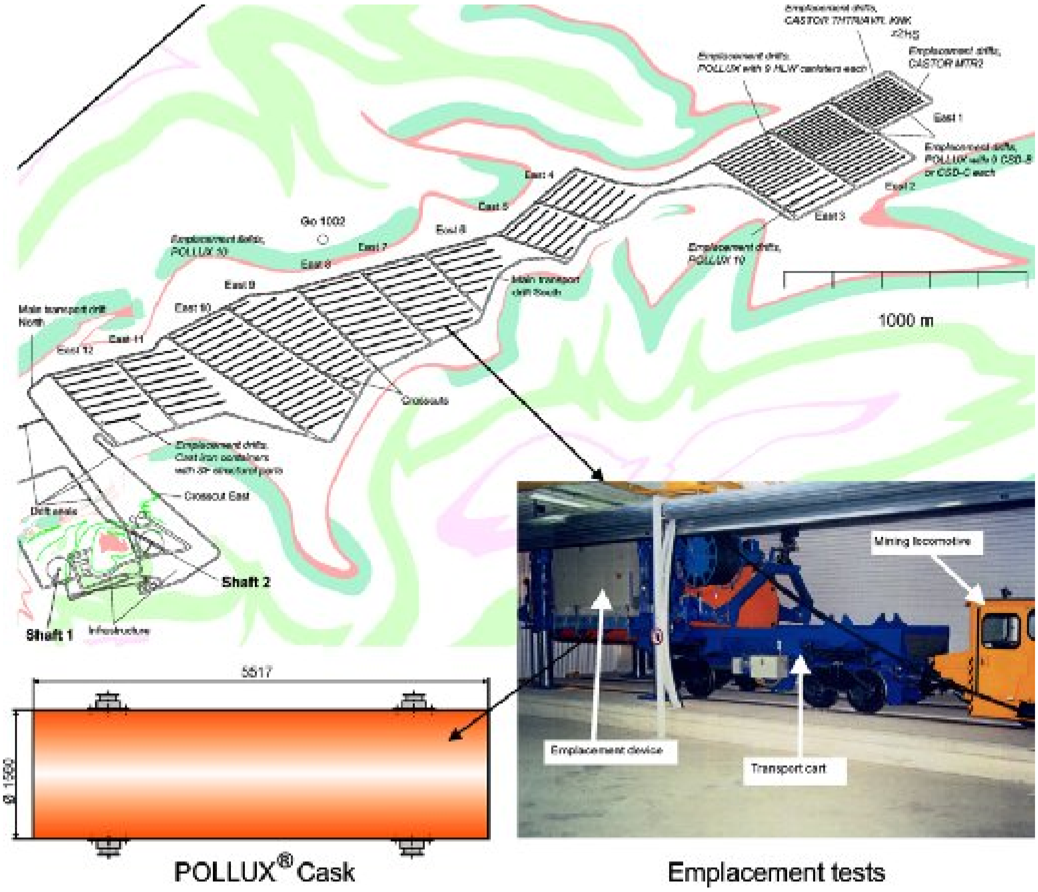

Fig. 1: Repository design for the emplacement of all heat-generating spent fuel and vitrified waste in horizontal drifts (adjusted to the assumed geologic structure).

For comparison, a completely different emplacement strategy was considered and a repository design developed:

- Variant 2: Disposal of canisters for fuel rods and vitrified waste in vertical boreholes.

  In this case, the total inventory of heat-generating radioactive waste will be disposed of in canisters into 300-m deep, lined vertical boreholes drilled from the 870-m level of the repository mine. The canisters (weight 5.2 Mt) contain fuel rods, vitrified waste, or structural parts from the conditioning of spent fuel assemblies.

  The results of the thermal calculations took into account the heat transfer into the surrounding rock salt at a depth of more than 300 m. The results provided borehole and drift distances, thus again guarantying that the temperature limit of 200 °C at the contact between the liner and the salt will not been exceeded. The corresponding repository mine layout is shown in Figure 2. In total, the north-eastern part of the mine – adjusted to the geologic structure of the Gorleben salt dome at the emplacement level of 870 m below surface – will have a length of approximately 1 km and a width varying between 400 m and 800 m. Again, the emplacement of non-heat-generating waste was considered as an option in the south-eastern part of the mine.

Figure 2 shows a sketch of a vitrified waste canister and a spent fuel canister and a photograph of the test set-up for the full-scale canister emplacement demonstration tests in vertical boreholes which were successfully performed in 2008 and 2009.

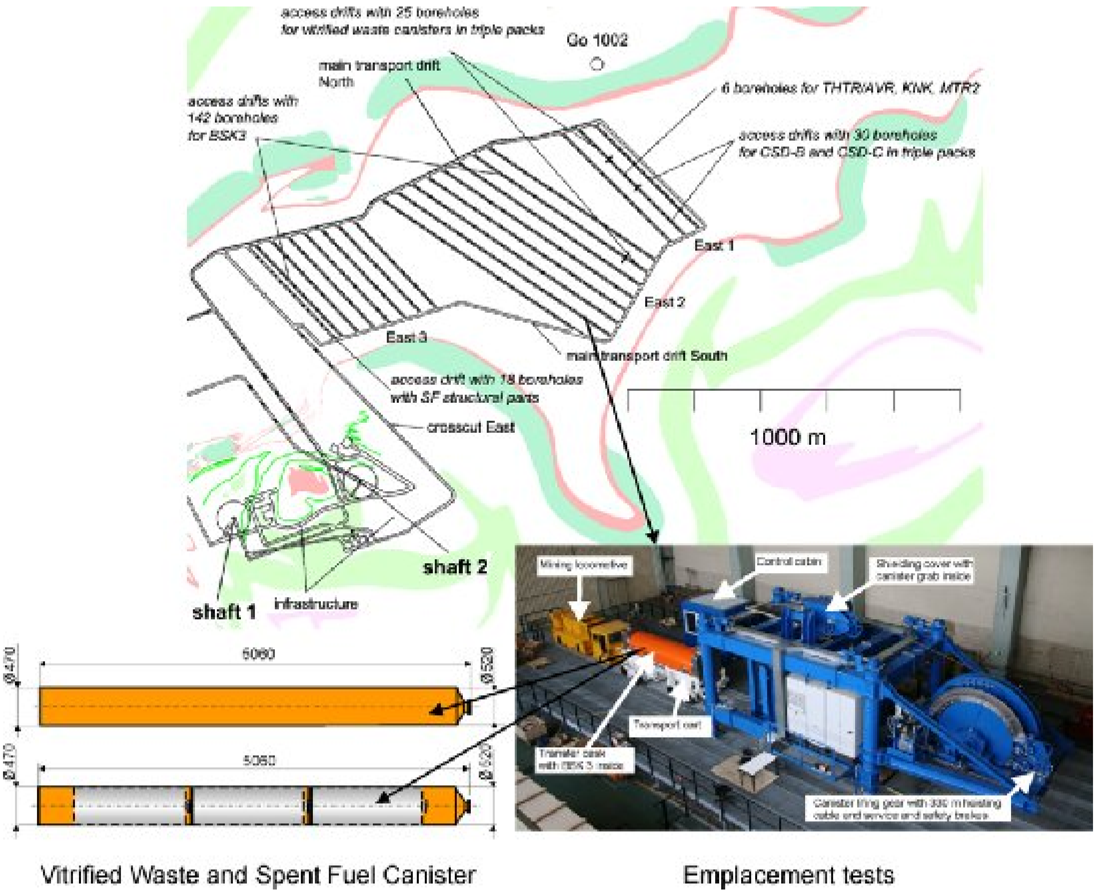

Fig. 2: Repository design for the emplacement of all heat-generating waste in lined vertical boreholes (adjusted to the assumed geologic structure)

Thermo-Mechanical Design Calculations

From a thermo-mechanical (TM) standpoint, the design of a repository for heat-generating radioactive waste strongly depends on the demonstration that thermal limits, operational safety, mechanical integrity of the barriers, and long-term safety requirements are met. The following section is dedicated to the calculations performed to meet the thermal limit.

A design temperature of 200 °C was considered as an upper thermal limit only for halite materials like rock salt and crushed salt (backfill). The design temperatures of the other material groups were disregarded. However, the temperature behavior in specific locations of the repository, e.g., the potash layer, dam locations, or on top of the salt dome was investigated by means of numerical calculations. The thermal designs of the casks were not considered.

Pure thermal (T) or combined TM calculations were performed depending on the disposal concept. TM calculations were necessary due to the mechanical influence on thermal state variables, e.g., for crushed salt used as backfill material within the drift emplacement concept. Crushed salt has an initial porosity of approx. 35% and will be completely compacted over time. The material behavior changes depending on this compaction, e.g., the heat conductivity increases from approx. 1 W/m·K to approx. 5.5 W/m·K. Generally and independent of the mechanical behavior, the temperature dependence of the material properties has to be considered, which is particularly important for the geo-materials. The thermal layout of the repository is based on three-dimensional (3D) TM calculations of transient heat conductivity with compaction-state-dependent parameters.

The calculations for both emplacement concepts (drift disposal and borehole disposal) were performed in the following three steps:

1. Investigation of design variations
2. Layout of the repository based on suitable subsystems
3. Estimation of the thermal behavior in the entire repository

The calculations of the first two steps were carried out with the program FLAC3D, a code of finite-difference method for 3D TM calculations. LinSour was used in the third step. LinSour is an analytic code for 3D T calculations of heat conductivity based on line sources.

In the past, only a few TM calculations were done with regard to repository design. A first, purely thermal layout of a repository with fixed coefficients was shown in [3], 2D TM calculations were considered in [4]. The results of TM calculations within the preliminary safety analysis, including those from thermal calculations, are shown in detail in [5]. An overview of these calculations were already given in [6], a short summary of the thermal design of the repository with regard to the drift emplacement concept is given in [7].

Figure 3 shows a sketch of the different models used in the last two steps. The models were generated to investigate the influence of the dissipation not only in one direction (model CM2: unit cell), but also in all three dimensions, (models CM4 = single field and CM5 = planning concept). The boundary conditions influence the results of the different numerical models significantly, see Figure 4. The intensity of the heat transport also depends on the field size examined in the different models, compare CM2 to the two CM3s with 8 and 14 boreholes respectively.

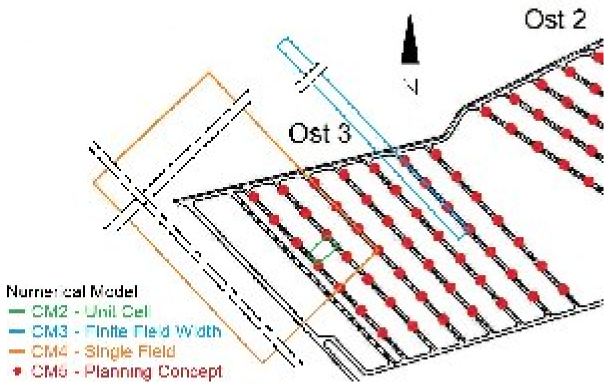

Fig. 3. Borehole disposal – Section of the emplacement concept and scheme of appropriated numerical models.

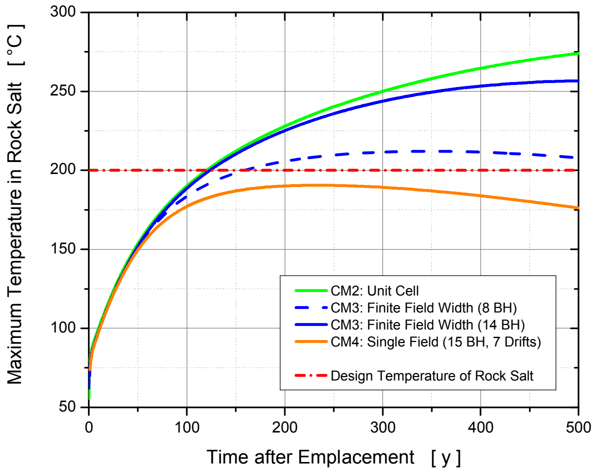

Fig. 4. Borehole disposal – Maximum temperature influenced by the boundary condition within the numerical models.

Figure 5 and Figure 6 show the temperature evolutions for drift disposal and borehole emplacement. All observation points are at the emplacement level (-870 m), which is the level with the backfilled and sealed drifts. Exceptions are the top of the salt dome and, in the case of the borehole concept, points on the mid plane of the active borehole. In both disposal concepts the temperature limit of 200 °C is met. Slightly higher temperatures were observed in the borehole disposal concept at the positions of the emplacement fields with non-heat-generating waste, dam locations, and the shafts. Another effect appearing in the borehole concept is the thermal impact on the rock layers surrounding the host rock. Here the impact is higher than in the drift disposal concept because of the more compact emplacement of the waste canisters, see thermal behavior at a distance of 50 m from the main drift. No differences exist at the top of the salt dome; here the max. temperature is about 35 °C approx. 2500 to 3000 years after emplacement.

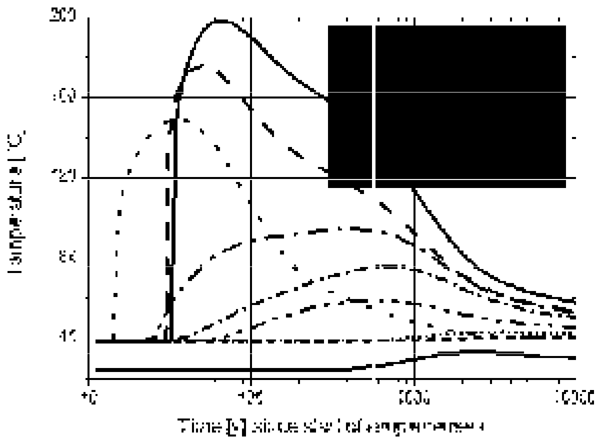

Fig. 5: Drift disposal – Temperature over time at different points in the repository.

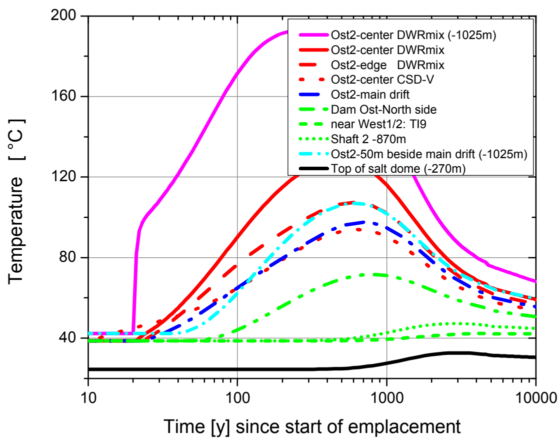

Fig. 6: Borehole disposal – Temperature over time at different points in the repository.

Results and conclusions:

- TM calculations showed that both disposal concepts (drift disposal and borehole emplacement) for the heat-generating waste meet the TM design criteria. The only difference is the smaller horizontal foot print in the case of borehole disposal.
- Compared with previous calculations (BAMBUS-Project) [7], the TM calculations used a more comprehensive and refined set of parameters (e.g., higher stress levels and faster creep classes of the host rock) which led to a substantially faster enclosure of the waste canisters or casks.

DESIGN OF THE SEALING SYSTEM

The objective of the repository closure concept and in detail of the sealing system is to create the conditions for a safe containment of the radioactive waste inside the host rock. As a first approach to safe containment, a continuous advective transport path for liquids from the overburden to the radioactive waste canisters and vice versa through man-made openings has to be prevented. For the design of the sealing system, a new methodology to demonstrate operational and long-term safety was applied; the so-called “Safety and Verification Concept” [2].

In accordance with the safety and verification concept, backfilling measures and engineered barriers are provided in all man-made openings of the repository mine. The drifts will mainly be backfilled with crushed salt, and other engineered barriers will be implemented in the drifts at selected locations and in the shafts. While the backfill material around the waste containers will be as dry as the naturally available material during excavation (< 0.02% of moisture content), the backfill material in the main transport drift will have a moisture content of 0.6%. The intention is to accelerate the compaction of the backfill material in order to heal the rock salt barrier as soon as possible.

In addition to backfilling, drift seals (engineered barriers) will be located close to the shaft filling station and infrastructure rooms at distinguished positions in all drifts connected to the shaft as well as at the exploration level and at the emplacement level. By this measure, potential pathways to the shaft will be sealed at an early stage, and the heat-generating waste will be separated from the non-heat-generating waste. The shaft filling station and the infrastructure rooms are backfilled with gravel which has negligible compaction capabilities and forms a permanent pore storage which delays brine pressure increase at the drift seals significantly. Eventually, both shafts will be sealed by shaft seals, i.e. engineered barriers consisting of several components (e.g. sealing elements, abutments, and pore storages). The components are selected in accordance with the geologic environment along the shaft length and the composition of brines that may intrude from the overburden.

Shaft Seals

The shaft seals are part of the overall repository sealing system. Based on the geological mapping of the existing shaft 1 in Gorleben, a draft for the shaft seal and a functional model were compiled. This draft took into account the detailed stratigraphic situation along the shaft length, the existing shaft accesses at the exploration level and the planned emplacement level as well as the composition of potentially intruding brine and the potential timing. Figure 7 shows the functional elements of the shaft seal. Starting from the bottom of the existing shaft, first a static abutment will be erected, followed by a sealing element (item 3 in Figure 7) with a twofold task. The sealing element a) separates the emplacement level from the shaft and b) seals a layer called the “Gorleben Bank”. It is followed by another abutment, which is connected to the pore storage of the infrastructure rooms at the exploration level, and a second sealing element (item 2 in Figure 7), again with the additional task to seal the “Gorleben Bank”. A long-term sealing element then forms the middle portion of the shaft seal. On top of this long-term seal, a combination of static abutment and porous material will be placed, followed by filter material. The sealing element (item 1 in Figure 7) on top of the filter again has the additional function to seal the “Gorleben Bank”. The final elements below the shaft foundation are filter materials. In the overburden the shaft is backfilled conventionally.

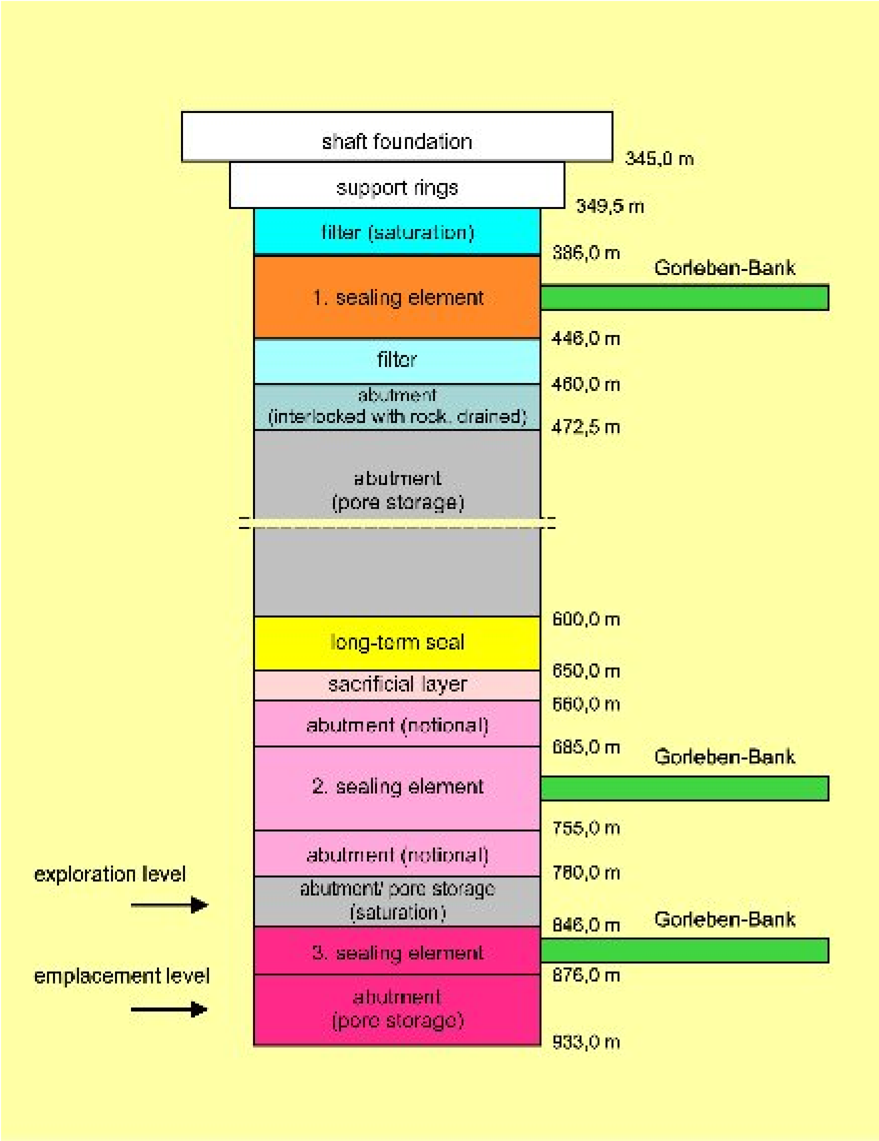

Fig. 7: Sketch of the functional model of the shaft seal.

The design of the shaft seal was investigated by preliminary design calculations. First geochemical calculations were carried out to analyse the influence of water/brine ingress from the top of the shaft through the sealing elements in order to confirm that the selected materials are suitable. The geochemical calculations were followed by preliminary mechanical calculations to determine the length of each abutment as well as to assess potential setting effects in order to avoid damage to the sealing elements. Then, it was checked roughly for the first time whether the shaft seal would be capable of retaining any intruding brine for such a period of time that the compacted crushed salt backfill would be able to prevent the transport pathway further on [9].

Based on a scenario analysis for the repository development, five design situations for the shaft seal were derived. These comprised the reference scenario with or without seismic impact, failure of a shaft seal, failure of a drift seal, and the impact of low/high convergence rates below/above expected values. In a second step the overall functional model and the functional elements in detail were investigated by means of a set of verification calculations (thermomechanical and hydromechanical). The results achieved showed that the time period (approx. 1000 years) is so long that in the meantime the backfill compaction has reached values which prevent advective brine flow to the waste canisters even if one seal fails. The entire description of the methodological approach and the calculations performed are compiled in a technical report [10].

Drift Seals

Verification calculations were performed for the drift seals as well. In all relevant scenarios, the adequate stability and tightness of the drift seal could be demonstrated.

RETRIEVABILITY

The repository design took into account the retrievability requirements in accordance with the new "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" as at 30 September 2010 [1]. The two main related requirements are:

- „Retrievability is the planned technical option for removing emplaced radioactive waste containers from the repository mine."
- „During the operating phase (of the repository) up until sealing of the shafts or ramps, retrieval of the waste containers must be possible."

As boundary condition, it was considered that a decision to retrieve waste canisters comprises all waste canisters disposed of and that the evolution of the repository in a reference scenario does not have an impact on the integrity of the waste canisters / casks.

Retrievability in the case of the drift disposal concept is planned as follows:

- The retrieval of waste canisters does in principle imply a reversion of the emplacement process. As a first step, a new drift is excavated parallel to the embedded POLLUX© casks while increased cooling is effected by means of extensive cooling and ventilation systems over a period of approx. 1 year. In a second step, the material above, to the side, and at the end of the cask is removed. Subsequently, the integrity of the containers is verified. After the containers have been recovered, they are moved into the new parallel drift. The POLLUX© casks can be picked up by a modified emplacement device. The transport process underground and to the surface is similar to the emplacement process. The total time necessary to retrieve all POLLUX© casks and to transport them to the surface accumulates to approx. 40 years.

Retrievability in the case of the borehole disposal concept is planned as follows:

- The original borehole disposal concept which consists of emplacing waste containers in 300-m-deep boreholes without casing does not comply with the new safety requirements. Therefore, the concept was adapted; i.e., the boreholes will be equipped with a casing closed/sealed tightly at the top. In addition to this, the design of the waste canister was modified. The casing would be designed to absorb the expected ground pressure of 40 MPa. For this purpose, calculations were carried out to determine a casing cross-section and a wall thickness that are able to withstand expected rock mass pressures. Accordingly, the casing will have an outer diameter of 800 mm and a wall thickness of 50 mm. The canisters were designed with a slightly conical shape in order to facilitate retrieval. The canister heads were also sloped to allow evacuation from the backfill material. The waste canisters will be placed in the center of the casing, and the annular space around the waste containers will be filled with backfill material. The backfill provides heat transfer through the casing into the surrounding rock mass and maintains its physical properties even under the expected high temperatures. Thus, in case of waste canister retrieval, a reverse extraction of backfill material out of the borehole is possible. All design steps of emplacing waste canisters in and retrieving them from vertical lined boreholes were analyzed. A more detailed design of the casing, the waste containers, the backfill material, and the overall processes has to be carried out in future R&D projects.

A further important aspect has to be taken into account when considering retrievability. Before the canisters may be retrieved, a concept for their subsequent storage aboveground must be implemented. Either an already licensed and constructed interim storage facility or a newly approved and constituted final repository may be used. For a period of up to 500 years after repository closure handleability of the waste canisters has to be shown [1]. This results in additional durability requirements on the canisters. The possibility to mechanically handle the canisters for the period mentioned has to be demonstrated. Additionally, the release of radioactive aerosols has to be prevented.

OPTIMIZATION OF REPOSITORY LAYOUT

When looking for possibilities for design optimization, the ventilation system for repository operation was investigated in detail. Preliminary calculation results showed that it is possible to provide sufficient amounts of fresh air in all mine areas and to transfer all exhaust air to the surface. In addition to this, the structures of drifts and emplacement fields were reconsidered in order to find possibilities to keep excavation to a minimum.

In addition to the investigations of the ventilation system optimization and the reconsideration of the structure of drifts and emplacement fields, there is still room for further optimization. This future R&D task should include a systematic comparison of emplacement concepts with regard to all technical components (e.g. transport and emplacement technique, technique and process of retrieving waste packages, arrangement of drifts and fields in the geologic environment etc.). And based on the TM calculation results, the repository layout and optimization should not only focus on a small footprint, it should also consider other aspects such as the overall drift lengths and the duration of the operational phase as well.

DEMONSTRATION OF SUBCRITICALITY

According to the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" [1] of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, it has to be shown that sufficient measures for ensuring subcriticality are provided both during the operational phase and during the post-closure phase for the whole reference period (1 million years). Substantial constraints and parameters which play a major role in the demonstration of subcriticality in the post-closure phase of the repository are, first, the condition of the spent fuel itself, i.e. constitution, enrichment, burn-up, geometric arrangement, conditioning mode, and the design of the disposal cask. Second, the potential long-term impacts on the disposal casks up considered.

Ingress of water or brine to the disposed spent nuclear fuels is a general prerequisite scenario for all cases examined in the post-closure phase within the scope of this work which lead to an increase in the multiplication factor. First, water as a neutron moderator can significantly increase the reactivity of dry configurations of spent nuclear fuel. Second, by means of chemical processes, it contributes to changes of initially subcritical configurations inside a cask. Reversely, it can be concluded that criticality is excluded for the final disposal of low enriched spent nuclear fuel if no ingress of water or brine occurs. For a repository in a salt dome, inflowing water generally means saturated brines. As the ingress of water or brine to the spent nuclear fuel is assumed to be an improbable event, ingress of brine was postulated for the criticality analysis at hand. Neither the point in time nor the probability of occurrence of this development was subjected to a criticality analysis. For future assessment and estimation of the probability of occurrence of an inadvertent criticality of spent nuclear fuel in the post-closure phase of the repository, a concerted approach of different areas of expertise is indispensable.

Analyses of the criticality safety of the considered disposal canisters BSK-3 and POLLUX©-10 casks, both loaded with fuel rods from light water reactor assemblies, as well as for generic transport and storage casks based on casks utilized for interim storage in Germany, were performed for the Gorleben repository site. Fuel assemblies and fissile material contents representative for German NPPs were taken as a basis. The fuel was conservatively assumed to be unirradiated, i.e. no reactivity decrease by burn-up was considered. Calculations performed showed, the occurrence of a self-sustaining nuclear chain reaction in a repository in a chlorine-based salt host rock based on the inventory of a single cask with spent fuel from light water reactors, BSK-3 or POLLUX©-10, as well as in case of the direct disposal of CASTOR© transport and storage casks, appears to be excluded. As shown by the calculation results for the cases studied, a significant decrease in reactivity – compared with pure water – is essentially caused by Cl-35, which is present in a high concentration in saturated brine in the salt dome in Gorleben. With regard to possible long-term effects, selected degradation cases such as flooding of the cask interior with water or brine, loss of implemented neutron absorbers (boron) or dissolution of the assembly basket structure have been modeled in the criticality calculations. Considering the saturation concentration of Cl-35 in the brine, all the systems and cases studied remain subcritical. Thus, the verification concept for subcriticality can be based upon the neutron absorbing properties of Cl-35.

Nevertheless, for some higher enriched fuels from research, test and prototype reactors, depending on fuel type and cask concept, additional conditioning measures may be necessary. A detailed assessment requires more extensive investigations which were beyond the scope of the current preliminary safety analysis. Altogether, the results of the current study on the exclusion of criticality in the post-closure phase of the repository are generally characterized as a feasibility study and may not be considered as a concluding demonstration of subcriticality which could be utilized directly in an approval procedure.

SUMMARY AND CONCLUSIONS

The preliminary safety analysis of the Gorleben salt dome carried out to investigate its suitability as a HLW repository is based on the "Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" as at 30 September 2010, and took into account the amounts of expected heat-generating radioactive waste based on the decision of 2011 to phase out nuclear energy production. Two completely different emplacement strategies, i.e. emplacing all heat-generating waste in horizontal drifts and emplacing all heat-generating waste in deep vertical boreholes, respectively, were designed. It could be shown and confirmed by TM calculations that both strategies could be accommodated in reliable repository concepts that meet all applicable performance and safety requirements. The technical design work showed that the Gorleben salt dome provides sufficient space on a single level to host a repository for all the heat-generating waste arising in Germany. Technical approaches how to retrieve waste containers were developed for both disposal concepts as well. Detailed designs of the geotechnical barriers were developed and provided promising results for the site-specific preliminary safety analysis. In addition, it could be shown that sufficient measures for ensuring subcriticality are provided both during the operational and the post-closure phases of the repository.

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