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KOSINA

Concept developments for a generic repository for heat-generating waste in bedded salt formations in Germany

BGE TEC 2018-13

Synthesis Report

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Abstract

A new Site Selection Act for a repository for HLW and SNF in Germany entered into force in July 2013 and was amended in spring 2017 [StandAG 2017]. It stipulates that the safety of repository systems for heat-generating radioactive waste and spent nuclear fuel in different host rock formations must be compared in order to identify the site with the highest possible safety. This requires that generic repository concepts and suitable safety and demonstration concepts for all potential host rock formations in Germany (salt, claystone and crystalline rock) exist. For many decades, the development of repository concepts and safety analyses for a repository in a salt dome was prioritized in Germany while repository concepts for claystone and crystalline rock have been taken into account for the past two decades only. So far, bedded salt formations have not been the subject of comparative investigations. Thus, in summer 2015, the Federal Ministry for Economic Affairs and Energy (BMWi) launched the R&D project KOSINA to develop repository designs and carry out safety analyses for different disposal options in a generic bedded salt formation and a generic salt pillow. KOSINA is a German acronym for "Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept". Together with its partners BGR, GRS, and IfG, BGE TECHNOLOGY GmbH has carried out an almost three years lasting scientific programme. The core areas of the programme are the development of generic geological models, including derivation of model parameters, the development of a safety and demonstration concept, the development of technical repository designs for four different disposal options, the analysis of geomechanical integrity, the evaluation of operational safety as well as the analysis of radiological consequences. An interim report, which compiles the basic data of the waste inventory, the repository design requirements, the data basis for geological model developments, and the outline of a safety and demonstration concept, was already published in February 2016. The main achievements of R&D project KOSINA are the development of four different disposal options, two per each generic geological model (flat-bedded salt, salt pillow) based on thermo-mechanical calculations. This includes the implementation of a safety concept that provides containment of the radioactive materials with regard to the technical designs of waste packages, transport and emplacement technologies, as well as backfilling and sealing concepts. Furthermore, the integrity of the geological barriers could be demonstrated for all four disposal options, and the long-term predictions showed no radiological releases during the demonstration period of one million years.

Zusammenfassung

Im Juli 2013 trat ein neues Standortauswahlgesetz für ein Endlager für hochradioaktive wärmeentwickelnde Abfälle und ausgediente Brennelemente in Kraft, das im Frühjahr 2017 geändert wurde [StandAG 2017]. Es schreibt vor, dass die Sicherheit von Endlagersystemen für radioaktive Abfälle in verschiedenen Wirtsgesteinsformationen verglichen werden muss, um den Standort mit der höchstmöglichen Sicherheit zu identifizieren. Dies setzt voraus, dass generische Endlagerkonzepte und geeignete Sicherheits- und Sicherheitsnachweiskonzepte für alle potenziellen Wirtsgesteinsformationen in Deutschland (Salz, Ton, Kristallin) vorliegen. Viele Jahrzehnte lang wurde in Deutschland die Entwicklung von Endlagerkonzepten und Sicherheitsanalysen für ein Endlager in einem Salzstock priorisiert, während Endlagerkonzepte für Tongestein und kristallines Gestein erst seit zwei Jahrzehnten berücksichtigt werden. Flachlagernde Salzformationen waren bisher ebenfalls nicht Gegenstand von Vergleichsuntersuchungen. Deshalb startete das Bundesministerium für Wirtschaft und Energie (BMWi) im Sommer 2015 das FuE-Projekt KOSINA zur Entwicklung von Endlagerkonzepten und zur Durchführung von Sicherheitsanalysen für verschiedene Entsorgungsoptionen in einer generischen flachlagernden Salzformation und in einem generischen Salzkissen. KOSINA ist die Abkürzung für "Konzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flachlagernden Salzschichten in Deutschland sowie Entwicklung und Überprüfung eines Sicherheits- und Nachweiskonzeptes". Gemeinsam mit ihren Partnern BGR, GRS gGmbH und IfG hat die BGE TECHNOLOGY GmbH ein fast dreijähriges wissenschaftliches Programm durchgeführt. Die Kernbereiche des Programms sind die Entwicklung generischer geologischer Modelle, einschließlich der Ableitung von Modellparametern, die Entwicklung eines Sicherheits- und Nachweiskonzeptes, die Entwicklung technischer Endlagerkonzepte für vier verschiedene Einlagerungsoptionen, die Analyse der geomechanischen Integrität, die Bewertung der Betriebssicherheit sowie die Analyse der radiologischen Konsequenzen. Bereits im Februar 2016 wurde ein Zwischenbericht veröffentlicht, der die Eckdaten des Abfallinventars, die Anforderungen an die Endlagerauslegung, die Datenbasis für geologische Modellentwicklungen und den Entwurf eines Sicherheits- und Sicherheitsnachweiskonzepts zusammenfasst. Die wichtigsten Ergebnisse des FuE-Projektes KOSINA sind die Entwicklung von vier verschiedenen Einlagerungsoptionen, jeweils zwei für jedes generische Modell (flachlagernde Salzformation, Salzkissen) basierend auf thermomechanischen Berechnungen. Dazu gehört die Umsetzung eines Sicherheitskonzeptes, das den Einschluss der radioaktiven Stoffe durch die technische Auslegung von Abfallgebinden, Transport- und Einlagerungstechnologien sowie Versatz- und Abdichtungskonzepten vorsieht. Darüber hinaus konnte die Integrität der geologischen Barrieren für alle vier Einlagerungsoptionen nachgewiesen werden; die Langzeitvorhersagen zeigten keine radiologischen Freisetzungen innerhalb des Nachweiszeitraums von einer Million Jahren.

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1 Introduction and Objectives

The Site Selection Act for a repository for heat-generating radioactive waste and spent nuclear fuel in Germany was issued in July 2013 and amended in Mai 2017 [StandAG 2017]. This act directs the selection process for a repository site in Germany that best ensures the repository safety for a demonstration period of one million years. This requires the existence of generic repository concepts as well as of suitable safety and demonstration concepts for all potential host rocks (rock salt, claystone and crystalline rock) in Germany.

In Germany, a reference concept for the disposal of heat-generating radioactive waste and spent nuclear fuel in salt domes was developed in the early 1980s. Comparable investigations for a generic repository in claystone or crystalline host rock formations were launched in the early 2000s. Up to now, bedded salt formations were not considered as host rock for the disposal of radioactive materials. For this reason, the R&D project KOSINA was launched in summer 2015, funded by BMWi represented by the Project Management Agency Karlsruhe. KOSINA is a German acronym for "Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept". The KOSINA project primarily serves to investigate the technical feasibility and safety of a generic repository for heat-generating radioactive waste and spent nuclear fuel in bedded salt formations for a demonstration period of one million years. In addition, it contributes to providing a basis for the safety-related comparison of repository systems in different host rock formations in accordance with the regulations of the Site Selection Act.

The following objectives were defined for the KOSINA project:

- Derivation of generic geological models and corresponding material parameters as well as requirements for the minimum thickness of the saliniferous formation
- Development of a safety and demonstration concept
- Development of technical repository designs for four different disposal options based on the generic geological models
- Identification of a containment providing rock zone
- Analyses of the integrity of the geological barriers as well as analyses of radiological consequences
- Generation of scientific and technical fundamentals for a safety-related evaluation of repositories in different host rock formations

To achieve the aforementioned objectives, the work programme of the KOSINA project was structured into eight work packages: basic data and requirements, generic geological models and material parameters, safety and demonstration concepts, demonstration of integrity of geological barrier, repository designs for four different disposal options, analysis of radiological consequences, investigation of operational safety, and summary of the results in a synthesis report. Most work packages are strongly linked to each other and had to be worked on iteratively. The methodical approach and the results of each work package however are compiled in individual work package reports (see list below).

The structure of this synthesis report follows the work break-down structure of the KOSINA project. Having in mind that the basic data and design requirements were already compiled in an interim report (as of February 2016), chapter 2 comprises a brief description of the safety and demonstration concepts which provide the basis for the repository designs and analyses of geomechanical integrity and radiological consequences. Chapter 3 provides a summary of the methodical approach as well of the results of representative geological models for both flat-bedded salt formations and salt pillows. The four disposal options considered are described in chapter 4. The mine layout, derived from TM-calculations, the transport and emplacement technique, the backfilling and sealing measures as well as operational safety investigations are highlighted. Chapter 5 shows the approach and the results of the geomechanical integrity analyses for the geological barriers, while chapter 6 summarizes the results of the analyses of the radiological consequences for the four disposal options. Finally, unsolved issues and needs identified for additional R&D are compiled in chapter 7.

List of WP-Reports:

WP 1 Konzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flach lagernden Salzschichten in Deutschland sowie Entwicklung und Überprüfung eines Sicherheits- und Nachweiskonzeptes KOSINA – Zwischenbericht, Dezember 2015, DBE TECHNOLOGY GmbH

WP 2 Zusammenstellung der Materialparameter für THM-Modellberechnungen – Ergebnisse aus dem Vorhaben KOSINA, Dezember 2017, BGR & IfG

Entwicklung generischer geologischer Modelle für flach lagernde Salzformationen – Ergebnisse aus dem Vorhaben KOSINA, Oktober 2017, BGR

WP 3 Sicherheits- und Nachweiskonzept für ein Endlager in flach lagernden Salzformationen – Ergebnisse aus dem Vorhaben KOSINA, April 2018, GRS

WP 4 TM- und THM-gekoppelte Modellberechnungen zur Integritätsanalyse der geologischen Barrieren in flach lagernden Salzformationen – Ergebnisse aus dem Vorhaben KOSINA, Mai 2018, BGR & IfG,

WP 5 Technische Konzepte für ein Endlager in flach lagernden Salzformationen – Ergebnisse aus dem Vorhaben KOSINA, Juni 2018, DBE TECHNOLOGY GmbH

WP 6 Bewertung der Wirksamkeit des Radionuklideinschlusses für ein Endlager in flach lagernden Salzformationen – Ergebnisse aus dem Vorhaben KOSINA, May 2018, GRS

WP 7 Bewertung der Betriebssicherheit für ein Endlager in flach lagernden Salzformationen – Ergebnisse aus dem Vorhaben KOSINA; Juni 2018, DBE TECHNOLOGY GmbH

WP 8 Synthesis Report

2 Safety and Demonstration Concept

A safety concept describes in a verbal, argument-based way how the natural conditions, processes, and technical measures contribute to accomplishing and maintaining the required level of long-term safety. A fundamental principle of the safety concept is the concentration and containment of the radionuclides and of other contaminants in the waste in the containment-providing rock zone (CRZ), which ensures isolation from the biosphere. Based on the principle of safe containment inside the CRZ, guiding principles, design objectives, and strategic measures are derived.

A safety demonstration concept describes the means, such as analyses and arguments, that are used to demonstrate the safety of a repository system based on the safety concept, its guiding principles, design objectives, and strategic measures. The decisive elements are: the demonstration of integrity of the geological barrier, the demonstration of integrity of the geotechnical barriers, the scenario analysis, and the evaluation of the scenarios identified. These elements are complemented by concepts on how to consider criticality, non-radiological protection targets, and operational safety.

2.1 Framework and Objectives

The framework for disposal of radioactive waste is given by national laws and regulations. The most important laws and regulations that must be taken into account in Germany are the Atomic Energy Act [AtG 2017], the Radiation Protection Act [StrlSchG 2017], the German Mining Act [BBergG 2017], and the General Federal Mining Regulation [ABBergV 2017]. Further specifications are given in the “Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste” [BMU 2010][1]. Additionally, relevant recommendations of international organizations like ICRP, IAEA [IAEA 2006], [IAEA 2011], and OECD-NEA [NEA 2004], [NEA 2009] have to be taken into account as far as they complement and substantiate the national regulations.

The Safety Requirements demand the development of a safety concept for the operational phase as well as for the post-operational phase. In this context, the safety concept has to consider safety-relevant aspects of the operational phase as well as in the post-operational phase unambiguously in a holistic approach. According to section 8.6 of the Safety Requirements, during the operating phase up until sealing of the shafts or ramps, retrieval of the waste casks must be possible. Measures taken to secure the options of retrieval must not impair the passive safety barriers and thus the long-term safety.

Safety-relevant aspects of operations (see sections 8.1 and 8.9 of the Safety Requirements) can only be assessed in detail if the repository concepts exist in a sufficient degree of detail, which was not scheduled in the present project. But it has been evaluated, whether the de-

[1] Throughout this text denoted as “Safety Requirements”. At the time this report was written, BMU was revising the Safety Requirements.

rived repository concepts are state of the art and whether there is evidence to give basic concerns against their feasibility from an operational safety point of view, cf. Chapter 4

Thus, the safety and demonstration concept developed in R&D project KOSINA for a repository in bedded salt formations is mainly related to the post-operational phase and substantiates the requirements in [BMU 2010]. Suitable results from the former R&D projects ISIBEL [Bollingerfehr et al. 2017] and VSG [Mönig et al. 2012] have been taken into account. The concept comprises the following tasks:

1. Development of a safety concept for a repository for heat-generating radioactive waste and spent fuel elements in bedded salt formations
2. Development of a safety demonstration concept based on the safety concept
    a. Specification of indicators and criteria to assess the capacity of containment, e. g. “safe containment”, “total containment”, and radiological safety
    b. Specification of a procedure to set out the position and boundaries of the containment-providing rock zone (CRZ)
    c. Specification of methodological concepts
        i. for the assessment of integrity of geological barrier
        ii. for the assessment of integrity of geotechnical barriers
        iii. for the safety related assessment of the effectiveness of radionuclide containment in the CRZ
3. Development of a concept to handle uncertainties

2.2 Safety Concept

2.2.1 General Approach

The safety concept is primarily based on a concept developed earlier and described in R&D project ISIBEL [Bollingerfehr et al. 2013], [Bollingerfehr et al. 2017]. This concept has been developed for domal salt formations. The original ISIBEL concept was developed further and described in more detail in [Mönig et al. 2012]. In the present report, the concept is extended to repositories in bedded salt formations.

As mentioned in Chapter 2.1, the focus of the concept is on the systematic demonstration of the safe long-term containment of the waste. The relevant barriers for this containment are the rock salt, the shaft seals, and the drift seals. Any void volume in the emplacement areas is to be backfilled with crushed salt, which will be naturally compacted by convergence. During compaction, the porosity and permeability of the crushed salt decrease until, in the long term, it has barrier properties comparable to the rock salt.

2.2.2 Specifications in the Safety Requirements

The specifications on HLW disposal in Germany are defined by the Safety Requirements governing the final disposal of heat-generating radioactive waste [BMU 2010]. The relevant specifications regarding the development of a safety concept and a corresponding safety demonstration are summarised in this chapter.

The protection targets of the Safety Requirements are to protect man and the environment. Unreasonable burdens and obligations for future generations are to be avoided. These protection targets are to be achieved by a final disposal concept that is based on the disposal of the radioactive waste *in a deep geological formation with a high containment capacity*[2].

The protection objectives and basic assumptions are expressed by eight safety principles that are defined in the Safety Requirements. In the context of the safety concept and the safety demonstration, the following three safety principles should be mentioned.

- Safety principle 4.1: The radioactive and other pollutants in the waste must be concentrated and contained in the containment providing rock zone (CRZ)[3], and thus kept away from the biosphere for as long as possible.
- Safety principle 4.2: Final disposal must ensure that in the long term, any release of radioactive substances from the final repository only negligibly increases the risks associated with natural radiation exposure.
- Safety principle 4.6: The final repository shall be constructed and operated in such a way that no intervention or maintenance work is required during the post-closure phase to ensure the reliable long-term containment of the radioactive waste in the containment providing rock zone.

While the safety concept described in the following chapters has to consider all safety principles, safety principles 4.1, 4.2, and 4.6 above are of particular importance. The determination of the CRZ and the confirmation of its containment capacity, by demonstrating the integrity of the geological barrier and the geotechnical barriers, are key elements of the safety demonstration (see chapter 0).

The Safety Requirements stipulate that the demonstration of the safety of the repository be documented in a comprehensive safety case and that this safety case be documented for all operating states of the final repository. Important parts of the safety case are a safety analysis and a safety assessment covering a period of one million years, which have to be carried out to provide evidence of long-term safety. This analysis comprises the following aspects:

- description of the geologic situation and of the final repository concept,
- identification, characterization, and evaluation of safety-relevant features, events and processes,
- comprehensive identification and analysis of safety-relevant scenarios and their allocation to probability categories,
- strategy for the identification, evaluation, and handling of uncertainties,

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2 Text written in italics is directly taken from the English translations of the Safety Requirements.

3 The English translation of the Safety Requirements uses the expression „isolating rock zone“ and defines this zone *as the part of the repository system which, in conjunction with the technical seals, ensures the containment of the waste*. Since this zone refers explicitly to the safety function “containment”, the term “containment providing rock zone” is used in this report.

- long-term statement on the integrity of the CRZ,
- proof of the integrity of the technical components during their functional period,
- long-term radiological statement,
- proof of subcriticality, and
- monitoring and evidence preservation programme.

All of these fundamental aspects were dealt with in the R&D projects ISIBEL [Bollingerfehr et al. 2017] and VSG [Fischer-Appelt et al. 2013], with the exception of the description of a monitoring and evidence preservation programme.

2.2.3 Guiding Principles and Basic Requirements

Based on the safety principles set out in the Safety Requirements (cf. chapter 2.2.2), and on existing knowledge concerning the processes that could impair the safety of the repository and the site properties, three guiding principles have been derived:

- the radioactive waste must be contained as widely as possible in the CRZ,
- containment shall be effective immediately after closure, and it must be provided by the repository system permanently and maintenance-free, and
- immediate and permanent containment shall be accomplished by preventing or limiting intrusion of brine to the waste forms.

These guiding principles are the main themes that set up the safety and demonstration concept.

The geological barrier should provide permanent containment. The rock salt within the CRZ is essential for the containment as it is practically impermeable to solutions. Accordingly, the integrity of the rock salt within the CRZ must be ensured.

A penetration of the geological barrier is inevitable during mine construction and will result in local impairment. Creep processes promoted by the visco-plastic-elastic properties of the rock salt will eventually lead to the closure of such mine openings, thus restoring the original properties of the geological barrier. Since this process requires time, engineered high-performance shaft seals and drift seals that provide the required sealing immediately upon construction shall be built. These engineered barriers may be affected by thermal and mechanical impacts and by chemical processes and, therefore, their long-term performance may not be irrefutably proven. To guarantee the long-term sealing of the penetrations, the mine workings shall be backfilled with crushed salt as long-term stable material. The compaction of the crushed salt, which is driven by salt creep, results in a very low permeability of the crushed salt over a certain period of time. Evidence must be provided that sealing by the compacted backfill material is fully developed by the time the performance of the engineered barriers can no longer be demonstrated. The evolution of the sealing effect over time for important barriers in the repository system is schematically shown in Figure 2-1.

In the event that brine inflow to the waste occurs, these barriers in combination with other barriers contribute to the containment of the radionuclides in the CRZ through different processes. This is achieved either by restricting the movement of contaminated solutions along the former drifts or, as in the case of the waste immobilizing matrix, by retarding the dissolution of the radionuclides.

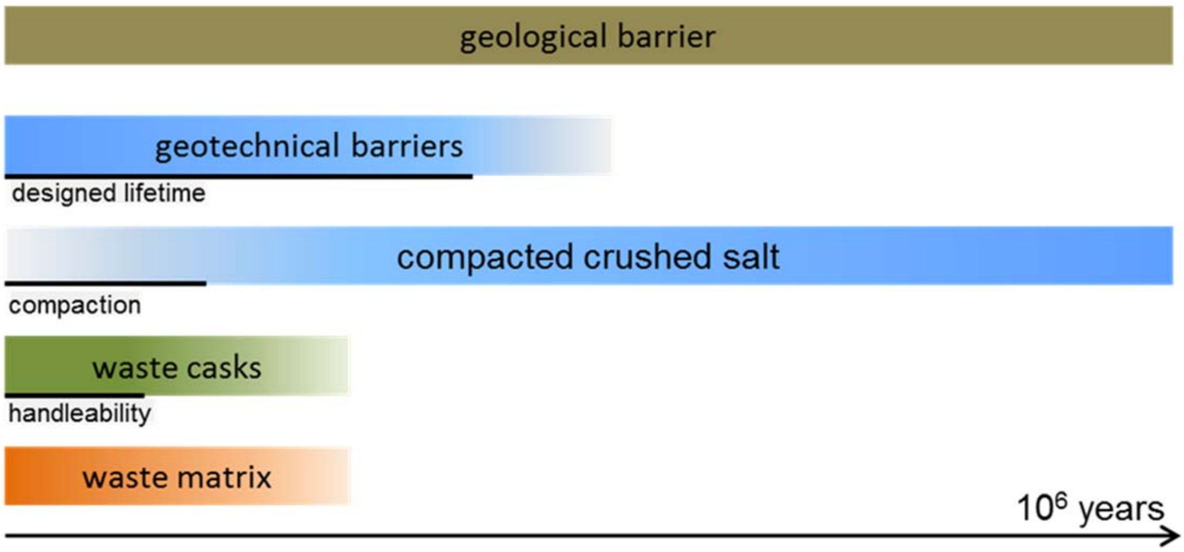

Figure 2-1: Evolution over time of the sealing effects of important barriers in the post closure phase of a repository system (the colour intensity represents the degree of the respective sealing effect, not to scale)

According to the Safety Requirements [BMU 2010] *handleability of the waste containers must be guaranteed for a period of 500 years in case of recovery from the decommissioned and sealed final repository. Care should be taken to avoid the release of radioactive aerosols. During the operating phase up until sealing of the shafts or ramps, retrieval of the waste containers must be possible.*

For a further development of the safety concept, the guiding principles were supplemented with the definition of two further design requirements; a third additional design requirement stems from the regulatory requirement to avoid criticality in the repository.

- Basic requirement A – Containment: The emplaced waste canisters shall be enclosed quickly and as tightly as possible by the salt.

- Basic requirement B – Performance of CRZ: During the demonstration period of one million years, the CRZ shall remain intact and its barrier function shall not be impaired by internal or external processes and effects.

- Basic requirement C – Subcriticality: Subcriticality must be guaranteed in all phases of the repository evolution.

These basic requirements were used to derive specific objectives and to determine strategic measures that embrace design specifications, for example with respect to the mine position in the salt formation, and technical provisions. Typically, each strategic measure supports a number of specific objectives. The strategic measures in their entirety combine to meet the objectives of the safety concept. The principle types of correlation between design requirements, specific objectives, and measures are schematically shown in Figure 2-2.

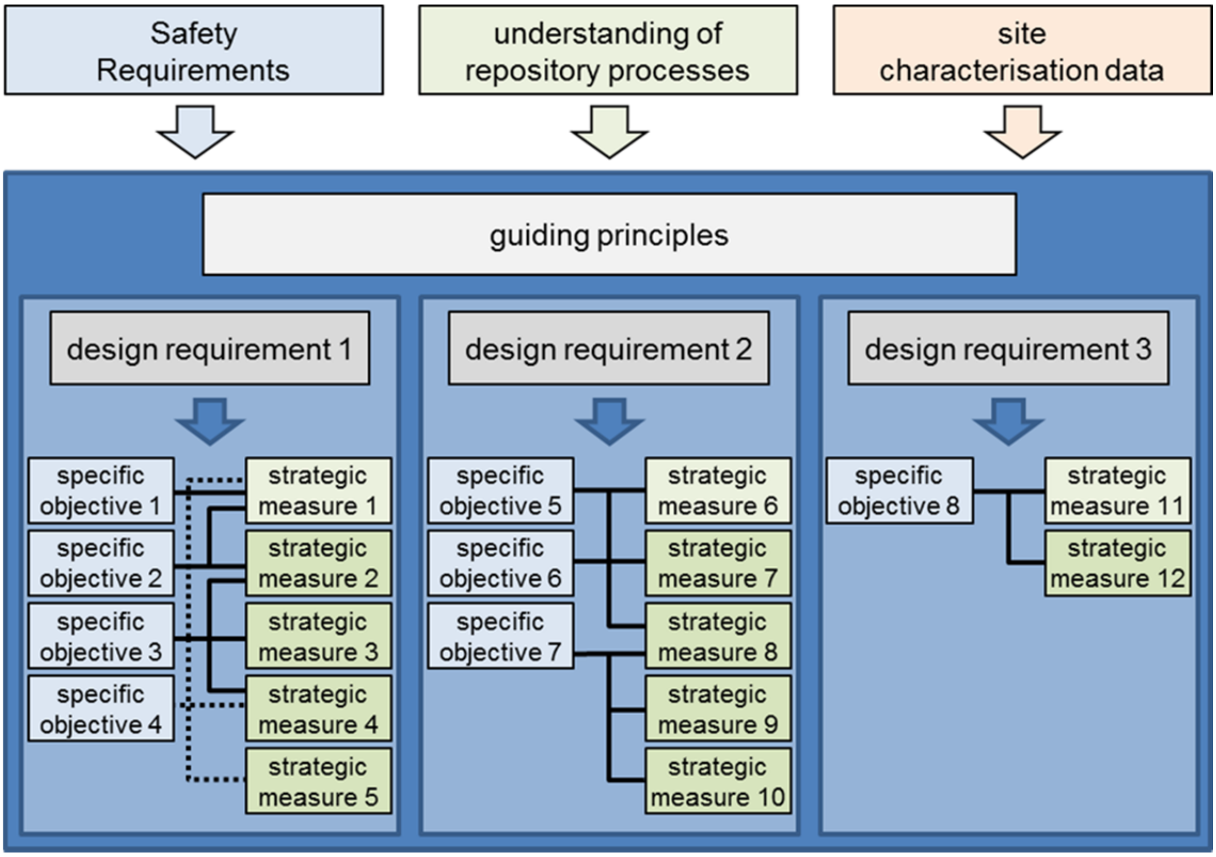

Figure 2-2: Schematic diagramm of the basic approach to derive specific objectives and strategic measures for the safety concept

Another basic requirement results from the Safety Requirements [BMU 2010]. It states that in the case of recovery, the waste casks must be handleable for all probable developments within a time period of 500 years after closure of the mine. A release of aerosols from the interior or from the casks must be excluded. Although a proof of this requirement for existing casks is lacking, it is assumed that appropriate cask designs will be available in the future and that this requirement can be met.

2.2.4 Objectives and Strategic Measures for the Post-Operational Phase

In total, 14 objectives and 17 strategic measures were set up and are summarized in the following subsections. Detailed explanations can be found in [Mönig et al. 2012]. The strategic measures as a whole provide the basis for the site-specific design and layout of the repository (chapter 4).

2.2.4.1 Objectives

For requirement A, to enclose the emplaced waste canisters quickly and as tightly as possible by the salt, eight specific objectives have been derived:

O1: No solution, or at best very minute amounts of solution, shall come into contact with the waste canisters emplaced in all probable evolutions of the repository system.

O2: Only limited amounts of solution shall come into contact with the waste canisters in less probable evolutions of the repository system.

O3: In the event of radionuclides being mobilised from the waste, transport in gas and liquid phase of these pollutants shall be retarded by chemical and physical processes.

O4: The properties of both, the rock salt and the engineered barriers that are responsible for the containment of the radionuclides, shall be readily predictable.

O5: The repository shall be designed in such a way that no intervention is necessary from the outside during the post-closure period.

O6: The engineered barriers shall be designed robustly, in order to ensure their safety functions, taking into account different load cases and possible degradation processes.

O7: The immediate and long-term containment of the radioactive waste in the CRZ shall be ensured by a staggered barrier system. The individual elements shall act redundantly or on diverse processes and they shall complement each other in their temporal effectiveness.

O8: The number of emplacement fields which are open at the same time shall be minimized to allow a robust disposal concept. Therefore, the disposal concept shall provide a segmentation of emplacement areas to allow a fast emplacement of the waste and the prompt backfilling and sealing of the corresponding drifts and boreholes.

Requirement B states that the CRZ must remain intact and that its barrier function is not impaired by internal or external processes and effects. This requirement results in five specific objectives:

O9: The quality of the containment shall not be impaired by surficial or salt tectonic processes during the assessment period.

O10: The quality of the containment shall not be impaired by thermal processes during the assessment period.

O11: Salt minerals containing crystal water, e.g. carnallite, shall not be thermally degraded.

O12: Gas production and gas production rate shall be sufficiently low to avoid impairment of the CRZ by a frac during the assessment period.

O13: The consequences and possibility of unintended human intrusion in the CRZ shall be reduced by repository layout and administrative measures as long as these measures do not have negative effects on long-term safety.

Requirement C is to maintain subcriticality. This relatively explicit requirement leads to one further objective:

O14: Subcriticality has to be maintained for the operational and post-closure phase by the loading and design of the casks and the design of the repository.

2.2.4.2 Strategic Measures

In total, seventeen strategic measures are derived from the objectives listed in Chapter 2.2.4.1. In general, a measure covers several objectives, thus in the listing, the corresponding objectives are given for every measure. The following measures are related to the objectives O1 to O8 (containment); more details to some of the measures are given in [Kindlein et al. 2018]:

M1: The excavation volume of the repository will be as small as possible. The excavation will be performed using gentle methods in order to limit the impact on the geological barrier. Due to the restrictions in a bedded formation, the vertical extension of the disposal rooms will be as small as possible. (→ O1, O2, O3)

M2: The mine openings of the emplacement areas will be excavated in salt regions with homogeneous structures and properties, e.g. in the Staßfurt rock salt Series (Hauptsalz). (→ O4)

M3: The mine openings of the emplacement areas will be excavated in salt regions that are free of brine pockets of significant volume and that provide favourable creep properties for fast enclosure of the waste. These emplacement areas will be excavated in the Staßfurt rock salt Series (Hauptsalz). (→ O1, O2)

M4: The mine openings of the emplacement areas will be excavated with sufficient safety pillars to the shafts, to rock strata below the Staßfurt rock salt series with potentially larger brine and gas pockets, and to potential transport paths for solutions in rock strata above the Staßfurt rock salt series. Based on the existing experience in salt mining, a safety pillar of 50 m was determined. Additionally, a horizontal safety pillar of 500 m around the mine is stated [Minkley et al. 2010]. The safety pillar between emplacement areas and the shafts is preliminary stated as 300 m and has to be proven by site-specific calculations. (→ O1, O2)

M5: Engineered barriers with defined hydraulic properties will be erected in the shafts and in the access drifts between infrastructure area and the emplacement areas. Their design is based on load cases which should cover the potential range of future impacts during the required duration of effectiveness. The engineered barriers must be adequately tight until the hydraulic resistance of the compacted crushed salt effectively hinders the brine intrusion to the waste. (→ O1, O2, O3, O5, O6, O7)

M6: The mine openings of the emplacement areas will be backfilled with crushed salt. The convergence process will result in a temperature-dependent compaction of the crushed salt with a reduction in its porosity and permeability. The pressure build-up in crushed salt introduces a reduction of strain differences in the host rock and a faster healing of the rock salt in the excavation damaged zone. In addition, this measure reduces the void volumes in the emplacement areas that could be filled with solution. (→ O1, O2, O5, O6, O7)

M7: The backfill in the access drifts must consolidate in short time to be acceptably tight. Thus, small amounts of moisture will be added to the crushed salt that is used to backfill the access drifts, in order to increase the plasticity of the crushed salt and thus to accelerate its compaction. (→ O1, O2, O5, O6, O7)

M8: The amount of humidity in the vicinity of the emplaced waste will be minimized in order to constrain the corrosion of waste canisters and thus to limit gas production. Crushed salt having only the small natural aqueous content of the Staßfurt rock salt Series, Hauptsalz, will be used as backfill material in the mine openings of the emplacement areas. To this end operational provisions will be taken for handling the crushed salt upon excavation. (→ O1, O2, O5, O6, O7)

M9: The shaft seals will be designed such that their seal efficiency relies on several different sealing elements that are independent from each other and that have diverse functionalities due to their configuration. (→ O6, O7)

M10: Emplacement areas will be segmented in order to minimize the simultaneously open volume to be backfilled with crushed salt and to guarantee a prompt backfilling of the emplacement areas already filled with waste. The emplacement areas most distant from the shaft area will be filled first. Afterwards, the emplacement areas will be closed immediately by suitable geotechnical barriers. (→ O8)

M11: The emplacement areas with waste that differ in expected gas production or chemical properties will be separated in two different areas in the repository in order to prevent physical and/or chemical interactions between both waste types. The separation will be guaranteed by seals. (→ O8)

The following measures are related to the objectives O9 to O13 (permanence of CRZ):

M12: The repository's drifts and boreholes will have a sufficient distance from crystal water containing salt minerals such as carnallite in order to avoid their thermal degradation under local temperature and stress. Together with measure M14 it is guaranteed that these rock areas remain stable and their properties predictable. (→ O11)

M13: The disposal level will be at a depth that guarantees a permanent position in the salt formation and a sufficient thickness of the salt formation above the disposal level. The minimum thickness of the Zechstein salt formation was set to > 100 m. A depth of 500 to 1000 m below ground will exclude negative influences of processes close to the earth surface on the CRZ. The depth of disposal level will also reduce the possibility of human intrusion. (→ O9, O13)

M14: The repository will be built in a calm tectonic regime, i.e. salt movement is practically excluded. During the assessment period, the salt formation (Zechstein) will therefore not be reduced in thickness to a relevant extent and the CRZ will not be affected from the outside. (→ O9)

M15: The maximum temperature in the salt formation will be limited to 200 °C[4] by applying appropriate thermal loading and emplacement geometry of the casks (→ O10, O11).

M16: To avoid fractures in the CRZ and a loss of integrity of the geological barrier, gas production and the gas production rate are limited by minimizing the moisture in the backfill and, if necessary, by using appropriate cask materials. (→ O12)

The following measure is related to objective O14 (subcriticality):

M17: The loading and the design of the waste casks and the layout of the emplacement areas must guarantee subcriticality. Corresponding analyses have to be carried out on the basis of potential repository evolutions and of the radioactive inventories of the waste casks including the consideration of uncertainties. (→O14)

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[4] This temperature criterion is only used for the repository layout. It aims at two things: firstly, it shall ensure that the maximum temperature within the waste casks is low enough to avoid negative alterations of the waste (reduced stability of fuel rods or degradation of the glass matrix in vitrified waste). Secondly, taking the foreseen safety distance of at least 50 m from the emplacement fields to the bounding salt layers (including Carnallite) around Staßfurt Hauptsalz into account, it can be assumed that by limiting the temperature in the emplacement fields Carnallite is not thermally degraded and no crystallization water can be released.

The temperature limit of 200 °C corresponds to the design temperatures applied in former R&D projects concerning the disposal of heat-generating radioactive waste in domal rock salt formations, such as ISIBEL and VSG, respectively. By using the same temperature limit in KOSINA, the findings can be directly compared to those of the former R&D projects. As yet no scientific findings challenge substantially a maximum temperature of 200 °C for a repository in rock salt.

In the German site selection act [StandAG 2017], though, at first a maximum temperature of 100 °C at the surface of the casks is assumed as a precautionary measure for each host rock as long as no higher host rock specific maximum temperatures can be warranted based on the results of prospective R&D projects.

2.3 Safety Demonstration Concept

In the same way as the safety concept, the safety demonstration concept is based on concepts developed and refined in the projects ISIBEL and VSG. According to these concepts, the decisive elements are:

- demonstration of integrity of the geological barrier,
- demonstration of integrity of the geotechnical barriers,
- scenario analysis, and
- evaluation of release scenarios.

The key elements of the safety demonstration concept are schematically shown in Figure 2-3. The concept focuses on the demonstration of long-term safe containment of the waste by demonstrating the integrity of the geological barrier, whereas the proven designs of geotechnical barriers were taken over from former R&D projects ISIBEL and VSG.

While operational safety has been investigated in detail, other additional elements of the safety demonstration concept, such as proof of subcriticality, non-radiological protection targets, and human intrusion are just mentioned (represented as blue columns in Figure 2-3).

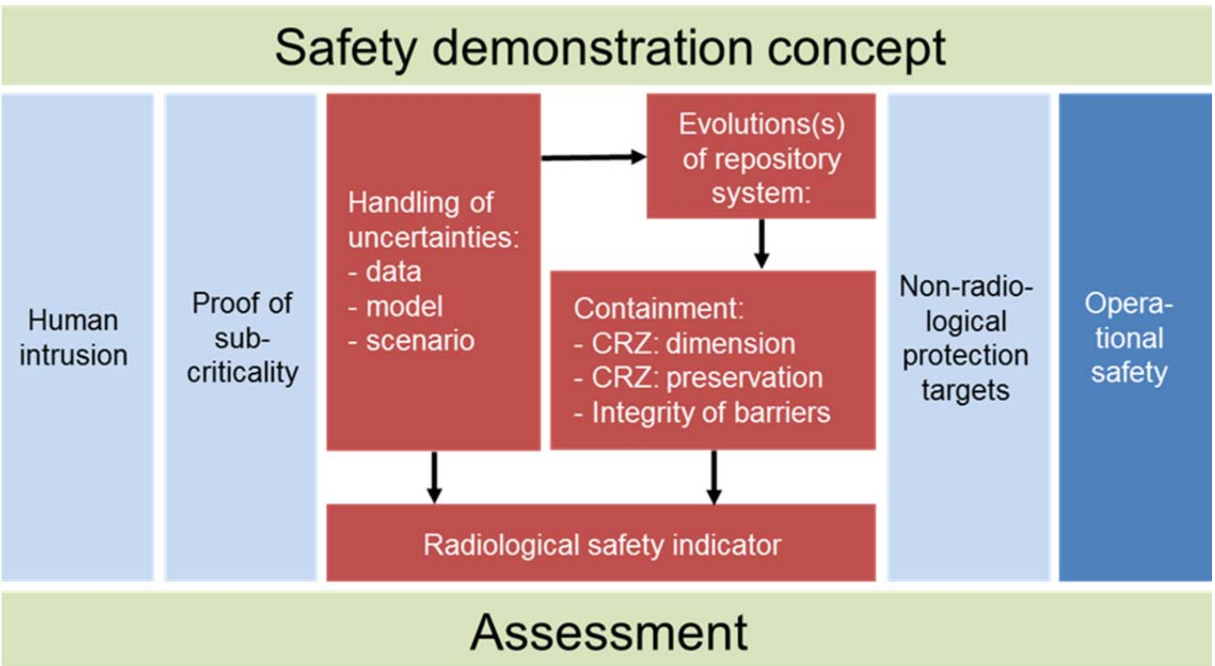

Figure 2-3: Elements of Safety Demonstration

The specifications of the Safety Requirements as discussed in chapter 2.2.2 must be supplemented by further specifications related to the demonstration of safety. Among these are specifications regarding optimization of the repository layout, the role of indicators for dose or risk, details for the assessment of potential releases, integrity of the containment-providing rock zone, robustness of the technical components, uncertainty and sensitivity analyses, and consequences of other contaminants [Mönig et al. 2012]. These specifications are taken into account in the following.

Determination of containment-providing rock zone

The determination of the containment-providing rock zone, in particular its dimensions, is essential for the assessment of the containment of radionuclides in this zone. According to the Safety Requirements, the applicant should provide a clear spatial and temporal definition of the containment-providing rock zone.

The Safety Requirements do not specify or restrict the size of the CRZ. Nevertheless, a CRZ with very large extension would contradict the idea of concentrating the waste at the emplacement site. To be able to assess the containment of pollutants in the CRZ, its size and position must be specified, see [Bollingerfehr et al. 2017]. For the model calculations presented in chapter 6, a preliminary CRZ is defined according to former projects. By variation of the boundary of the CRZ, the final extension of it can be determined [Kindlein et al. 2018].

Preservation of containment-providing rock zone during the assessment period

According to the Safety Requirements, the barrier function of the CRZ may not be impaired by internal or external processes. Therefore, it must be checked whether in this period the thickness of the salt barrier within the CRZ is reduced from the outside by geological processes. This can be done by a geological long-term prognosis, which was not part of the KOSINA project.

Another tool for checking the barrier function of the CRZ is the analysis of integrity of the geological barrier. The term “integrity” is used to describe the containment capability of the rock salt. Integrity means, in the case of rock salt, the absence of interconnected pore spaces such that practically no hydraulic or diffusive flow processes can occur. Thus the integrity indicates the ability of the salt barrier to permanently prevent the inflow of fluids into the repository from the overlying rock and to prevent leakage of contaminated fluids and gases from the repository to the outside environment. The assessment of integrity is performed by rock mechanical calculations for the entire rock region. Details are given in chapter 5.

Integrity of the geotechnical barriers

The prerequisite for the long-term safe containment of radioactive waste is the integrity of the geological and, during their anticipated functional lifetime, of the geotechnical barriers. The barriers should prevent or minimize solution inflow to the waste or a release of contaminated solutions. The integrity of geotechnical barriers was not investigated in this project. This task has to be carried out upon a site-specific project in the future. However, reference was made to comparable geotechnical barriers in VSG [Müller-Hoeppe et al. 2012b].

Radiological safety indicators

Radiological safety can be assessed by indicators:

- an effective dose occurring additionally[5] in the biosphere, and
- a radiological indicator, which is based on the release of radionuclides from the CRZ.

To implement the specifications in the Safety Requirements, the concept of so-called RGI (Radiologischer Geringfügigkeits-Index (index of marginal radiological impact)) is applied. Details are given in chapter 6.

Proof of subcriticality

Criticality must be excluded in all parts of the repository and over the entire assessment period. In the previous R&D project VSG [Bollingerfehr et al. 2012], subcriticality was assessed for mainly the same cask types, the same inventories and similar repository designs as here. Thus, subcriticality was not investigated in KOSINA.

Human intrusion

The Safety Requirements stipulate the analysis of scenarios of future inadvertent human intrusion to identify potential optimization measures for the repository layout. Potential starting points for optimization are the reduction of probability of human intrusion or the reduction of radiological consequences. Human intrusion aspects for repositories in salt formations have been investigated in detail in R&D project VSG [Beuth et al. 2014] and are not repeated here. It is assumed that the results of this investigation hold for bedded salt formations as well.

2.4 Handling of Uncertainties

Handling of uncertainties was a major task in former R&D project ISIBEL and discussed in detail in [Buhmann et al. 2010b] and [Buhmann et al 2016]. The present investigation is based on this experience and the details are not repeated here. In the model calculations of chapter 6, uncertainties are treated by parameter variations, What-If cases and probabilistic calculations, see also [Kindlein et al. 2018].

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5 Additional to other effective doses in the biosphere such as from natural background radiation.

3 Generic Geological Models

3.1 Structural-geological Characteristics of Flat-Bedded Rock Salt Sequences and Salt Pillows

Unlike salt diapirs (salt domes, salt walls), where evaporitic horizons have broken through parts of the cap rock as a result of upward movement of the salt, flat-bedded salt horizons within sedimentary sequences are characterised by concordant (sub-parallel) bedding conditions over large areas (see Figure 3-1, A). Flat-bedded rock-salt-bearing sequence can also contain localised slightly wavy deformation structures (intra-evaporite structures with dipping beds and fluctuations in the thickness of the rock salt), as well as some intensely folded evaporite layers in part (e.g. potash seams). These are usually only small-scale bedding disruptions or locally folded salt horizons, as well as flexures, which are mainly attributable to the "buffering" of fault zones in the horizons above and below the salt sequence, or as a result of the halokinetic redistribution of salt into neighbouring salt structures. Despite these intra-evaporite structures, flat-bedded evaporitic sequences are usually conformably bedded with respect to the cover rocks.

Salt pillows are considered as a special type of bedded evaporitic sequences in the KOSINA project. Salt pillows are dome-like structures (brachyanticlines) that developed as a result of the migration of salt into the structure. A crucial aspect of the genesis of these structures is the accumulation of rock salt by the lateral inflow and accumulation of the most easily mobilisable parts of a salt sequence (frequently the rock salt horizons belonging to the Staßfurt Formation). During the course of the accumulation, the younger, less creepable rock salts in the evaporitic sequence, as well as the cover rock, become domed upwards (see Figure 3-1, B). The cover rock horizons influenced by the structural genesis are bedded conformably with the strike and dip of the outer contours of the salt pillow. At the crest of the salt pillow, the sequence of beds in the cover rock can have a reduced sedimentary thickness, and in parts, even lack certain horizons altogether. By contrast, the thickness of these sediments is often increased in the rim synclines surrounding the salt structure. Salt pillows characterised by significant updoming and steep flanks are referred to as mature salt pillows. The crests of such salt pillows are often associated with faulting in the cover rock.

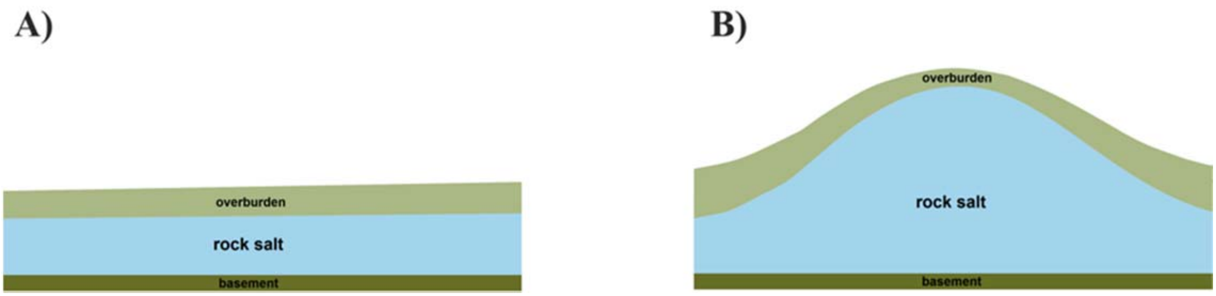


Figure 3-1: **Schematic diagram of the bedding in model A (type "flat-bedded") and model B (type "salt pillow").**

3.1.1 Flat-bedded Rock Salt Sequences

Information on the spatial distribution of flat-bedded rock salt successions in Germany and their lithological composition are summarised in the BGR-BASAL project [Reinhold et al. 2014], [Reinhold & Hammer 2016]. This project focuses on evaporitic formations with regionally occurring flat-bedded rock salt sequences with thicknesses of at least several tens of metres. A sequence of rock salt horizons of this kind within an evaporite formation is classified as a rock salt deposit or a rock salt succession. They occur in Germany in the following stratigraphic units: Rotliegend, Zechstein (both Permian), Röt, Muschelkalk, Keuper (all Triassic), Malm (Upper Jurassic) and Tertiary (Palaeogene) (see Figure 3-2).

Whilst today's distribution of Rotliegend, Röt, Keuper and Malm evaporites is limited to the North German Basin or at least parts of this basin which were actively subsiding in the Mesozoic, rock salt deposits of Zechstein, Muschelkalk and Tertiary age also occur in south Germany. Differentiation of the deposition in some sub-basins as well as synsedimentary tectonic and halokinetic movements caused a significant reduction in the distribution of the rock salt deposits in the Keuper and Malm evaporitic sequences, compared to the Zechstein, Röt and Muschelkalk evaporitic sequences – as well as locally limited resulting in strong variations in the thickness and composition of the evaporites. Many flat-bedded rock salt deposits occur at depths of more than 1000 m bgl and are therefore of only limited economic use. In those areas where flat-bedded rock salt successions occur at shallower depths (e.g. evaporite formations in some of the marginal basins of the overall area of Zechstein deposition, or in the Muschelkalk and Tertiary sediments in south Germany), these salt deposits have in some cases been intensely exploited for the extraction of rock salt or potash salt, or for the construction of caverns.

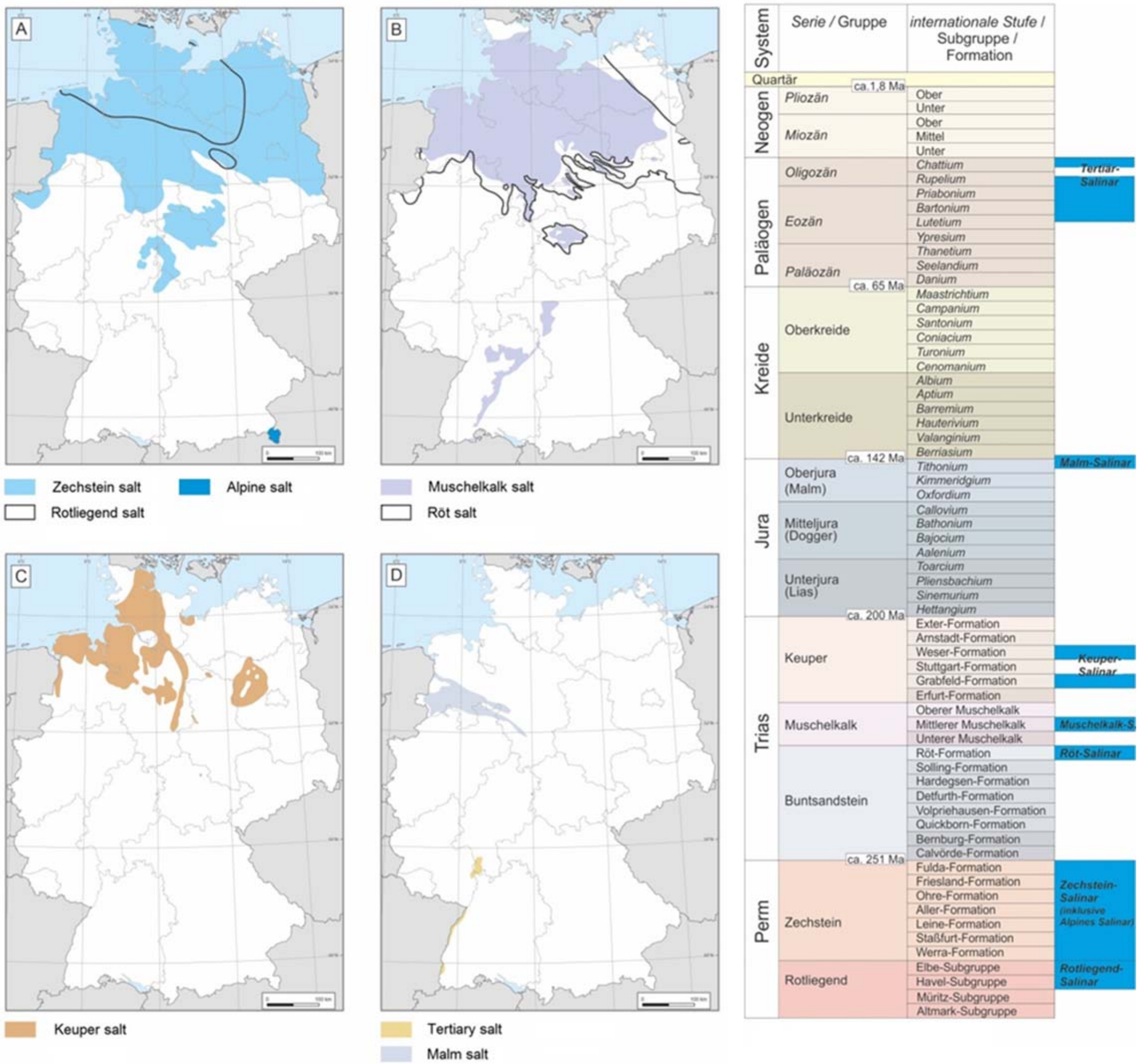


Figure 3-2: **Distribution of rock salt deposits in Germany**

An overall assessment of all the flat-bedded rock salt successions in Germany reveals that the rock salt deposits of the Zechstein are particularly interesting for more detailed repository-specific investigations because of their thickness and depths. [Reinhold et al. 2014] specified the following six exemplary areas containing flat-bedded rock salt successions of Zechstein age with larger thicknesses and situated at the necessary depths:

- Lower Rhine Basin
- Solling Basin
- Werra-Fulda Basin (including the Frankish Basin)
- Thuringian Basin
- Calvörde Block
- Lower Lusatia Basin (SE-Brandenburg)

The rock salt successions in these areas were deposited in the southern part of the marine Zechstein basin (and/or in its sub-basins). The cover rock in these regions today is often less than 1000 m thick. Rock salt deposits of the Werra Formation (z1) in particular are present in the Lower Rhine, Lower Lusatia and Werra-Fulda Basins. Thick rock salt deposits of the Werra, Staßfurt and Leine formations (z1 to z3) have been confirmed in the Thuringian Basin. The Staßfurt rock salt deposit is over 100 m thick on the Calvörde Block where the rock salt deposits of the Leine Formation are also several decametres thick. Thick rock salt deposits in the Staßfurt, Leine and Aller formations (z2 to z4) occur in the Solling Basin [Krull et al. 2004], [Reinhold & Hammer 2016].

3.1.2 Salt Pillows

The most up-to-date information on the distribution and geological properties of the salt structures occurring in Germany was elaborated in the InSpEE project from 2012 to 2016 [Gast & Riesenberg 2016], [Pollok et al. 2016]. According to this information, the genesis of the salt structures is mainly influenced by rock salt deposits of one stratigraphic unit (e.g. Zechstein). In exceptional cases, two evaporitic sequences of different ages can also be involved in the genesis of the salt pillow, such as in the case of the structure-driving Rotliegend evaporite sequence which forms so-called double-evaporite structures together with the Zechstein evaporites. Examples of this are the Karla, Helgoland and Hahnöfersand salt pillows which contain both Zechstein and Rotliegend evaporite deposits. These structures usually lie at depths greater than 2000 m below sea level [BGR 2017].

The salt pillows with the widest distribution are those which developed within the Zechstein evaporite sequence. The rock salt deposits creating these structures are in most cases part of the Werra, Staßfurt or Leine formations. This is dependent on the regional distribution and thickness of each of the rock salt deposits [Pollok et al. 2018]. The thicknesses of the salt pillow structures of Zechstein salt range from around 350 m to more than 3400 m. The crests of the salt pillow structures range in depth from 134 m bsl (Teutschenthal salt pillow) to over 5100 m bsl (Ahe salt pillow). According to the information currently available, there could be several salt pillows which match the project-specific specifications (see Chap. 3.2) in places including Brandenburg, Sachsen-Anhalt and southern Niedersachsen.

Salt pillows formed by Röt or Muschelkalk evaporites have not been discovered in north Germany to date. Thick concentrations of salt formed by Keuper evaporites are mainly in the northwest of Niedersachsen and over the whole of Schleswig-Holstein. The tops of these structures reach as deep as approx. 1200 m bsl.

Salt pillow structures consisting of Malm evaporites are horizontally extremely localised and consist of interbedded salt-clay and anhydrite. The structures involved have several hundred metres of rock salt in some cases. The tops of these Malm salt pillows today lie at depths of between around 300 m bgl to 800 m bgl [Kockel & Krull 1995], [Reinhold et al. 2014].

3.2 Conditions for the Elaboration of generic geological 3D Models

The elaboration of generic geological 3D models requires definitions of the geological conditions for the potential host rock and the repository site. The statutory criteria defined in the

Site Selection Act [StandAG 2017] which came into force in 2017 were not foreseeable when the KOSINA project began in 2015. As the project progressed, the Commission for the "Storage of high-level radioactive waste" largely confirmed in its recommendations the geoscientific requirements advocated by the Committee for a Site Selection Procedure for Repository Sites [AkEnd 2002], [Endlagerkommission 2016]. The amendment of the StandAG in 2017 stipulated in law the geoscientific exclusion criteria, minimum requirements and weighing criteria for a geological site selection process.

The KOSINA project used the geological criteria that were up for discussion in 2015 for the selection of a site for a repository for heat-generating radioactive waste and spent fuel in Germany (see [AkEnd 2002], [Krull et al. 2004], [Hammer et al. 2009]). AkEnd (Committee for a Site Selection Procedure for Repository Sites) elaborated exclusion criteria, minimum requirements, and assessment criteria [AkEnd 2002]. The exclusion criteria are used to exclude areas with particularly unfavourable geological conditions "*in which the barrier system of a repository located at a depth of around 1000 m would be significantly impaired during the isolation time period, or whose establishment cannot be forecast using prudent and practical benchmarks*" [AkEnd 2002].

Five exclusion criteria were defined as follows:

- The site must not have any uplift over a wide area of more than a millimetre per year during the forecasting time period.
- There must be no active faults at the site.
- Expected seismic activity at the site must not exceed earthquake zone 1 pursuant to DIN 4149.
- There must be no Quaternary volcanic activity at the site, nor should such activity be expected during the forecasting time period.
- No young groundwater must be present in the section of the rock mass required to create an effective barrier, and the groundwater must not contain any tritium and/or C-14.

In addition, areas which are not ruled out on the basis of the exclusion criteria must also satisfy a number of minimum requirements proposed for the host rock. [AkEnd 2002] defined the following host rock independent minimum requirements:

- containment-providing rock zone must consist of rock types which have a rock mass hydraulic conductivity of below 10^{-10} m/s.
- The containment-providing rock zone must be at least 100 m thick.
- The depth of the surface of the necessary containment-providing rock zone must be at least 300 m (bgl).
- The repository must not be deeper than 1500 m (bgl).
- The containment-providing rock zone must extend over an area which allows the realisation of a repository (e.g. at least 3 km^2 within rock salt).
- The containment-providing rock zone and/or the host rock must not be at risk of rock bursts.
- There must be no known information or data which appears to contradict compliance with the geoscientific minimum requirements for rock permeability, thickness and the extent of the containment-providing rock zone over a time period of one million years.

In the KOSINA project it was considered that a depth of more than 500 m bgl for the highest roof of the repository is favourable for the reliability of the long-term safety demonstration with respect to an adequate safety distance to the biosphere (see M 13, chapter 2.2.4.2.). This therefore satisfies the specifications proposed by [AkEnd 2002] and stipulated by [StandAG 2017] with respect to a minimum depth of 300 m bgl.

According to [AkEnd 2002], the base of the repository should be above 1500 m bgl. This depth was justified by the increasing cavity convergence which occurs at increasing depth, as well as the rising formation temperature which should not exceed 50 °C in the actual emplacement zone of the repository [Hammer et al. 2009]. A depth of between 300 m and 1500 m was also considered to be realistic for a repository in the justification for the regulations defined in Section 1 (4) of [StandAG 2017]. Because temperatures in the North German Basin at a depth of 1000 m fluctuate between 40 °C and 50 °C (according to [Jung et al. 2002], this depth was defined as the maximum depth in the KOSINA project.
In conclusion, the following project-specific depths were defined as boundary conditions for the elaboration of the generic geological 3D models in the KOSINA project:

- Minimum depth of the repository > 500 m bgl
- Maximum depth of the repository < 1000 m bgl

The following safety margins were defined for the repository (see Figure 3-3):

- 50 m to the top and base of the rock salt deposit (thickness of the emplacement horizon > 100 m)
- 150 m from the top of the evaporite body
- 500 m lateral safety pillar (to exclude any influence from potentially existing salt edges, taking into consideration the dip of the beds)

The parameterised generic geological 3D models comply with the requirements of [StandAG 2017].

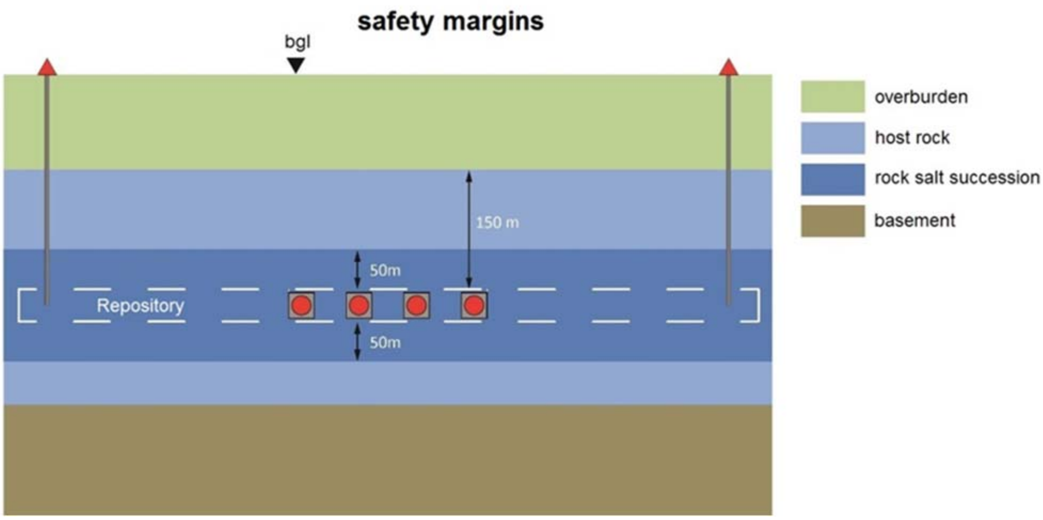


Figure 3-3: Schematic diagram of the safety margins in the KOSINA project

Moreover, a maximum design temperature of 200 °C at the casks was stipulated (see. chapter 2). The calculation of minimum spacing between the waste casks and the emplacement drifts and/or emplacement boreholes was based on this temperature (see chapter 4).

3.3 Stratigraphic Sequence for the Reference Profiles and homogenous Zones

A comparison of the boundary conditions for the generic geological 3D models formulated in Chapter 3.2 and the information previously available on the flat-bedded rock salt successions in Germany, revealed that the rock salt deposits in the Werra, Staßfurt and Leine formations of the Zechstein evaporites were particularly interesting for the elaboration of reference profiles and generic geological site models (see chapters 3.4 and 3.5). The cyclic successions of sedimentary rocks with different lithological compositions are characteristic of the Werra, Staßfurt and Leine formations of the Zechstein evaporites. One cycle consists of basal fine-grained clastic sediments followed by carbonates and then followed by a sequence dominated by evaporites. The latter begins with anhydritic rocks followed by rock salt, and then by usually very thin potash and magnesium salt horizons. This is then frequently followed by a regressive phase of the cycle with halitic and anhydritic-argillaceous deposits. The thickness and character of each horizon in the sequence varies depending on its regional geological location. The reference areas stipulated in Chapter 3.2, and the information in [Reinhold et al. 2014], were used to derive a synthetic sequence for the Staßfurt (z2) and Leine (z3) formations of the Zechstein evaporites, supplemented by regional-geological information on the sedimentary sequence (see Figure 3-4).

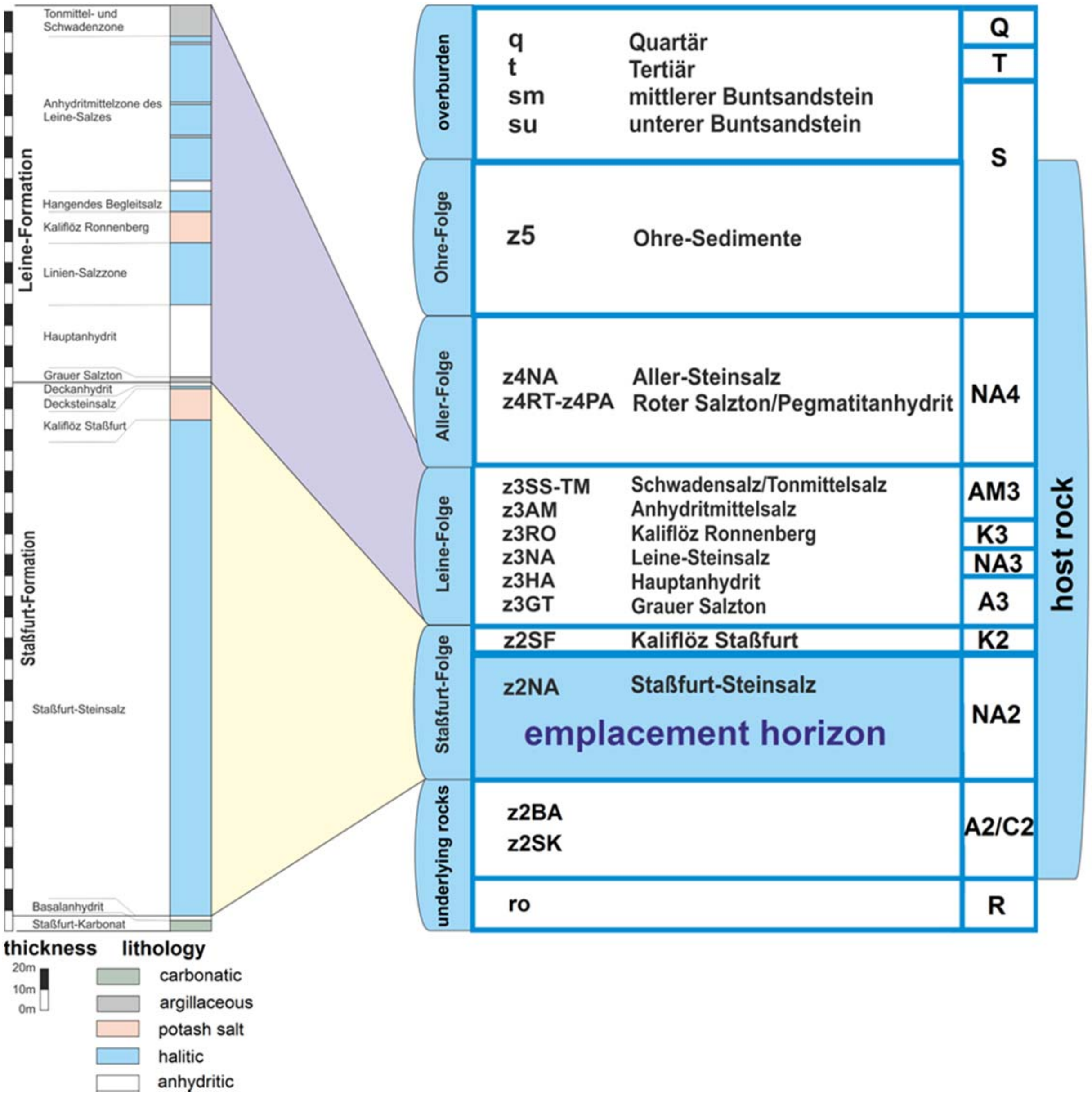


Figure 3-4: **Generalised standard profile of the Staßfurt and Leine formations (left) as well as their conversion into a schematic geological reference profile for the 3D modelling (right)**

The findings of the evaluations led to the definition of 18 regionally well characterizable lithostratigraphic units which were included in generic geological 3D models. These are as follows from top to bottom

- q (Quaternary)
- t (Tertiary)
- sm (Middle Bunter)
- su (Lower Bunter)
- z5 (Ohre sediments)
- z4NA (Aller rock salt)
- z4RT-z4PA (Roter Salzton/Pegmatitanhydrit)
- z3SS-TM (Schwadensalz/Tonmittelsalz)

- z3AM (Anhydritmittelsalz)
- z3RO (Ronnenberg potash seam)
- z3NA (Leine rock salt)
- z3HA (Main Anhydrite)
- z3GT (Grauer Salzton)
- z2SF (Staßfurt potash seam)
- z2NA (Staßfurt rock salt)
- z2BA (Basalanhydrit)
- z2SK (Staßfurt-Carbonate)
- ro (Rotliegend)

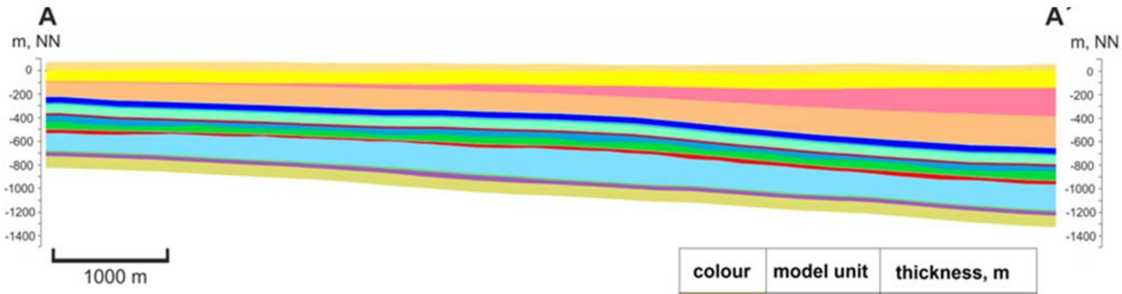
The generic geological 3D models for the "flat-bedded" type and for the "salt pillow" type provide the basis for the THM model calculations. To optimise the computing times it is necessary to generalise the geological 3D model of the structure and the reference profile with respect to the model units. This involved bundling geological horizons with similar geomechanical properties into homogenous zones. The following 12 lithostratigraphic units from top to bottom were looked at as representative homogenous zones within the evaporite formation:

- Q-Quaternary (consisting of q)
- T-Tertiary (consisting of t)
- S-Bunter (consisting of sm, su and z5)
- NA4 – Aller rock salt (consisting of z4NA and z4RT-z4PA)
- AM3 - Anhydritmittelsalz (consisting of z3SS-TM and z3AM)
- K3 - Ronnenberg potash seam (consisting of z3Ro)
- NA3 – Leine rock salt (consisting of z3NA)
- A3 – Main Anhydrite (consisting of z3HA and z3GT)
- K2 - Staßfurt potash seam (consisting of z2SF)
- NA2 – Staßfurt rock salt (consisting of z2NA)
- A2/C2 - Anhydrite/Carbonate (consisting of z2BA and z2SK)
- R – Underlying Red (consisting of ro)

THM material parameters were then defined for these homogenous zones after a comprehensive literature search on the data sets for bedded salt formations in Germany [Liu et al. 2017].

3.4 Geological Reference cross-section and Model for the "Flat-bedded" Type and Definition of the Host Rock and Emplacement Zone

The approx. 8.8-km-long generic geological cross-section AA' (Figure 3-5) was elaborated based on the available knowledge on flat-bedded evaporitic horizons in Germany. The cross-section represents a characteristic geological total situation in the regions with flat-bedded rock salt successions of Zechstein age in Germany. The thicknesses and depths of the 18 model units can be taken from the generic geological cross-section ("reference profile") and the associated table (see Figure 3-5). The thicknesses compiled in the standard profile are used for most evaporitic model layers.



colour	model unit	thickness, m	
	q	70	
	t	90	150
	sm	0	250
	su	115	270
	z5	5	
	z4NA	50	
	z4RT-z4PA	5	
	z3SS-TM	15	
	z3AM	75	
	z3Ro	18	
	z3NA	32	52
	z3HA	35	70
	z3GT	5	
	z2SF	17	40
	z2NA	150	265
	z2BA	15	
	z2SK	35	
	ro	100	

Figure 3-5: Geological reference profile for the "flat-bedded" type

The rock salt deposit of the Staßfurt Formation (z2NA) was defined as the emplacement horizon for the "flat-bedded" type. This lies at a depth considered favourable according to the criteria for constructing a repository for heat-generating waste and spent fuel elements described in Chapter 4, and has a thickness of greater than 100 m (see Table 3-1).

Table 3-1: Depth and thickness of z2NA in the "flat-bedded" reference profile

	Minimum value	Maximum value
Top depth	-540 m NN (610 m bgl)	-980 m NN (1050 m bgl)
Base depth	-700 m NN (770 m bgl)	-1200 m NN (1270 m bgl)
Thickness, approx.	150 m	265 m

The slight dip of the bedding is characteristic of all of the regions looked at with flat-bedded salt horizons in Germany, and is therefore reflected in the generic geological cross-section. The bedding conditions in the generic geological cross-section are characterised by a 5° to 7° dip of the evaporitic sedimentary sequence.

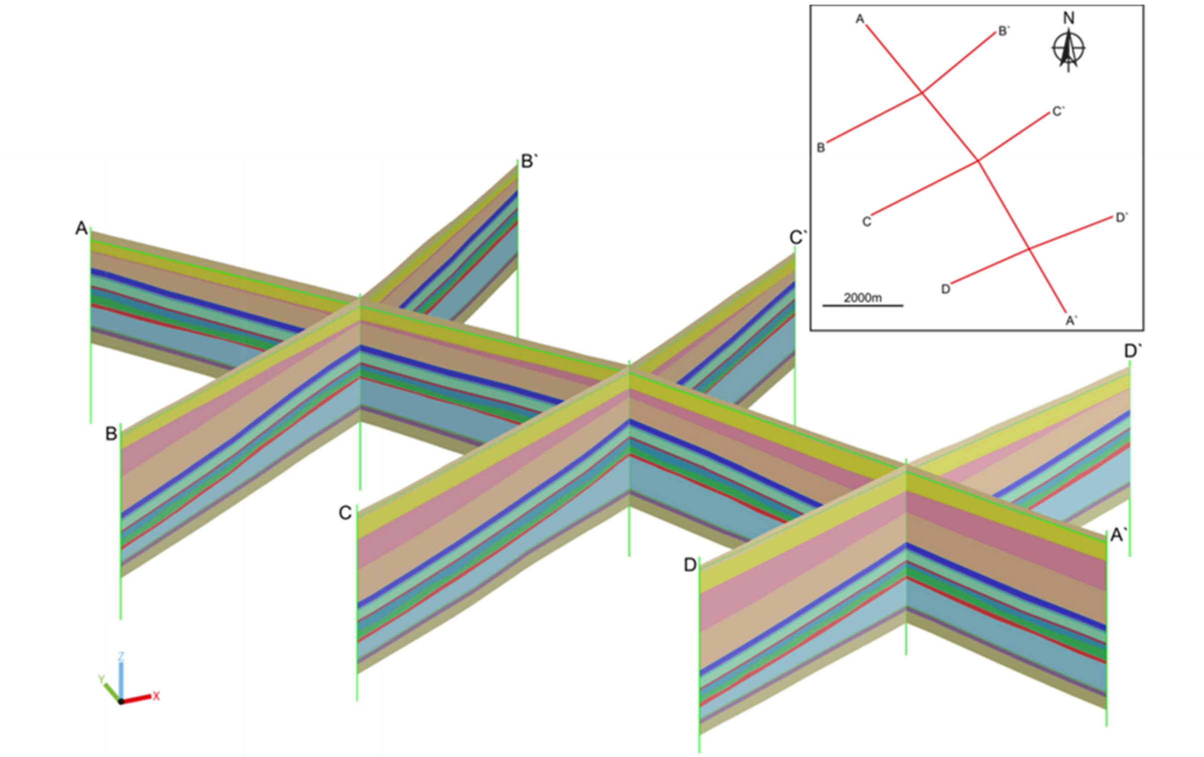


Figure 3-6: Generic geological cross-sections in the "flat-bedded" model region

To improve the spatial visualisation of the distribution, dip and changes in thickness of the beds, three more cross-sections were prepared orthogonal to section AA' (see Figure 3-6. Figure 3-6 shows that the evaporitic sedimentary sequence dips mainly south in the model region. The faults in the pre-evaporitic sediments typical for flat-bedded evaporitic sequences, as well as the joining of the Main Anhydrite, are not part of the reference profile, and thus also not part of the 3D model derived from the profile. The cross-sections formed the basis for selecting a sub-region for the spatial positioning of the repository. The size of the model area was outlined after defining the position and size of the repository zone. The associated part of cross-section AA' was then used as the basis for preparing the generic geological 3D model. The "flat-bedded" model area extends for approx. 5.0 km in a NW-SE direction parallel to reference profile AA'. It extends approx. 2.5 to 3.0 km in a NE-SW direction parallel to the lateral profiles. Profile BB' forms the north-western margin, and profile DD' the south-eastern margin of the model area.

The "flat-bedded" 3D model is visualised in Figure 3-7. The thickness of the cover rock, consisting of geological units q, t, sm and su, varies in the model area between approx. 200 m in the N and approx. 650 m in the S. The evaporitic host rock consisting of Staßfurt, Leine, Aller and Ohre formations, reaches a thickness of up to 650 m. The bedding in the site model dips to the S and/or SW at around 5° to 7°.

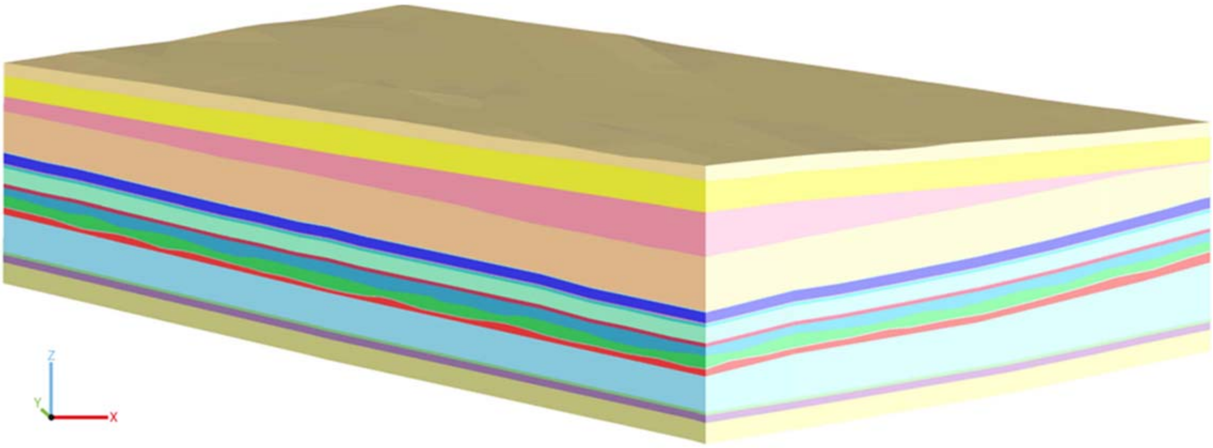


Figure 3-7: Geological 3D model "flat-bedded" (from Völkner et al. 2017)

The thickness of the rock salt succession in the Staßfurt Formation selected as the emplacement horizon varies in the "flat-bedded" model area between 160 m in the western part of the model area and 290 m in the eastern part. The parts of the model area with thicknesses exceeding 200 m are the preferred areas for locating the repository. It is also necessary here to take into consideration the criteria concerning the depth of the emplacement horizon. The base of the emplacement horizon (z2NA base) in the southern part of the model area is at depths of approx. 1,100 m bsl and < 700 m bsl in the north - which favours positioning of the repository in the northern part of the model area. The top of the emplacement horizon (z2SF base) lies at depths of between 900 m in the south and 500 m bsl (approx. 970 m and 570 m bgl respectively) in the north (see Figure 3-8), and thus corresponds to the defined depth range of 500 m to 1000 m bgl according to measure M13 (see chapter 2.2.4.2).

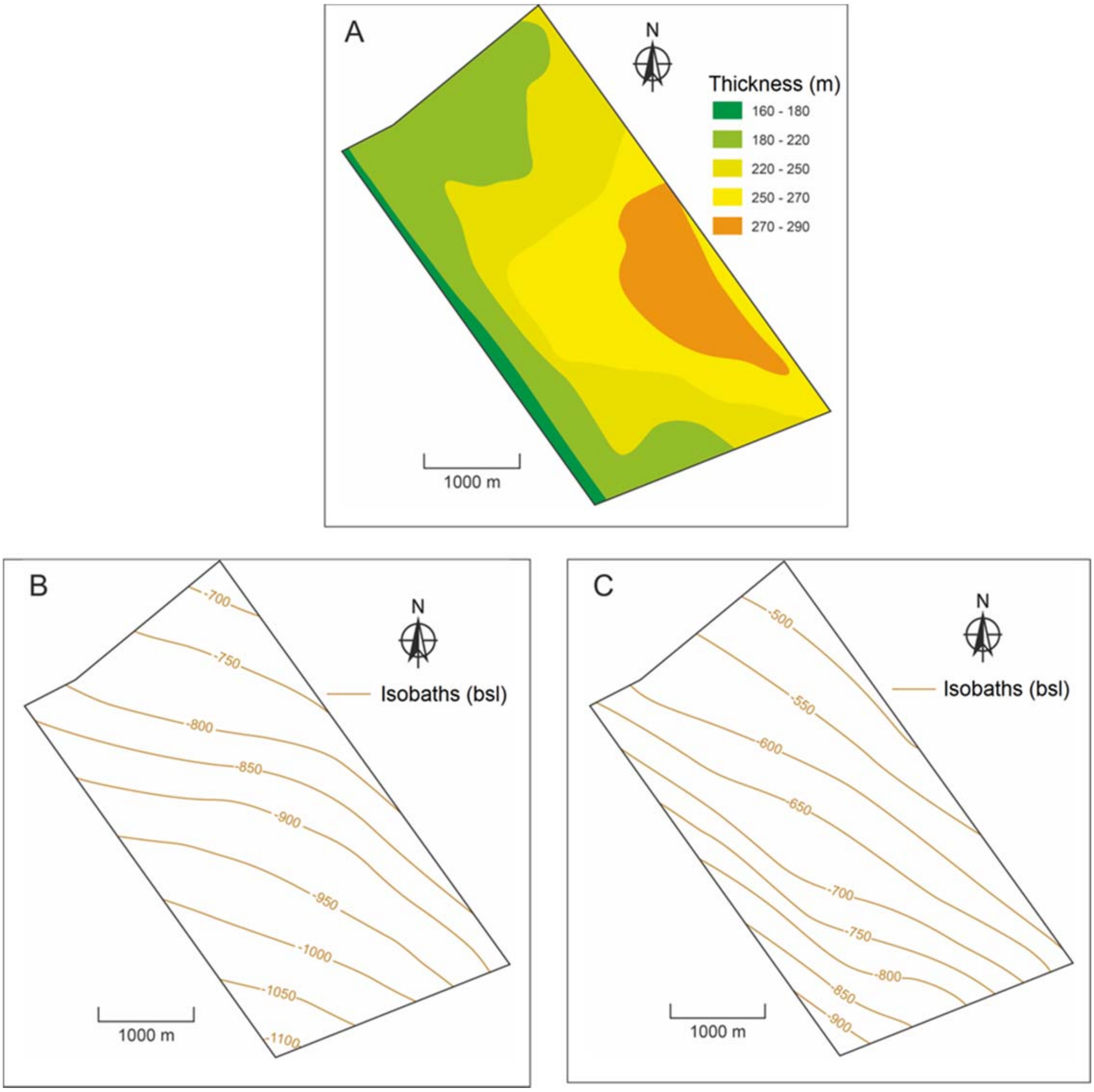


Figure 3-8: **Thickness (A) and depth map of the base (B) and top (C) of the z2NA model unit in the "flat-bedded" model type**

3.5 Geological Reference cross-section and Model for the "Salt Pillow" Type

The approx. 12.5-km-long reference profile for the "salt pillow" type (see Figure 3-9) shows a characteristic salt pillow structure of the Zechstein rock salt succession in Germany. The 18 geological model units are identical with the reference profile for the "flat-bedded" model type. Their thicknesses are listed in the table in Figure 3-9.

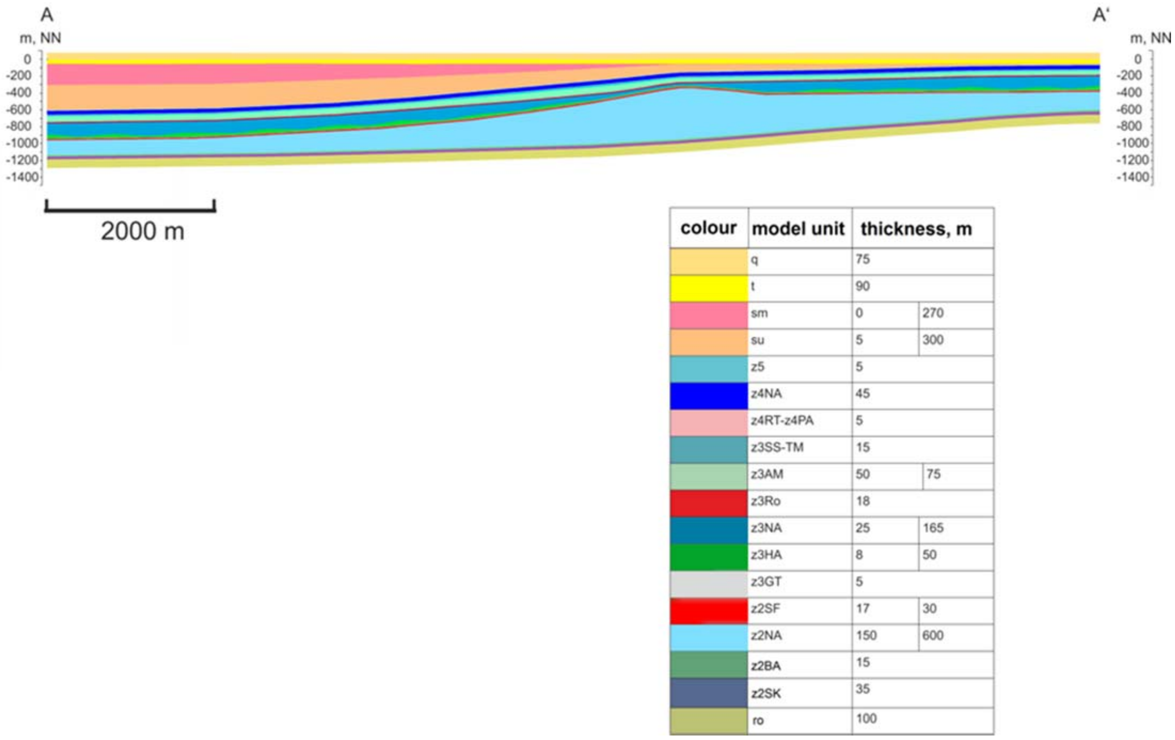


Figure 3-9: Geological reference profile for the "salt pillow" type

Analogous to the "flat-bedded" type, the Staßfurt Formation (z2NA) rock salt deposit was defined as the emplacement horizon for the "salt pillow" type as well. The depths and thicknesses of the emplacement horizon are shown in Table 3-2. Analogous to the "flat-bedded" type, three additional cross-sections were prepared orthogonal to the reference profile (see Figure 3-10).

Table 3-2: Depths and thicknesses of z2NA in the "salt pillow" reference profile

	Minimum values	Maximum values
Top depth	-390 m NN (460 m bgl)	-975 m NN (1,045 m bgl)
Base depth	-600 m NN (670 m bgl)	-1,150 m NN (1,220 m bgl)
Thickness, approx.	150 m	600 m

The bedding of the Zechstein basis in the generic geological cross-section for the "salt pillow" model type are characterised by a dip of 5° to 7° for the evaporitic sedimentary succession. The greatest thickness (600 m) of the salt pillow is reached at the cross-section of profile AA' and CC'. Unlike the "flat-bedded" model type, there is a relatively strong variation in the thickness of the cover rock units. In general, the horizons are thinner over the salt pillow and reach their greatest thicknesses at the edges of the model. The faults characteristic of the pre-saline horizons, as well as the fragmentation of the Main Anhydrite into blocks, are not part of the reference profile, and thus not included in the 3D model based on the profile.

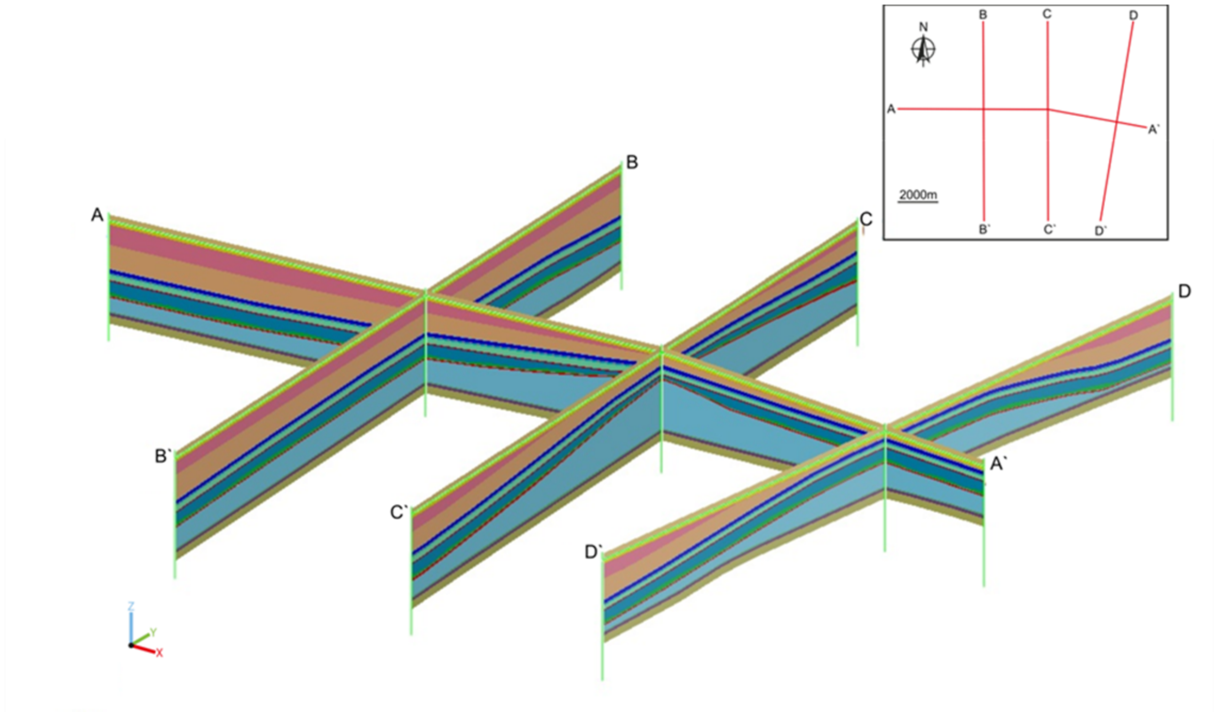


Figure 3-10: **Generic geological cross-section in the "salt pillow" model area (from: Völkner et al. 2017)**

The thickness of the cover rock consisting of geological units q, t, sm and su, varies in the model area between approx. 800 m in the west and approx. 140 m in the east. The evaporitic host rock consisting of Staßfurt, Leine, Aller and Ohre formations, reaches a thickness of more than 800 m in the centre of the salt pillow. No modelling of potentially existing cap rocks at the top of the salt was undertaken. The geological units overlying z2NA in the centre of the salt pillow are strongly thinned, and the Middle Bunter (sm) in particular is almost non-existent. Away from the salt pillow, however, sm reaches a thickness of more than 300 m at the western edge of the model area (see Figure 3-11).

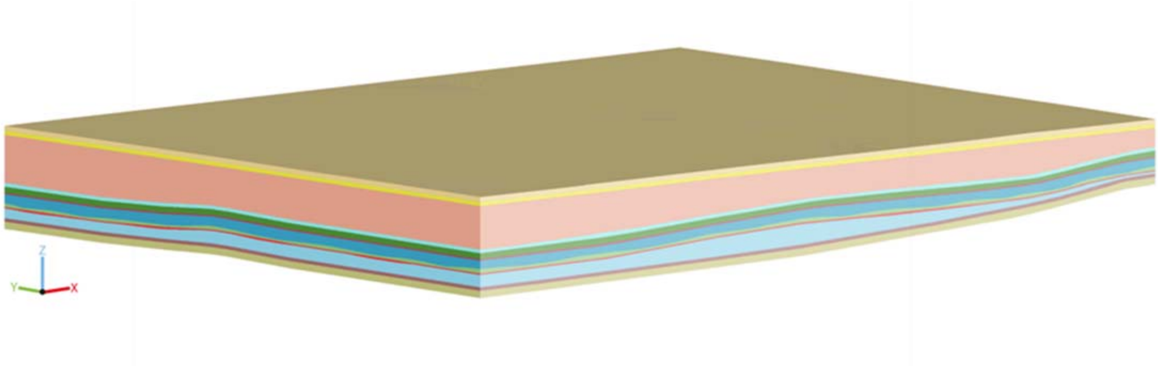


Figure 3-11: **Geological 3D Model "Salt Pillow" (from: Völkner et al. 2017)**

The Staßfurt Formation rock salt sequence selected as the emplacement horizon is up to 600 m in thickness in the centre of the salt pillow. The thickness diminishes rapidly (< 300 m) in the direction of the edges of the model, and even thins to below 100 m in the NE and SE. The thicknesses > 500 m in the centre of the salt pillow are favourable for the location of a repository. The base of the emplacement horizon (z2NA base) is approx. 600 m bsl (approx. 670 m bgl) in the east, and deepens in the NW to over 1,200 m bsl (> 1,270 m bgl). The depth of the top (z2SF base) also decreases to the west (to > 1,000 m bsl), and is largely determined by the symmetry of the salt pillow. The top of the emplacement horizon in the centre of the salt pillows is < 400 m bsl (see Figure 3-12).

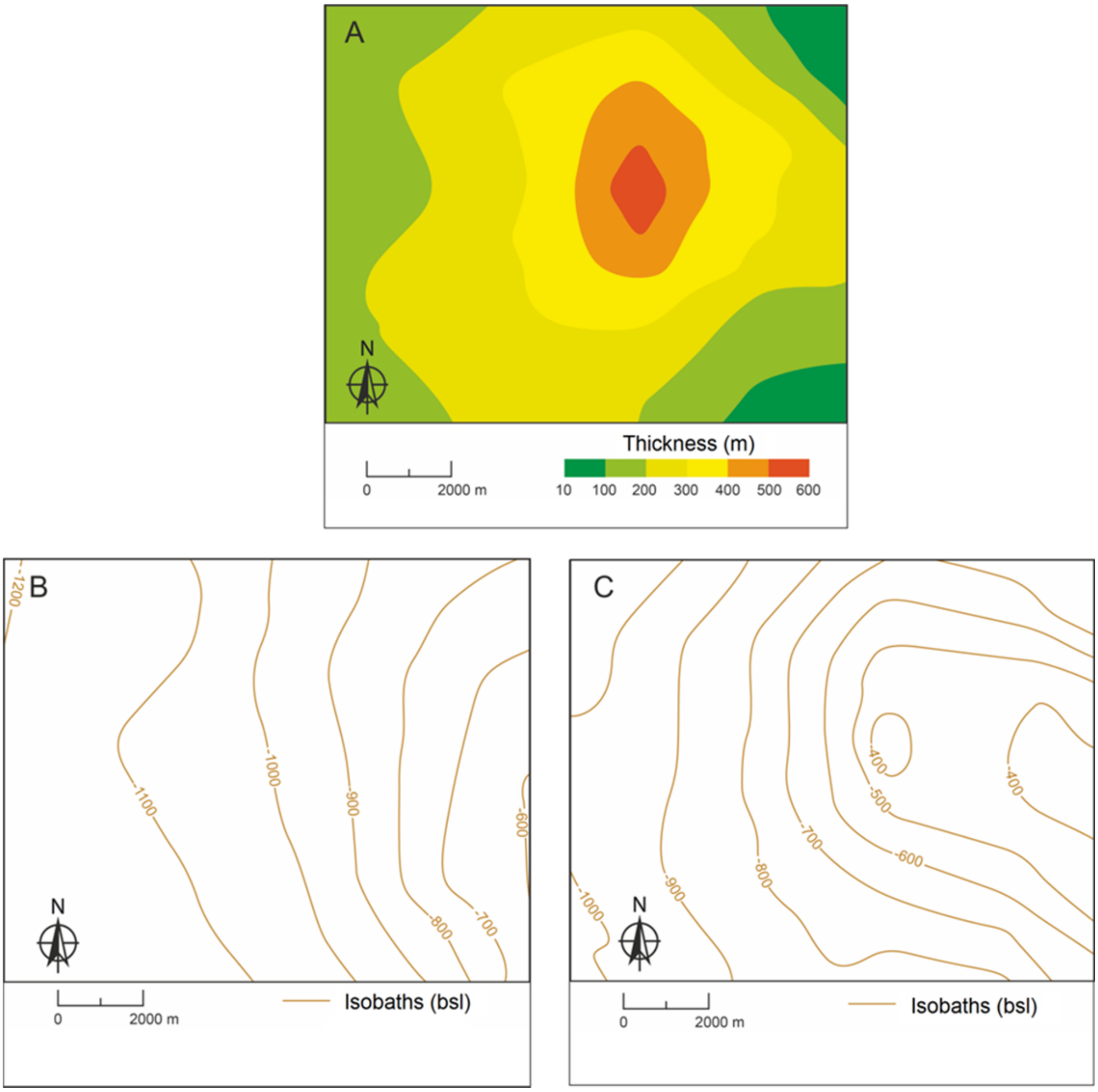


Figure 3-12: **Thickness (A) and depth maps for base (B) and top (C) of the z2NA model unit in the "salt pillow" model type**

4 Repository Concepts and Repository Designs

4.1 Planning Fundamentals and Requirements

The design of a deep geological repository relies on detailed information about the types and amounts of radioactive waste to be emplaced, on good knowledge about the geology at the site and on a large variety of requirements. One very important design requirement stipulated in the safety requirements is that all designs have to meet the requirement of retrievability during repository operation. This has been taken into account for all four disposal options. In order to allow the demonstration of long-term safety, the design respects the stipulations of the safety concept. All these different pieces of input data have to be compiled before the repository development process can be started.

The German Mining Act sets up requirements for the operational safety in the mine. These are for instance the minimum number of shafts, the maximum working temperature, the ventilation in the mine, the minimum drift cross sections or the maximum working time for the miners. The nuclear law gives stipulations for the radiation protection of the personnel during the handling of the radioactive waste in the repository.

According to [BMUB 2015], the predicted radioactive waste stream in Germany including spent nuclear fuel from reactors of NPPs as well as from test and prototype reactors and from research reactors, and waste from reprocessing has to be disposed of in a geological repository. In total, an amount of 10,445 MTHM (metric tons heavy metal) of spent nuclear fuel is expected (VSG AP4). The quantity structure of spent nuclear fuel from test and prototype reactors and from research reactors is available as well and has been updated for this project by including the spent nuclear fuel of the research reactors Rossendorf and Mainz.

Depending on the disposal option, the spent fuel is to be disposed of either in so-called POLLUX® casks, which can accommodate the fuel rods of up to 10 PWR elements, in small spent fuel canisters (German abbreviation BSK) containing the fuel rods of up to 3 PWR elements, or in transport and storage casks (mostly of the CASTOR® type) containing complete spent fuel elements.

Structural parts of fuel elements also have to be emplaced when the fuel elements are disassembled before emplacement. They exhibit only a small heat production. They shall be disposed of in cast iron casks of type MOSAIK®-II.

Furthermore, waste casks of different types, adjusted to the spent fuel elements of the research or prototype reactors (CASTOR® type: THTR/AVR, KNK and FRM2), have to be considered.

Until 2005, spent nuclear fuel from German NPPs was sent to France and the United Kingdom for reprocessing. The corresponding waste casks comprise either vitrified fission products, feed sludge (CSD-V), vitrified flushing water (CSD-B) or compacted claddings and structural parts (CSD-C).

Other waste types with negligible heat production were not considered in the KOSINA project. The amount of waste is summarized in Table 4-1.

Table 4-1: Inventory of the radioactive waste and spent nuclear fuel considered

Waste from NPPs		**N° of fuel elements**	**Metric tons of heavy metal**
PWR	UO_2	12,450	6,415
	MOX	1,530	765
BWR	UO_2	14,350	2,465
	MOX	1,250	220
WWER	UO_2	5,050	580
Total	UO_2	31,850	9,460
	MOX	2,780	985
	Sum	34,630	10,445
Waste from research and prototype reactors	**N° of fuel elements/rods**		
AVR	288,161 fuel element pebbles		
THTR 3000	617,606 fuel element pebbles		
KNK	2,484 fuel rods		
Otto-Hahn	52 fuel rods		
BER II	120 fuel rods		
FRM II	150 fuel rods		
FRMZ	89 fuel rods		
RFR	950 fuel elements and 1 fuel rod cask with 16 fuel rods		
Waste from reprocessing	**Waste casks from reprocessing**		
CSD-V	AREVA-NC	3,024	
	Sellafield Ltd.	565	
	VEK	140	
	Sum	3,729	
CSD-B	AREVA-NC	140	
CSD-C	AREVA-NC	4,104	
Total		7,973	

4.2 Disposal options

Two different disposal options were investigated for each of the two geological situations (see chapter 3):

- For "flat-bedded salt": emplacement of POLLUX® casks in horizontal drifts ("drift disposal", see chapter 4.3.1) and emplacement of fuel rod casks (BSK-H) in lined horizontal boreholes ("horizontal borehole disposal", see chapter 4.3.2). These options were chosen due to the vertical restrictions of the geological formation which do not reasonably allow vertical borehole disposal.

- For the "salt pillow": emplacement of fuel rod casks (BSK-V) in lined vertical boreholes (“vertical borehole disposal”, see chapter 4.4.1) and emplacement of transport and storage casks (TSC) in short horizontal boreholes [Filbert et al. 2014] (“direct disposal of transport and storage casks”, see chapter 4.4.2).

For each disposal option, detailed descriptions of the waste casks and their corresponding quantities are given in the KOSINA interim report (WP 1). The respective repository concepts and designs are briefly described in the following chapters. For the design of the repository concepts it was assumed that spent fuel elements from experimental and prototype nuclear power plants and research reactors are encapsulated in small transport and storage casks, which will be disposed of in horizontal drifts in each of the four disposal options. This is a simplification; however, these casks do neither dominate the thermal input into the host rock nor the footprint of the repository mine. The potential criticality of these fuel elements or the proliferation of highly enriched uranium was not considered.

4.3 Repository Concepts for Flat-bedded Rock Salt

The initial task for the repository design of all disposal options was to assess the outer horizontal and vertical dimensions of the repository layouts. This was mainly accomplished by the method of analogous estimation based on the analyses in previous R&D projects. The results established in the form of a rectangular box for each option with sufficient side lengths to encompass the repository of the respective disposal option and the required minimum safety distances as put forward in the safety concept.

Every repository box was then moved into the respective 3D geological model in order to find a suitable position for the repository. Fixing the repository positions inside the geology then allowed feeding geological parameters into the thermal calculations to determine the arrangement of heat producing wastes in the repository – a major input parameter for repository planning.

4.3.1 Drift Disposal of POLLUX® Casks

The work on the drift disposal option relied on extensive experience gained from the preliminary safety analysis for the Gorleben site [Bollingerfehr et al. 2012], which also examined the emplacement of waste in drifts, and on the development of the emplacement technology for the final disposal of POLLUX® casks in [Engelmann et al. 1995] which still represents the state of the art. The focus of the research and development work for this disposal option therefore lied in the thermal calculations for the design of the repository underground with bedded rock salt as host rock.

For the drift disposal option, the following waste casks were selected:

- Fuel rods of spent fuel elements from nuclear power reactors in 2120 POLLUX®-casks (POLLUX®-10),
- Radioactive wastes from reprocessing in 887 POLLUX®-casks (POLLUX®-9), from which 415 are loaded with CSD-V and 472 with CSD-B/C wastes,
- Spent fuel elements from experimental, prototype and R&D reactors in 530 CASTOR®-casks,
- Structural parts from spent fuel elements of nuclear power reactors in 2620 cast iron casks type II (MOSAIK®-casks).

POLLUX® casks were designed for final disposal in rock salt. For the CASTOR® casks and the type II cast iron casks for the structural parts, a respective analysis has never been performed. This project assumes that these casks, too, are suitable for final disposal.

The planning of the repository layout is essentially based on the results of the thermal calculations and the space requirements of the transport and emplacement technology.

Compared to a domal salt formation, a bedded rock salt formation offers only minor restrictions on the horizontal expansion of a repository. Provided that the integrity of the host rock can be proven convincingly, a large distance between the emplaced waste and the shafts offers advantages for long-term safety, namely in the form of a delay in both solution access to the waste and solution migration from the waste to the surface.

For these reasons, an elongated form of the repository mine was preferred, in which the emplacement fields are arranged in a row and are accessed by two main drifts running along the sides. Each emplacement field consists of the cross cut that connects the two main drifts with each other and the blind (dead-end) emplacement drifts that start from the cross cuts.

Within this elongated repository form, the various types of waste are distributed in such a way that those with the strongest heat generation are emplaced in the fields nearer to the shaft. The heat generation promotes the convergence of the rock salt and thus the enclosure of the waste. As a result, the order of waste emplacement in the repository is as follows (starting in the emplacement field nearest to the shaft and proceeding away from the shaft): PWR/BWR in POLLUX®-10 casks, WWER in POLLUX®-10 casks, CSD-V in POLLUX®-9 casks, finally the negligibly heat-producing waste of type CSD-B/C in POLLUX®-9 casks and waste from prototype, research and experimental reactors in various CASTOR® casks. The structural parts of the fuel elements represent a special case. They are continuously generated during the entire operating time of the repository by disassembling the spent fuel elements in a hot cell of a conditioning plant above ground. As a result, the structural parts must be continuously emplaced during the operating time of the repository. Therefore, the emplacement drifts for the structural parts must remain open until the end of the operating time. Furthermore, the waste emplacement starts at the far side of the repository and progresses towards the shafts while emplacement drifts are backfilled and discarded after emplacement. Therefore, the structural parts have to be emplaced in drifts in proximity to the shaft. However, the structural parts have a negligible thermal output. Thus, compared to emplacement drifts with POLLUX®-10 casks containing PWR/BWR spent fuel rods the enclosure of the

Type II cast iron casks with structural parts due to compaction of the crushed salt backfill would be significantly retarded. In order to foster the long-term safety, they shall be emplaced in the centre of the first emplacement field nearest to the shaft. For this further blind drifts are excavated between the central emplacement drifts.

An exemplary result of the planning in the form of the repository mine layout can be seen in Figure 4-1 for the disposal option of drift disposal.

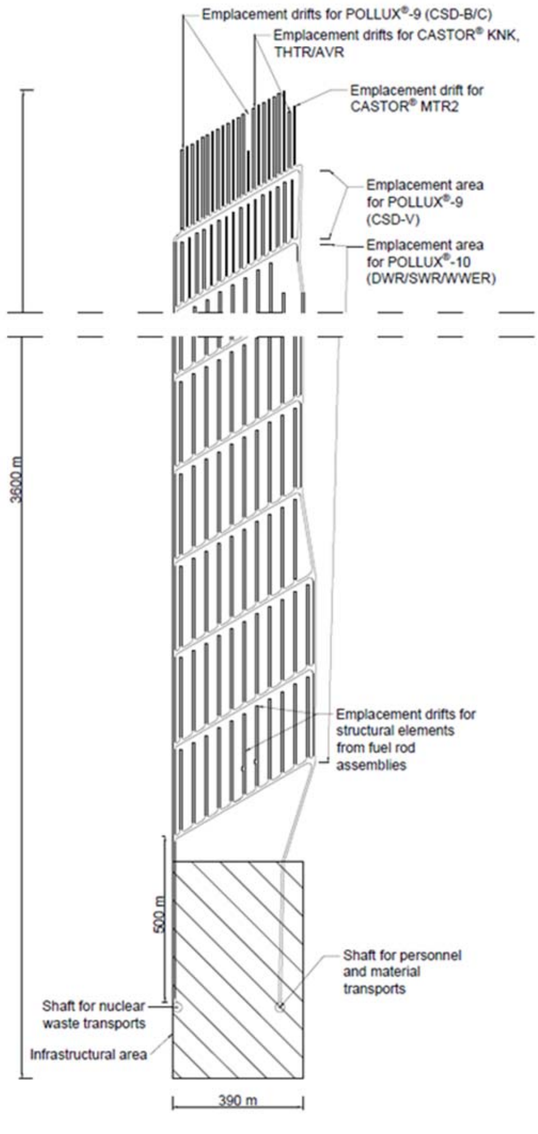


Figure 4-1: Repository Mine layout for drift disposal

The thermal optimization of the emplacement geometry of the repository for the drift disposal option was carried out in compliance with a maximum temperature criterion of 200°C. According to the final report of the repository commission on the disposal of high-level radioactive waste, the beginning of emplacement was assumed for the year 2050 [Endlagerkommission 2016]. Using the FLAC3D software, thermo-mechanical calculations were carried out in order to optimize the repository layout by varying drift spacing. The cask spacing within a drift was set to 3 m for technical reasons. The evaluation point, the hottest point on a cask which is also the hottest point in the repository, is located at the topmost point of a cask skin in contact with the crushed salt backfill in the center of the repository. The calculated temperatures at this point are presented in Figure 4-2. The curves show a first temperature peak directly after the emplacement. This is due to the low thermal conductivity of the crushed salt backfill. With the ongoing compaction of crushed salt, its thermal conductivity increases and the temperature at the design point decreases. Afterwards additional peaks occur as the consequence of the superposition of heat from casks in the same and adjacent emplacement drifts. One of these peaks is higher than the first peak and determines the maximum occurring temperature in the repository. By varying the drift spacing it is possible to meet the temperature limit of 200°C.

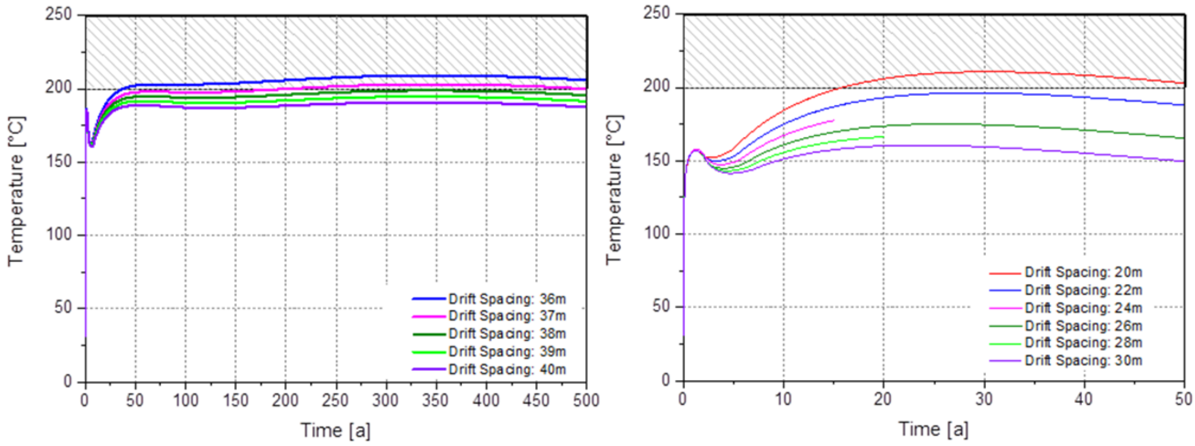


Figure 4-2: Results of Thermal Calculations for the disposal option drift disposal of POLLUX-Casks with a temperature criterion of 200 °C (POLLUX®-10 on the left, (POLLUX®-9 on the right)

The optimized design parameters are shown in Table 4-2.

Table 4-2: Thermally deduced minimum distances between emplacement drifts and cask spacing within a drift for drift disposal with a temperature criterion of 200 °C

	Cask spacing	Drift spacing
POLLUX®-10	3 m	38 m
POLLUX®-9 (CSD-V)	3 m	22 m
Other waste	Distances derived by technical requirements, because heat production is negligible	

The resulting repository is approximately 3600 m long and 400 m wide. The repository width is limited in order to comply to mining regulations concerning the operational safety. The corresponding footprint of the repository is approximately 1.4 km². The repository is composed of ten emplacement fields. WWER-, CSD-V and the negligibly heat-producing waste of types CSD-B/C in POLLUX®-9 casks are emplaced in one field each. The seven remaining fields are filled with the PWR/BWR waste casks. The maximum length of an emplacement field is limited to 250 m in order to insure a good ventilation system in the emplacement drifts without having to increase its cross section. The shafts are located 500 m from the closest emplacement field. An area of 350 m x 650 m surrounding the shafts is reserved for operational infrastructures.

The design of the cross sections of the different types of mine openings (main drifts, emplacement drifts and cross cuts) is based on the necessary technical equipment that needs to be transported through or to be used in these sections.

The transport and emplacement technology in the drift disposal option is based on technology that has already been successfully tested, see Figure 4-3. A prototype was planned, manufactured and successfully tested in continuous operation as part of an R&D program for the direct final disposal of spent fuel elements [Engelmann et al. 1995]. The transport and emplacement process is therefore state-of-the-art. The transport technology for drift emplacement comprises a battery-operated locomotive and a platform wagon for transporting the waste casks. The battery locomotive is designed for the transport of the platform wagon from the shaft landing station to the emplacement device which will be positioned prior to the waste cask delivery at the calculated position in the emplacement drift. For the emplacement of waste casks, the „emplacement device in drifts" (ELVIS) is used. The main components of the device are: the rigid base frame with four screw jacks as lifting device, a frame construction for receiving, holding and supporting emplacement casks with loads of up to 65 t as well as their transfer to a transport wagon, a control station and crawler tracks.

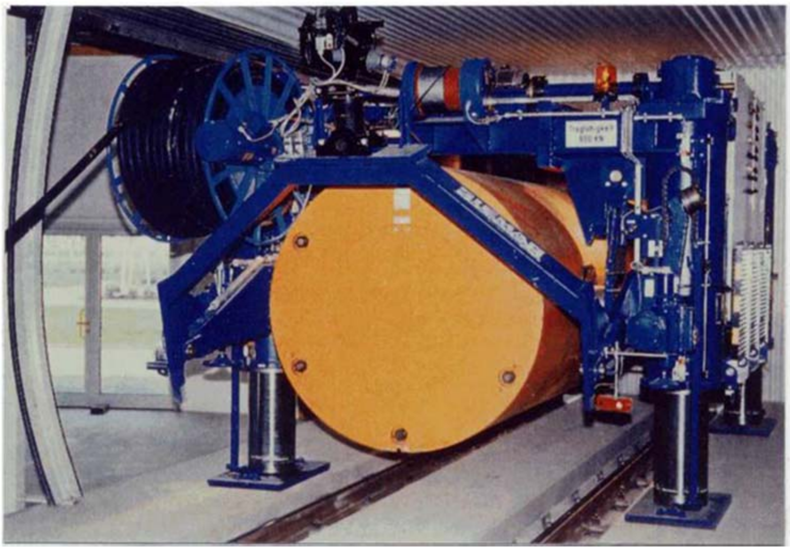


Figure 4-3: Emplacement of POLLUX® Casks on the floor of an emplacement drift (Foto from demonstration tests)

Immediately after emplacement of a POLLUX®- cask in the emplacement drift and the removal of the emplacement device the remaining void around the waste cask is backfilled with naturally dry crushed salt. Thus, emplacement of a cask and backfilling are alternatively carried out until all casks of one drift have been emplaced and the whole drift has been backfilled. After emplacement of all casks in one emplacement field, the remaining cross-cut is backfilled in the same way. Since the emplacement starts in the emplacement fields farthest from the infrastructure area, proceeding then towards it, a growing part of the main drifts at the sides of the repository is over time also backfilled, again with crushed salt.

Rock salt is a generally dry host rock. The barrier effectiveness of the host rock provided, the major objectives of repository closure are:

- to prevent or at least slow the flow of fluids towards the emplaced waste casks through the man-made accesses (shafts and drifts) since fluids are the main transportation medium for radionuclides
- to prevent or at least slow the transport of radionuclides towards the biosphere through the man-made accesses (shafts and drifts)

Due to convergence of the host rock and the resulting compaction of the crushed salt in the backfilled areas, it can be expected that the integral permeability of the drifts will be comparable to that of undisturbed rock salt in the long term. At this point in time, the major objectives will be achieved by the backfilled drifts. To allow the achievement of these objectives also directly after repository closure, seals are constructed in the repository. The logic of seal construction follows [Müller-Hoeppe et al. 2012a] but had to be adjusted to the different geological settings.

The infrastructure area and the emplacement fields are connected only by the two main drifts. These drifts constitute the only transportation route for fluids from the infrastructure area to the emplaced waste casks or for radionuclides vice versa. Therefore, both main drifts are equipped with drift seals positioned in the drifts between the infrastructure area and the emplacement area. Each drift seal is constituted by two sealing elements of sorel concrete with a length of 100 m. In between both elements, a 300 m long part of the drift is backfilled with crushed salt. To enhance the speed of compaction of the crushed salt in this area, it is moistened before backfilling.

The infrastructure area and the biosphere are connected only by the shafts. Integrity of the host rock provided, these shafts constitute the only transportation route for fluids from the biosphere to the infrastructure area or for radionuclides vice versa. Therefore, both shafts are equipped with shaft seals. In comparison to a domal salt formation, the thickness of the host rock above the emplacement level is limited. In case of the shaft for material and personal transport, only approximately 100 m of host rock are available to hold a shaft seal. This shaft is exemplarily chosen for the shaft seal design for both shafts since the host rock thickness above the repository level is higher at the nuclear shaft.

The major elements of the shaft seal are described from the bottom to the top of the shaft. The first component of the shaft seal is an abutment made of salt concrete. It extends from the bottom of the shaft sump to the top of the former shaft landing station. The first sealing element is positioned on top, also made of salt concrete. Salt concrete is chosen especially due to its diversity to sorel concrete. It is followed by a layer of moistened crushed salt to serve as a long-term barrier, similar in function to the crushed salt with which the underground was backfilled. A layer of porous material, e.g. gravel, is installed above as a filter, mostly to avoid canalisation effects. An abutment and a sealing element of sorel concrete are then used to protect from the possibly $MgCl_2$-rich brine migration into the shaft from the potash layer above. Another layer of porous material, foreseen for the same purpose as the layer below, concludes the shaft seal. The shaft backfill above the seal is not designed for the containment of radionuclides. Still, the backfill material should be chosen to have similar properties than the surrounding geological layers and to separate natural aquifers as much as possible from each other.

The infrastructure area is backfilled with porous material, e.g. gravel, to serve as a reservoir for fluid inflow. This causes a retardation of a possible fluid migration towards the emplacement area.

4.3.2 Horizontal Borehole Disposal

So far, no conceptual studies regarding the technology for emplacing waste packages in horizontal boreholes have been carried out in Germany. The fuel rod waste casks envisaged for vertical borehole emplacement (BSK-V, see chapter 4.4.1) are considered with minor adaptations as repository casks for horizontal borehole emplacement (called BSK-H) as well. The following waste casks must be emplaced in this disposal option:

- Fuel rods of spent fuel elements from nuclear power reactors in 7068 BSK-H,
- Radioactive wastes from reprocessing in 2659 BSK-H, including 1244 with CSD-V and 1415 with CSD-B/C waste,
- Spent fuel elements from experimental, prototype and R&D reactors in 530 CASTOR®-casks,
- Structural parts from spent fuel elements of nuclear power reactors in 2620 cast iron casks type II (MOSAIK® casks).

The repository design of the horizontal borehole disposal option was carried out in the same way as for the drift disposal. The planning of the repository layout was essentially based on the results of the thermal calculations and the space requirement of the transport and emplacement technology.

Like for the drift disposal option, an elongated form of the repository mine was preferred, in which the emplacement fields are arranged in a row and are accessed via two main drifts running along their sides. An emplacement field consists of the cross cut that connects the two main drifts with each other and the horizontal emplacement boreholes, which connect two adjacent crosscuts with each other. The crosscuts in this option are also called borehole access drifts.

The various types of wastes are distributed within this elongated repository form just as in the drift disposal option, i. e. the hot waste is emplaced near the shaft, the cooler wastes in the emplacement fields far away from the shaft. Again, the structural parts of the fuel elements represent a special case. They shall be emplaced in several short blind drifts in the centre of the first emplacement field in the middle of the boreholes with waste casks containing PWR/BWR.

The input parameters for the design are largely identical with the drift disposal option. The calculations were performed for different borehole spacings. The cask spacing in the horizontal borehole was initially fixed to zero. The results (see Table 4-3) were determined at the design point at the top of the steel piping for a borehole in the center of the repository. Back-filling of boreholes with sand was assumed for the thermal calculations. In this case, only thermal conduction is taking place in the boreholes. However further thermal investigations have shown that the thermal radiation in the boreholes leads to a better heat transport if the boreholes are not backfilled. This was considered in the elaboration of the final disposal concept.

Table 4-3: Thermally deduced minimum distances for the horizontal borehole disposal option with a temperature criterion of 200 °C

	Cask spacing	Borehole spacing
BSK-H (PWR/BWR)	0 m	18 m
BSK-H (CSD-V)	0 m	8 m
Other waste	Distances derived by technical requirements, because heat production is negligible	

The design of the cross sections for the different types of underground openings (main drift, cross cuts; also boreholes) is based on the technical equipment in these openings that needs to be transported through or used in these openings.

The final repository layout of this disposal option is similar in dimensions to the drift disposal option (see chapter 4.3.1). The width of the repository is about 400 m for the reason given above. The length is approximately 3700 m. This corresponds to a foot print of approximately 1.5 km². 27 emplacement fields are necessary to dispose of all the radioactive waste.

Except for the CASTOR®-casks which are emplaced in drifts, all other waste types are emplaced in lined horizontal boreholes. The length of each emplacement field is limited to 100 m. This is the maximum possible horizontal borehole length for the chosen drilling technology which does not use a drilling fluid. The steel lining must withstand the thermo-mechanical stresses which occur in the host rock due to creep and heat. It must retain its shape to insure a retrieval of the fuel rod casks. Therefore each borehole has a diameter of 76 cm and the steel liner is 10 cm thick. By using rigid roller dollies it is possible to center the casks in the boreholes as illustrated in Figure 4-4.

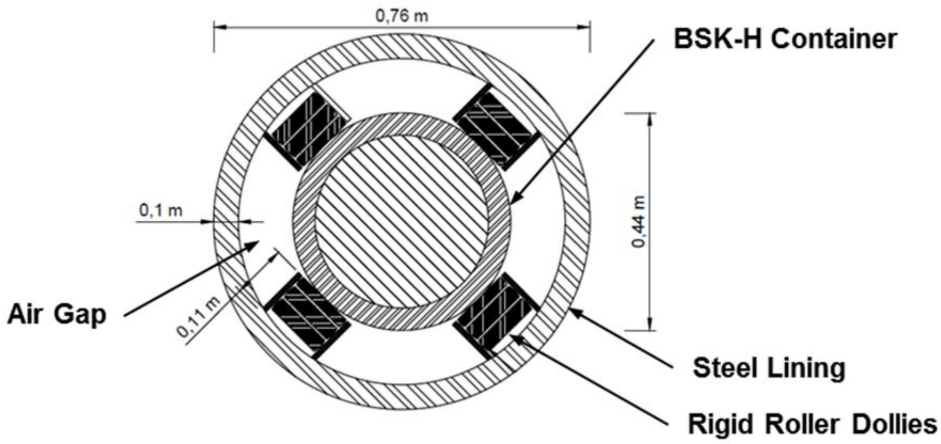


Figure 4-4: **Emplacement of fuel rod cask (BSK-H) in lined horizontal boreholes (schematic sketch os a cross section)**

In the current conceptual development stage of this horizontal borehole disposal option, the transport technology is assumed to be similar to the transport technology in the vertical borehole disposal option (see chapter 4.4.1). Since the BSK casks are not self-shielding, they must be transported in a suitable transfer cask to the emplacement boreholes on a platform wagon. The platform wagon is equipped with a rotatable superstructure in order to be able to align its platform and thus the transfer cask with the boreholes. The towing vehicle is a battery locomotive.

A value benefit analysis was carried out in which several criteria and technical solutions for a horizontal waste package emplacement were evaluated. The main challenge was to find a solution to the question of how BSK waste packages should be inserted into the horizontal boreholes. In contrast to vertical borehole emplacement, active pushing is required.

In order to secure radiation protection at all times throughout the transport and emplacement process, a sufficiently protective shielding system is provided for both the transfer cask and the emplacement borehole (cask lock, borehole lock). It must be ensured that personnel working in the mine are shielded from the BSK at all times.

For the emplacement of the BSK, first of all the cask lock of the horizontal transfer cask must be connected with the borehole lock of the horizontal borehole. For this purpose, the platform wagon on which the transfer cask is transported rotates its superstructure by 90° across the cross cut axis and aligns it with the borehole. A thrust chain magazine is mounted on the side of the transfer cask facing away from the borehole. The thrust chain from the chain magazine is able to push the BSK out of the transfer cask through the opened locks into the borehole. Shortly after passing the borehole lock, the thrust chain is decoupled and pulled back from the BSK. This step is repeated approx. two times with a newly delivered transfer cask/BSK, whereby the BSKs lying in the borehole are pushed further in. This process is schematically depicted in step ① in Figure 4-5.

The exact number of repetitions of this process depends on the results of an engineering design of the emplacement technology which would determine the mechanical parameters of the process in detail.

The emplacement tools are then replaced. Now, the three BSK which are already in the borehole are pushed down to its end. This is done via „push“-pipes, which are designed in a similar way as drill pipes. The thrust is generated by hydraulic cylinders outside of the borehole. By adding pipes, the BSK can be pushed over the entire length of the borehole. After pushing the BSKs in, the pipes are removed. Emplacement via thrust chain and pipes takes place alternately until the borehole has taken up all foreseen BSK per borehole. Steel rollers are provided in the borehole to reduce the necessary thrust force and guide the BSK and pipes. This process is schematically depicted in step ② in Figure 4-5.

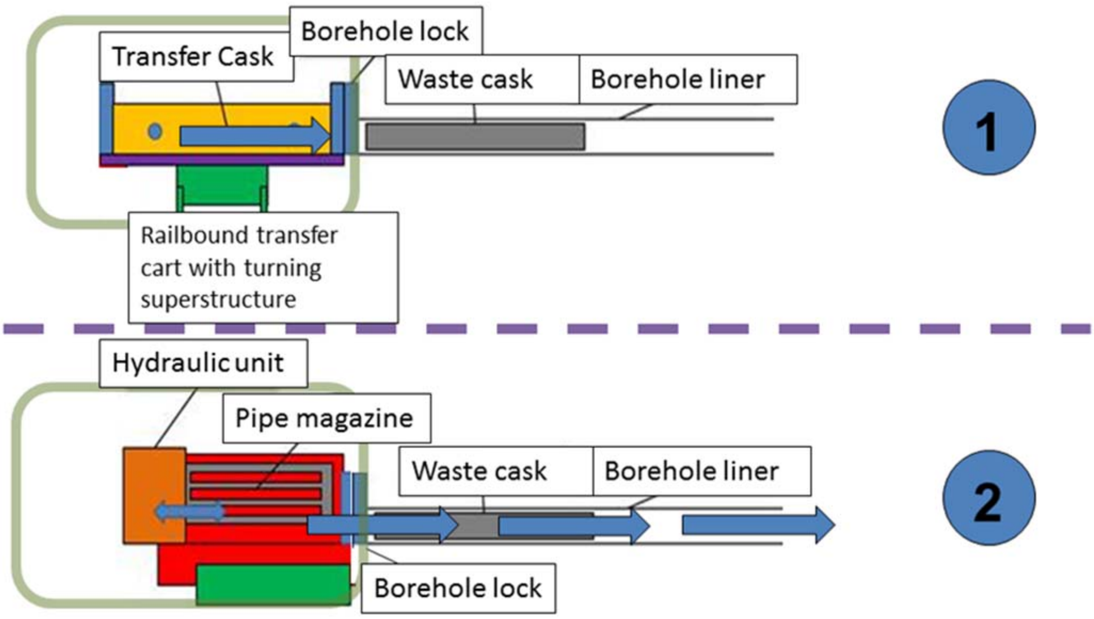


Figure 4-5: Emplacement schemes for pushing fuel rod cask (BSK-H) into a lined horizontal borehole

The entire repository layout is illustrated in Appendix 2.

The objectives and procedures of repository closure, namely backfilling and sealing, are almost equivalent (s. below) to those described for Drift Disposal of POLLUX® casks in chapter 4.3.1. The geological model and the position of the shafts are identical, therefore no adjustment is necessary.

The emplacement boreholes themselves are not backfilled. Instead, they are closed by a corrosion resistant steel cap. The thermal radiation is sufficiently high so that the waste casks do not overheat in the boreholes.

4.4 Repository Concepts for Salt Pillows

Across their central region, salt pillow formations have typically a greater thickness compared to flat-bedded salt formations. In addition to the direct disposal option this allows radioactive waste to be emplaced also in vertical boreholes.

4.4.1 Vertical Borehole Disposal Option

For the emplacement of radioactive waste in deep vertical boreholes, non-self-shielding fuel rod casks (BSK) are foreseen. The casks are conically shaped to facilitate retrieval from the boreholes, since the borehole void volume is backfilled with sand in this disposal option (s. below). The retrievable casks for vertical borehole emplacement are referred to as BSK-V.

In the vertical borehole disposal option the following types and quantities of waste casks are required for the different waste types:

- Fuel rods of spent fuel elements from nuclear power reactors in 7068 BSK-V,
- Radioactive wastes from reprocessing in 2659 BSK-H, from which 1244 with CSD-V and 1415 with CSD-B/C waste,
- Spent fuel elements from experimental, prototype and R&D reactors in 530 CASTOR®-casks,
- Structural parts from spent fuel elements of nuclear power reactors in 2620 cast iron casks type II (MOSAIK®-casks).

The repository design for the emplacement in vertical boreholes was carried out starting with the premise to emplace the BSK waste packages in 100 m deep boreholes. The planning of the repository layout is essentially based on the results of the thermal calculations and the space requirements of the transport and emplacement technology.

Like for the drift emplacement, an elongated form of the repository mine was preferred, in which the emplacement fields are arranged in a row and are accessed by two main drifts running along their sides. An emplacement field consists of the cross cuts that connect the two main drifts with each other and the vertical emplacement boreholes, which in turn are drilled from the floor of the cross cuts. For this reason, the cross cuts in this option are also called borehole access drifts.

Within this elongated repository form, the different types of waste are distributed in the same way as described for the drift disposal option, i. e. the hot waste in the emplacement fields near to the shaft, the cooler waste in the emplacement fields far away from the shaft. The structural parts of the fuel elements represent a special case. In order to store them safely over the long term, they are emplaced in a drift between the first and second borehole access drifts. This drift runs parallel to the adjacent borehole access drifts, but is designed as a blind drift. Therefore, it is only accessible from the main drift of the repository in which the waste transportation equipment is installed.

Thermal analyses were performed by considering the thermal behavior and the thicknesses of all geological units above and below the repository at this site. A numerical model was developed representing the thermal conditions in the center of the repository. The design point where the temperature was monitored is located in the middle of a vertical borehole in the center of the repository. Iteratively, several simulations were performed with different drift and borehole spacings, respectively, until a combination was found for which the temperature criterion was met. Figure 4-6 illustrates the results of the thermal analyses. Due to the 3-dimensional distribution of heat sources within the repository mine, the model complexity could not be reduced as much as for the other disposal options. The resulting long calculation times of several weeks made it necessary to reduce the optimization effort. Therefore, the borehole spacing for the design of the emplacement fields of the fuel assemblies was initially set to 50 m. For the vitrified waste, the distance between the boreholes was limited to the minimum mechanical distance of 13.2 m. The results of the calculation are shown in Table 4-4.

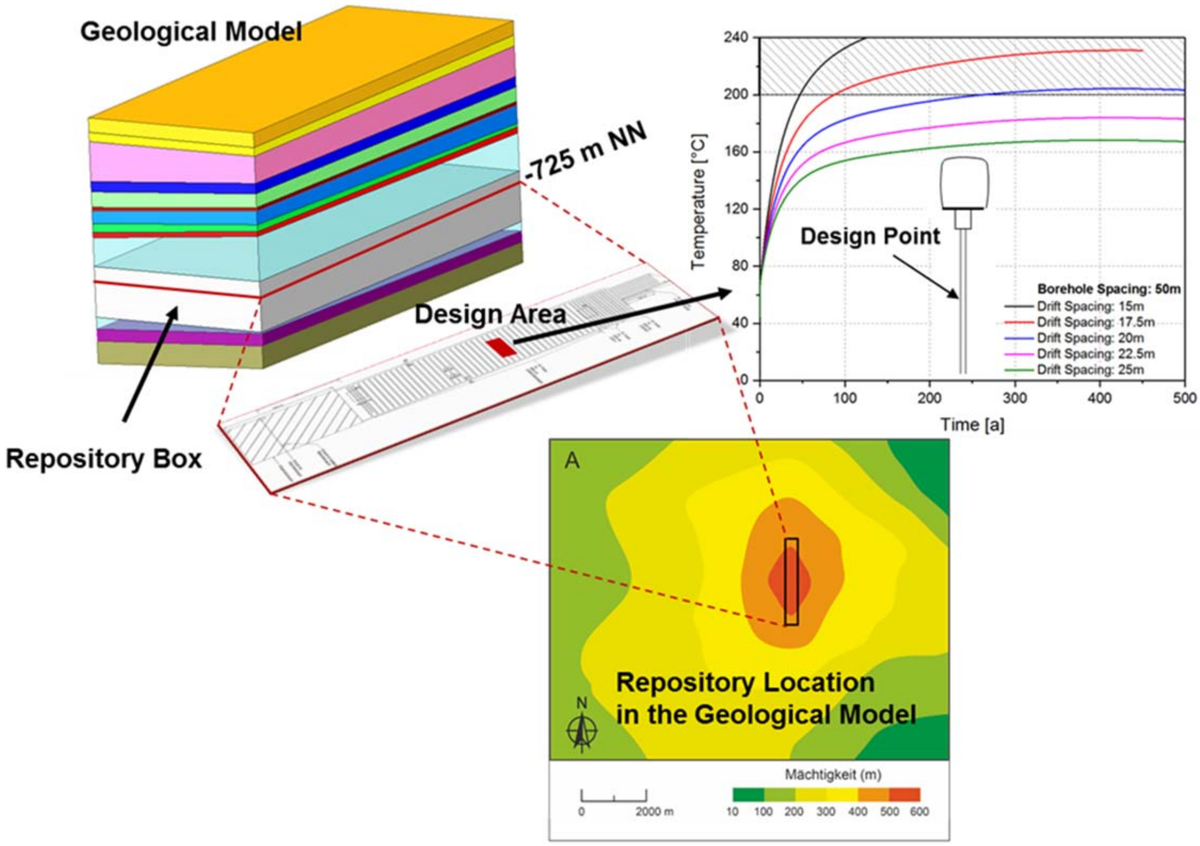


Figure 4-6: Thermal design calculations for the vertical borehole disposal option

Table 4-4: Thermally deduced minimum distances for the vertical borehole disposal with a temperature criterion of 200 °C

	Cask spacing	Distance of borehole access drifts
BSK-V (PWR/BWR)	0 m	22,5 m
BSK-V (CSD-V)	0 m	13,2 m
Other waste	Distances derived by technical requirements, because heat production is negligible	

The combination of a borehole spacing of 50 m and a distance between the borehole access drifts of 22.5 m and 13.2 m appeared to be unfavorable in terms of optimizing/ minimizing the excavated volume of the repository. Using trigonometric calculations, however, this could be converted to a borehole and drift spacing of equally 33.6 m (PWR/BWR) and 21.9 m (CSD-V) respectively. A borehole access drift of the same length can thus host a borehole every 33.6 m (21.9 m) instead of every 50 m, reducing the total excavated volume of borehole access drifts. The values of 33.6 m and 21.9 m are used in the repository design.

The design of the cross sections of the openings (main drifts, cross cuts/borehole access drifts, boreholes) is based on the technical equipment that needs to be transported to or be used in these openings.

The vertical borehole disposal option leads to the smallest footprint of all repository concepts developed in the project. With a length of 2600 m and a width of 400 m the footprint of this repository is with 1 km² around 30% smaller than the next smallest repository.

The transport and emplacement technology for vertical borehole disposal as described in [Filbert et al. 2010] corresponds to the state of the art. The transport technology includes a battery-operated locomotive and a platform wagon for transporting the non-self-shielding BSK in transfer casks. The battery locomotive is designed to transport the platform wagon from the shaft landing station to the emplacement device. The platform wagon is intended for transporting the transfer cask from the conditioning plant on the surface to the underground emplacement site. The special feature of the transfer cask is that a lock is fitted at each end to enable the cask to be unloaded underground in compliance with the radiation protection requirements.

The emplacement device is capable of picking up the transfer cask from the platform wagon and rotating it vertically. Furthermore, equipped with a shielding hood it has the option of opening the transfer cask at the upper end, in order to then attach its winch to the head of the cask and then lift it up slightly. Using the winch's electric motor, the cask can then be lowered into the borehole after opening the lower lid of the transfer cask and a borehole lock.

Figure 4-7 shows the prototype of the emplacement device of fuel rod cask in vertical boreholes.

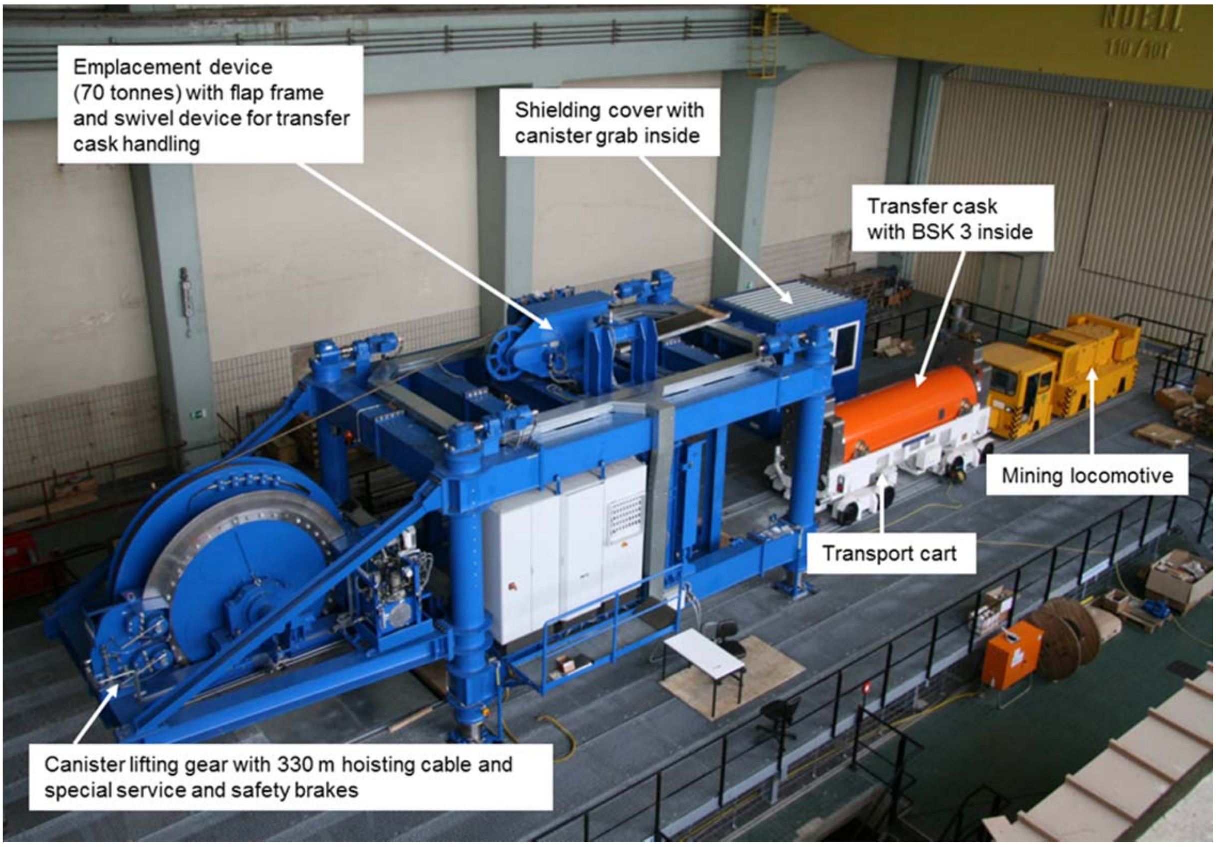


Figure 4-7: Emplacement device for the vertical borheole disposal option (foto of demonstration tests)

The entire repository layout is illustrated in Appendix 3.

The objectives and procedures of repository closure, namely backfilling and sealing, are almost equivalent to those described for Drift Disposal of POLLUX® casks in chapter 4.3.1. The geological model of a salt pillow provides significantly more thickness of host rock above the emplacement level than available in flat-bedded rock salt, hence more space for the installation of sealing elements. Therefore, the shaft seal design described above can also be applied in the salt pillow concepts.

The emplacement boreholes themselves are backfilled with quartz sand to guarantee the positional stability of the vertically stacked waste casks. Quartz sand also is a good heat conductor so that the waste casks do not overheat. The boreholes are closed by a corrosion resistant steel cap.

4.4.2 Direct Disposal of Transport and Storage Casks (TSC)

In the option of direct disposal of transport and storage casks (TSC), different TSC types were considered.

- For PWR, BWR and WWER fuel elements: CASTOR® V/19, CASTOR® V/52 and CASTOR® 440/84
- For waste from reprocessing: CASTOR® HAW 20/28 CG, TS 28 V, CASTOR® HAW 28 M and TN 85

The TSCs have an approval for the transport and interim storage of spent fuel elements and reprocessing waste. The suitability of such casks for final disposal must still be verified. In this project, it was assumed that this is possible.

The following waste casks must be emplaced in the direct disposal of TSC :

- Spent fuel elements from nuclear power reactors in 1097 CASTOR® casks,
- Radioactive wastes from reprocessing in 286 CASTOR® casks, 134 of which with CSD-V and 152 with CSD-B/C waste,
- Spent fuel elements from experimental, prototype and R&D reactors in 530 CASTOR® casks,

The planning of the repository layout is as always based on the results of the thermal calculations and the space requirements of the transport and emplacement technology. The transport and emplacement technology was specifically developed in [Filbert et al. 2014], the biggest challenge being the large weight of the CASTOR®- casks containing spent fuel elements, which is approximately 100 tons higher than that of POLLUX® casks.

Like for all disposal options, an elongated form of the repository mine was preferred, in which the emplacement fields are arranged in a row and are accessed by two main drifts running alongside. An emplacement field consists of a cross cut that connects the two main drifts with each other and horizontal short boreholes that can accommodate one TSC each and are excavated from the cross cuts.

Within this elongated repository form, the different types of waste are distributed in the same way as described for the drift emplacement, i. e. the hot waste in the emplacement fields near to the shaft, the cooler waste in the emplacement fields farer away from the shaft. In this option, there are no structural parts from the disassembling of fuel elements to dispose of as the fuel elements are not dismantled for final disposal. The design of the cross sections of the different types of openings (main drifts, cross cuts and boreholes) is based on the necessary technical equipment in these sections.

The final emplacement of transport and storage casks is carried out in short horizontal boreholes using crushed salt as backfill material. A special feature of this disposal option is the transport of the waste casks in the shaft and the drifts on different transport wagons, since the drift transport wagon also contains the emplacement device. For this reason, a transfer of the TSC from the shaft transport wagon (STW) to the drift transport and emplacement device (STEV) must take place at the landing station of the shaft. The STEV is transported in a train formation with two battery locomotives.

Due to the large number of different TSC geometries and the cooling fins of the TSC, it is advantageous to place the individual TSC on lost carriages and jointly emplace cask and carriage. The contour of the lost carriage is adapted to the borehole radius in the bottom area of the emplacement borehole and finds its counterpart in the receiving device of the drift transport and emplacement device (STEV). The designation "lost" indicates that the carriage remains in the borehole after emplacement.

The STEV is able to rotate its superstructure by 90°, thus aligning it to the borehole and finally pushing the TSC by means of a hydraulic push mechanism. The TSC is inserted and possibly retrieved by a telescopic cylinder integrated in the STEV. Figure 4-8 illustrates the emplacement process of the CASTOR® casks in short boreholes.

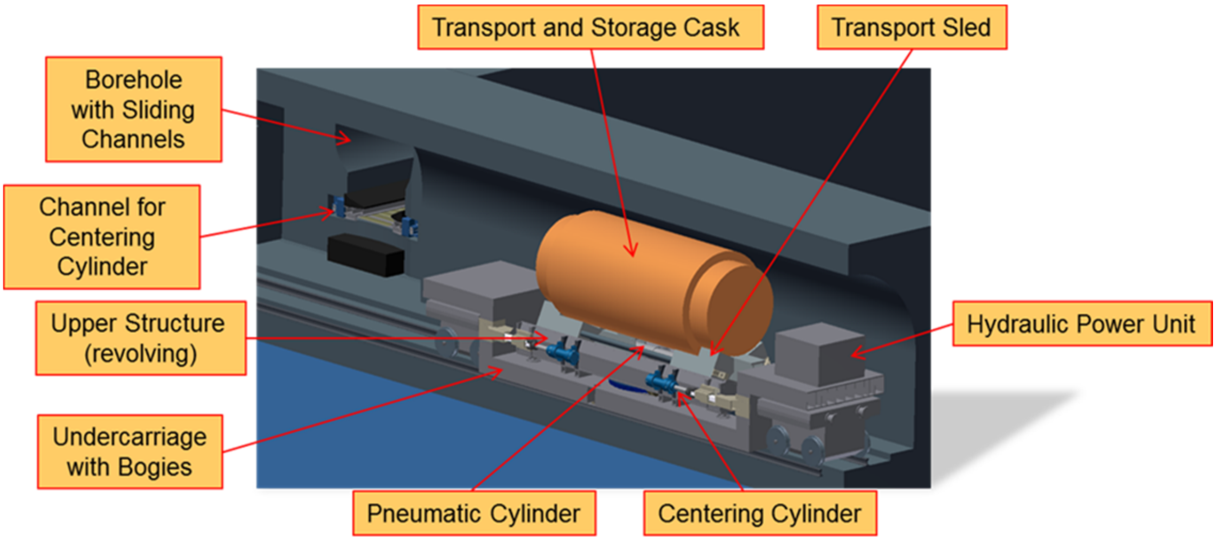


Figure 4-8: Emplacement technique for the direct disposal of TSC (schematic sketch of emplacement process) [Filbert et al. 2014]

Due to the high thermal output of CASTOR® casks it is necessary that the short borehole almost fits the diameter of the individual cask. The gap between the cask and the borehole which must be backfilled with crushed salt is therefore limited to 7.5 cm, see Figure 4-9. This provides a good thermal connection to the rock. The lower thermal conductivity of crushed salt as compared to rock salt will otherwise lead to a higher temperature if the gap is increased. This requires a thermomechanical simulation approach for the design of the repository based on the stress-dependent behaviour of crushed salt. The optimization of the emplacement geometry for the direct disposal option in salt pillows was also carried out in compliance with a temperature criterion of 200°C. The calculations were carried out by varying the pillar size among the emplacement drifts in the parameterized calculation model. The borehole spacing within a drift was set to 20 m. This value is derived from the requirements of the emplacement technology. The evaluation point, the hottest point on the cask, which is also the hottest point in the repository, is located at the lowest point of the cask skin in contact with the crushed salt. This is where the thickness of the crushed salt is greatest. The results of this evaluation are shown in Table 4-5.

Table 4-5: Thermally deduced minimum distances between emplacement drifts and cask spacing within a drift for the direct disposal of TLC with a temperature criterion of 200 °C

	Pillar size	Borehole spacing
CASTOR® (PWR/BWR)	28 m	20 m
CASTOR® (CSD-V)	32 m	20 m
Other waste	Distances derived by technical requirements, because heat production is negligible	

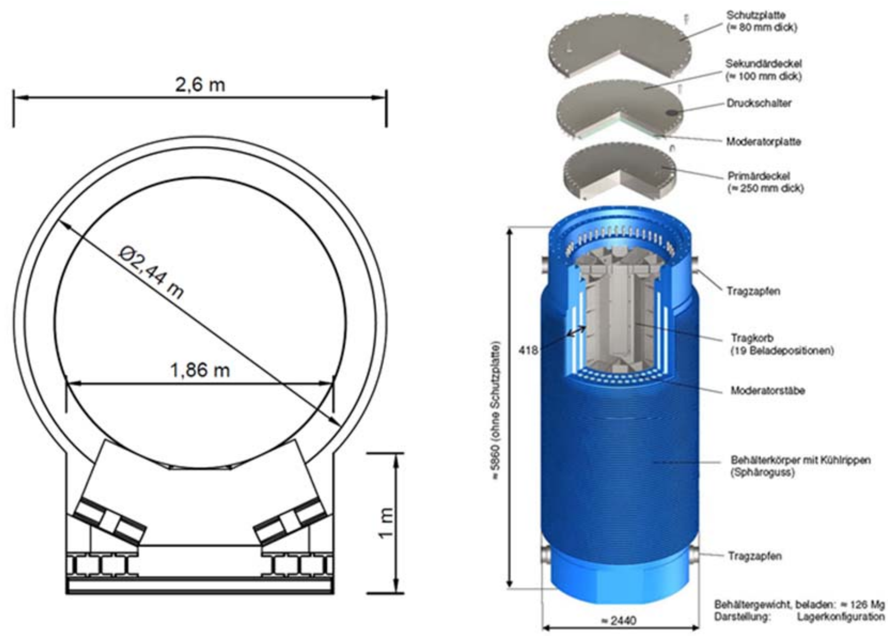


Figure 4-9: CASTOR® cask V/19 (exemplary) [GNS 2010]

The resulting mine layout is 3300 m long and slightly larger than other repository concepts. The width of the repository is 470 m. The infrastructure area and the position of the shafts are identic to the other repository concepts. The repository has a footprint of approximately 1.6 km².

The entire repository layout is illustrated in Appendix 4.

The objectives and procedures of repository closure, namely backfilling and sealing, are almost equivalent to those described for Drift Disposal of POLLUX® casks in chapter 4.3.1. The geological model of a salt pillow provides significantly more thickness of host rock above the emplacement level than available in flat-bedded rock salt, hence more space for the installation of sealing elements. Therefore, the shaft seal design described above can also be applied in the salt pillow concepts.

The small annulus between waste cask and host rock is backfilled directly after emplacement with naturally dry crushed salt.

4.5 Assessment of Operational Safety

For a repository for heat-generating radioactive waste and spent fuel elements, a safety case has to be provided. In accordance with the Safety Requirements [BMU 2010], a distinction is made between the operating phase and the post-closure phase. The operating phase begins with the emplacement of the waste in the repository and ends with the final closure of the shafts and the decommissioning of the surface facilities. The post-closure phase begins after the decommissioning work has been completed.

For the safety of the repository in the operating phase including decommissioning, the reliability and robustness of the safety functions within the repository have to be demonstrated. In addition, graduated measures are to be planned for the operating phase at four safety levels. These safety levels are defined as follows [BMU 2010]:

- normal operation (measures to prevent malfunctions)
- abnormal operation (measures to prevent design basis accidents)
- accidents (measures control accidents)
- severe accidents/events (measures reduce the probability of occurrence or reduce environmental effects)

In accordance with the Safety Requirements, the safety concept must explain and justify which operational disturbances and accidents may occur in the repository. An operational disturbance is an event or a series of events that is frequently expected to occur during the operating life of the facility and for which operation of the facility can be continued and for which the facility is designed or for which measures and facilities are provided as a precaution during the activity [BMU 2009]. An accident is an event or a series of events, the occurrence of which is not to be expected during the operating period of the facility, against which the facility is nevertheless to be designed and at the occurrence of which the operation of the facility or the activity cannot be continued for safety-related reasons [BMU 2009].

This chapter summarises the investigations of the operational safety of processes and procedures in the underground only. As the operational procedures on the surface are not considered within the framework of the KOSINA project, no operational disturbance analysis for these procedures is carried out. Details of all the investigations are given in [Prignitz et al. 2018].

As a first step to demonstrate the reliability and robustness of safety functions, in these investigations the operating procedures for the four disposal concepts are compiled. In a second step the work carried out to date comprises operational disturbances analyses for the drift disposal of POLLUX® casks, the vertical borehole disposal option and the direct disposal of TSC. The results are briefly outlined here. A detailed operational disturbances analysis was carried out for the horizontal borehole disposal option only. For the drift disposal of POLLUX® casks, the already existing results of the accident analysis and the calculation of the radiation exposure caused by the accident were summarised for the operating personnel and for the population in the vicinity [Engelmann & Heidekorn 1989].

The operating procedures of the four emplacement concepts were described in detail for the work in the monitored area, for the work in the controlled area, and for the emplacement process itself.

The analysis of operational disturbances for the drift disposal of POLLUX® casks was carried out as part of a research program for the direct final disposal of spent fuel elements [Engelmann & Heidekorn 1989]. A list of potential accidents, the radiation exposure of the operating personnel caused by the accident, and the radiation exposure of the population in the vicinity caused by the accident were determined. To compile this list, the accidents caused by internal hazards (EVI) and external hazards (EVA) were determined. Undesirable events were considered in the analysis of the operational processes for compilation of possible accidents. The calculations of radiation exposure showed that the limit values of the Radiation Protection Ordinance [StrlSchV 1989] effective at that time were met. Furthermore, the potential operational disturbances of the emplacement system were analysed and compiled with regard to their effects. The elimination of operational disturbances was demonstrated by means of handling tests, thereby achieving improvements in the planned measures. All operational disturbances simulated in the tests could be eliminated [Engelmann et al. 1995].

For the vertical borehole disposal option, an operational disturbances analysis for the emplacement process was carried out as part of the project Optimization of Direct Disposal Concept by Emplacing SF Canisters in Boreholes (DENKMAL) [Filbert & Pöhler 2008]. This analysis was not performed for the shaft and drift transport, as these processes are identical to the transport processes of the POLLUX® cask. To determine the operational disturbances, the emplacement process was divided into different phases and sub-steps. The possible disturbances have been divided into the three categories permissible system status, impermissible system status, and hazard status. The operational disturbances analysis identified and described the disturbances, their possible consequences, their evaluation, the precautionary measures and requirements for the system as well as the potential radiation exposure of the operating personnel. An accident analysis was not carried out, as it was assumed that the accidents are the same for all disposal variants (cf. [Engelmann & Heidekorn 1989]).

As part of the Direct Disposal of Transport and Storage Casks project (DIREGT) [Herold 2014], an operational disturbances analysis was carried out for the shaft transport, the drift transport, and the emplacement process for the direct disposal of TSC The operational disturbances analyses for the shaft transport were carried out on the basis of the analysis within the framework of the work on the direct final disposal of spent fuel elements (DEAB). The analysis for the drift transport and emplacement process was carried out based on the Failure Mode and Effects Analysis (FMEA). The identified disturbances were divided into four categories: interruption with repair without increased radiation exposure, interruption with repair with increased radiation exposure, mechanical impact (crash), and thermal impact (fire). For each possible disturbance, its causes and its consequences were determined. An assessment was made, and possible countermeasures were described. The results showed that operational disturbances can be managed.

An entirely new operational disturbances analysis was carried out for the emplacement process of horizontal borehole disposal option. Regarding operational safety of the shaft and drift transport, reference was made to identical transport processes for the vertical borehole disposal of BSK-V. The operational disturbances analysis was carried out in the form of a Failure Mode and Effects Analysis (FMEA). The evaluation of the identified disturbances was based on the operational disturbances analysis for the vertical borehole disposal of BSK-V, using the three states: permissible system state, impermissible system state, and hazard state. During the operational disturbances analysis, the system or component, its function, the potential disturbances, the cause of the disturbances, the potential consequences, the evaluation, and countermeasures were investigated. Most of the potential disturbances of the category impermissible system status were assessed based on a potential radiation exposure of the personnel during the operating process while eliminating the disturbance as such. For the disturbances identified as having hazard status, a future step is to investigate how the operational disturbances can be avoided or controlled and, if this is not possible, how the system or component must be modified in order to rule out such a case.

4.6 Conclusions and Recommendations

Based on detailed information about the types and amounts of radioactive waste (WP 1 report) and based on two generic geological models (chapter 3) as well as on a safety and demonstration concept (chapter 2), repository designs were prepared for four considered disposal options. Another design fundamental were national regulations, ordinances, and safety requirements. In this context it is important to mention that all repository designs had to fulfil the requirement of retrieving waste packages at any time during the operational period of some decades.

The repository mine layout (two different disposal options for each of the two geological models) was developed on basis of the aforementioned fundamental data and on the results of thermal calculations providing the geometric data for waste package, borehole and drift spacing. Transport and emplacement technology was adjusted to the appropriate disposal option and eventually backfill and sealing measures designed to meet the goals of the safety concept. Because of the advanced knowledge for the disposal option "drift disposal" and "vertical borehole emplacement" it became obvious that there still is a need for further R&D for the disposal options "horizontal borehole disposal" and "direct disposal of transport and storage casks". In particular the option "horizontal borehole disposal" needs detailed planning of safety-relevant technical components and processes.

Regarding operational safety all in all, it can be concluded that the level of knowledge for the individual analyses of operational disturbances varies. This is mainly due to the fact that demonstration tests were carried out for the drift disposal of POLLUX® casks and the vertical borehole disposal option only, but rough concepts are available for the horizontal borehole disposal option and the direct disposal of TSC.

5 Analysis of Geomechanical Barrier Integrity

To investigate the long-term integrity of the bedded salt barrier under thermal loading caused by the disposal of heat-generating radioactive waste, numerical analyses have been carried out both by BGR and IfG using different methods of modeling and constitutive models. BGR performed TM-coupled simulations with 3D models to analyse the far-field integrity of the salt barrier. IfG carried out THM-coupled model calculations focused on the pressure-driven percolation effects using 2D models.

5.1 Rock Salt as Hydraulic Barrier

In several countries, rock salt formations are under consideration for the final disposal of high-level nuclear waste [DOE 2016]. The intrinsic impermeability of undisturbed rock salts against fluids and gases is a central argument in favor of this type of material as a suitable host rock for the safe containment of the nuclear waste. Numerous natural analogues such as naturally developed cavities, where fluids were stored for millions of years in gaseous, liquid and supercritical state, support this notion ([Minkley & Knauth 2013] and [Minkley et al. 2015a]. Further favorable properties of rock salts are their comparatively high thermal conductivity and their ability to creep.

Within a geomechanical assessment of the geological barrier it has to be shown, that the system is able to withstand the thermally induced loading without the loss of the aforementioned property of tightness. In order to evaluate this, certain criteria of integrity are defined and assessed. In order to understand those criteria, it is appropriate to review the mechanisms by which a loss of integrity may be caused.

On a micro-mechanical scale, polycrystalline rock salt constitutes a discontinuous assembly of salt crystals, which are tightly joined to each other at their grain boundaries. The natural porosity of undisturbed rock salt consists of isolated disjointed intergranular pores. Since the crystal matrix itself is essentially impermeable, transport of gases and fluids in rock salts can only occur between the grains, and only after certain conditions are met. For a fluid or gas to propagate into or through the salt, respectively, it is necessary that these initially impermeable grain boundaries are opened. This may result from a fluid pressure, which locally exceeds the minimum principle (least compressive) stress, or by a mechanically induced fracture formation by deviatoric stress above the dilatancy strength of the rock salts. In both cases a threshold has to be exceeded before the hydraulic integrity is lost. Based on an analogue to a similar threshold on random lattices in standard percolation theory, the concept of pressure-driven percolation has been established as a description of the generation of connected flow paths on grain boundaries due to a fluid pressure that exceeds the minimum principle stress [Minkley et al. 2013].

It has been claimed that rock salts become permeable in depths greater than three kilometres, based on measurements of the dihedral angles between grain boundaries in a halite-brine two-phase system [Lewis & Holness 1996]. According to this hypothesis, the connectivity of brine-filled pores in rock salts, and thus the permeability, is controlled by temperature and pressure. For a nuclear waste repository in depths less than a kilometre, local temperatures can exceed 200°C for intermediate timescales. Hence, [Lewis & Holness 1996] postulate that the rock surrounding the repository will become permeable, and the temperature gradient can create a fluid-enriched porous zone in the repository horizon. More recently, the hypothesis has been put forward that rock salts can lose their tightness even in smaller depths by a process called deformation-assisted fluid percolation [Ghanbarzadeh et al. 2015].

The hypotheses are not supported by permeability measurements and are in contradiction to practical experiences for barrier integrity in salt and potash mining as well as cavern storage. Since there is little experimental or in situ data available for high pressure and temperatures conditions, it was necessary to check whether the postulated permeability transition occurs or not. IfG conducted laboratory experiments to test the hypotheses regarding percolation at high temperature and pressures. The experiments were performed on rock salt from a flat-bedded Zechstein deposit in Germany. The test condition of stresses up to 90 MPa and temperatures up to 95°C reaches the region where the dihedral angle falls below 60° (Figure 5-1) and the wetted grain boundary network should be fully connected. [Lewis & Holness 1996] hypothesize a permeability similar to sandstone for these conditions.

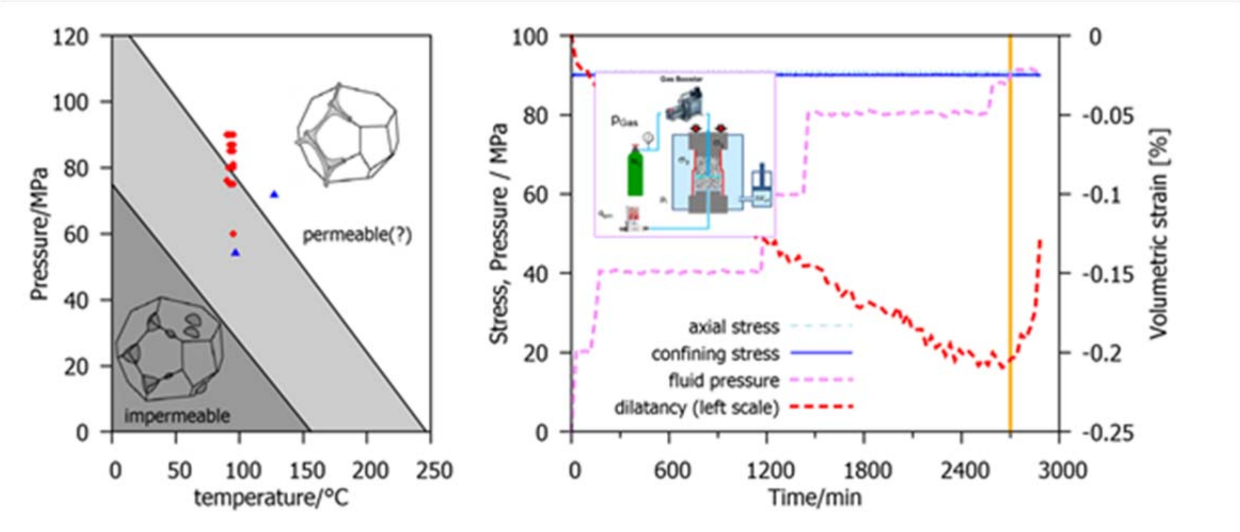


Figure 5-1: Left panel: Investigated stress & temperature states in the IfG laboratory experiments (red) and those of in-situ observations (blue). Right panel: Results of an experiment at T=90°C

Figure 5-1 shows the positions of the investigated regimes of stress and temperature (red dots) as well as those of in-situ observations (BAS-2 cavern and Altmark test, blue) within the alleged regions of impermeability (dark gray), high permeability (white) and their transition region (light gray). However, the results of the laboratory investigations of percolation at such high pressures and temperatures further support the concept of impermeability of rock salt even under these conditions. No gas flow or increase in volumetric strain was observed as long as the fluid pressure is lower than the minimum principle stress and a breakthrough only occurs once the threshold is exceeded (see Figure 5-1, right panel).

The experimental tests on natural rock salt specimens performed in the KOSINA project do not confirm this prediction because in the so-called permeable region no gas flow was observed despite the lower experimental permeability measuring limit is << 10^{-22} m². Hypotheses derived solely from measurements of the dihedral angle in synthetic two-phase systems of halite and brine [Ghanbarzadeh et al. 2015] are thus not supported by permeability tests of IfG (Figure 5-1). On the contrary, experiments show that rock salt is impermeable even under these high pressures and temperatures, in accord with previous experiments at lower stresses and temperatures. Because no permeability can be detected under high stresses and temperatures in natural rock salt specimen, the theory discussed above is falsified. fG tests show that natural rock salt loses its tightness only if the fluid pressure exceeds the minor principal stress, i.e. the percolation threshold, even under high stress and temperature. Only in this case, grain boundaries can be opened (increase in volumetric strain) and a connected fluid network can be created in the polycrystalline rock salt [Minkley et al. 2012]. This process, the pressure-driven percolation, led to the loss of integrity of saliferous barriers in salt and potash mining several times [Minkley et al. 2015b].

The lab tests (Figure 5-2) corroborate in-situ-determinations of the percolation threshold in salt formations: The threshold is given by the minimal stress in the rock mass (minimal stress criterion). If the threshold is exceeded, percolation starts and fluid migrates through the rock in a directed way: Grain boundaries with lower normal stress, i.e. with contact normals in the direction of the minor principal stress, are opened preferably, so that the overall motion proceeds in the direction of the major principal stress [Minkley et al. 2013]. Thus, pressure-driven percolation is a directed process determined by the stress field, seeking the path of least resistance along the grain boundaries, which is generally orthogonal to the minor principal stress.

The hypothesis [Ghanbarzadeh et al. 2015] that the percolation threshold vanishes at high temperature and pressure is thus refuted by experiments on natural rock salt, and hence a basic prediction of the theory is falsified. These experimental tests, performed in the framework of the KOSINA project, are an important prerequisite for the proof of integrity of saliferous barriers in the disposal of radioactive waste in rock salts.

In continuum-mechanical integrity assessments the two percolation thresholds minimum principal stress and dilatancy boundary are considered using the subsequently presented safety criteria.

5.2 Criteria for the Evaluation of Barrier Integrity

To evaluate the long-term integrity of the salt barrier, two safety criteria, the dilatancy criterion and the fluid pressure criterion, are considered [BMU 2010].

- Dilatancy criterion (Figure 5-2, top): The integrity of the rock salt barrier is guaranteed if rock stresses do not exceed the dilatancy boundary. If the deviatoric stress exceeds this boundary, microcracks will form and will cause progressive damage and permeability of the rock salt.

– Fluid pressure criterion (Figure 5-2, bottom): The integrity of the barrier is guaranteed if the hydrostatic pressure of an assumed column of brine extending from the ground surface to depth of the considered location of the salt body contour (e.g. top of the salt formation) does not exceed the minimum principal stress at that point.

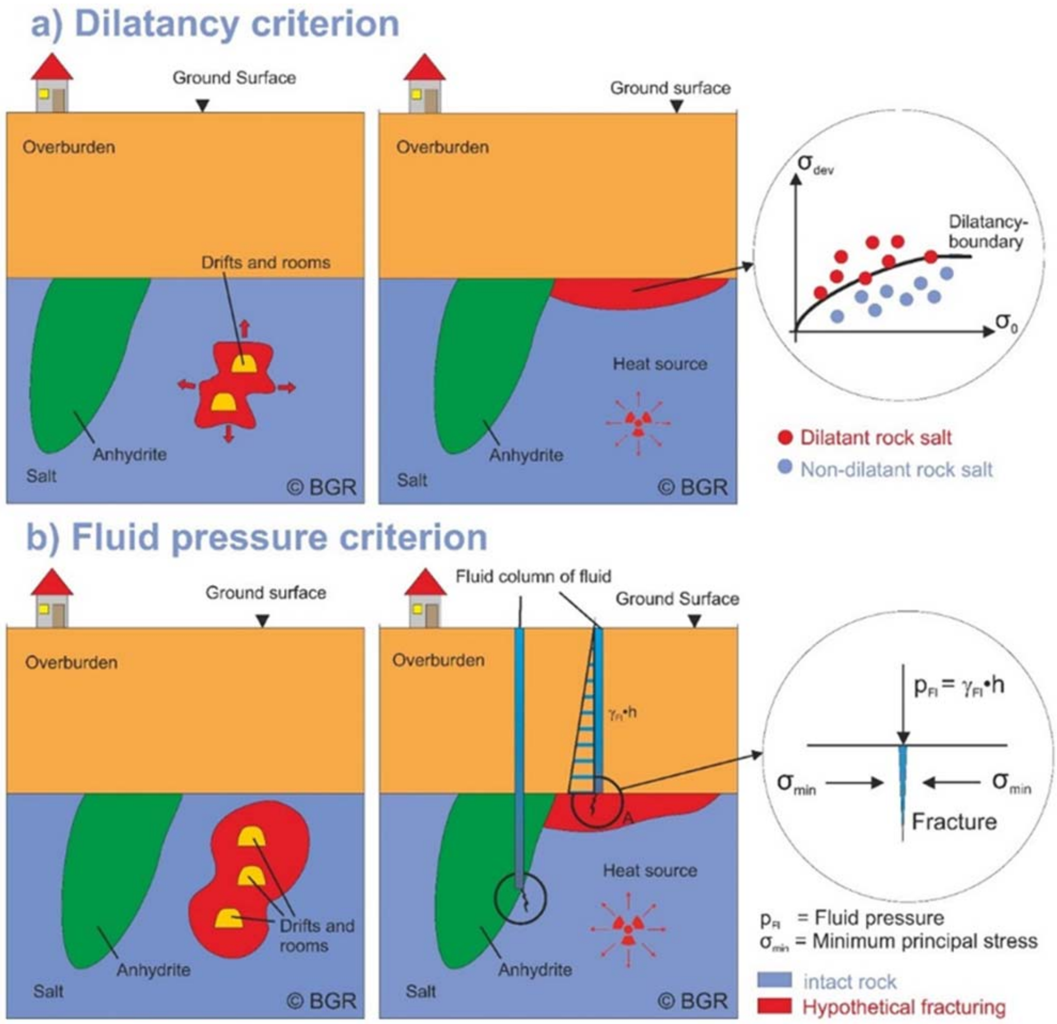


Figure 5-2: Schematic illustration of the dilatancy criterion (top) and the fluid pressure criterion (bottom) [Heusermann et al. 2007]

In other applications of geomechanical studies for related to the integrity of salt barriers, a so-called tensile stress criterion is often also used, stating that the tightness of rock salt can be lost if the tensile strength is exceeded [Minkley et al. 2015b]. This is done to differentiate whether damage is caused predominantly by shear or tensile stresses.

However, for the continuum mechanical calculation violations of this criterion are already encompassingly covered by the fluid pressure criterion and therefore not added as an additional criterion. In the discontinuum mechanical THM calculations, the tensile strength is conservatively set to zero, meaning that as soon as tensile stresses occur, grain boundaries in the rock salt are opened and percolation occurs in accordance with the previous descriptions on the hydraulic properties of rock salt.

5.3 Material Parameters and Constitutive Models

A literature review of homogenous geological salt layers including appropriate constitutive models and thermal, mechanical and hydraulic parameters of geological homogenous layers was conducted in order to provide the model input data. The material parameters and constitutive models are described by [Liu et al. 2017]. Table 5-1 summarizes material parameters used for the numerical model calculations for the bedded salt formations, the overburden and the basement rocks. In the TM-coupled calculations, the lithostatic pressure gradient for all layers is 0.022 MN/m^3 and the thermal conductivity for the salt formations excluding potash seam and main anhydrite is a parameter dependent on temperature.

Table 5-1: Summary of material parameters

Homogeneous zones	Symbol	Density	Thermal conductivity	Specific heat capacity	Thermal expansion coefficient	Young's modulus	Poisson ratio
		kg/m^3	W/(m·K)	J/(kg·K)	1/K	GPa	[-]
Quaternary	Q	2000	2.3	950	1.0E-05	0.1	0.33
Tertiary	T	2100	2.1	905	1.0E-05	0.5	0.33
Bunter	S	2500	2.6	760	1.0E-05	15	0.27
Aller rock salt	NA4	2235	5.2	860	4.0E-05	25	0.27
Anhydritmittelsalz	AM3	2275	5	860	3.5E-05	30	0.27
Potash seam Ronnen-berg	K3	1850	1.5	903	2.5E-05	16	0.26
Leine rock salt	NA3	2160	5.2	860	4.0E-05	25	0.25
Main anhydrite	A3	2700	4.2	860	1.6E-05	60	0.25
Potash seam Staßfurt	K2	1850	1.5	903	2.5E-05	17	0.28
Staßfurt rock salt	NA2	2160	5.2	860	4.0E-05	33	0.25
Anhydrite/carbonate	A2/C2	2700	4.2	860	1.6E-05	30	0.27
Underlying red	R	2500	2.7	760	1.0E-05	17	0.27

The deformation behavior of the ductile salt layers is described by BGR by a constitutive equation including elastic, steady-state creep and dilatant deformations (Eq. 5-1).

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{eff}^{cr} + \dot{\varepsilon}_{ij}^{dil} \qquad \text{(Eq. 5-1)}$$

where $\dot{\varepsilon}_{ij}^{el}$ is the elastic deformation rate, $\dot{\varepsilon}_{eff}^{cr}$ is the effective steady-state creep rate and $\dot{\varepsilon}_{ij}^{dil}$ is the dilatant deformation rate. The effective steady-state creep rate is given by Eq. 5-2 (creep law BGRa),

$$\dot{\varepsilon}_{eff}^{cr} = A \cdot e^{-\frac{Q}{RT}} \cdot \left(\frac{\sigma_{eff}}{\sigma^*}\right)^n \qquad \text{(Eq. 5-2)}$$

in case of high temperature by Eq. 5-3 (creep law BGRb)

$$\dot{\varepsilon}_{eff}^{cr} = \left[A_1 \cdot e^{-\frac{Q_1}{RT}} + A_2 \cdot e^{-\frac{Q_2}{RT}}\right] \cdot \left(\frac{\sigma_{eff}}{\sigma^*}\right)^n \qquad \text{(Eq. 5-3)}$$

and by Eq. 5-4 for carnallitite (creep law BGRsf):

$$\dot{\varepsilon}_{eff}^{cr} = A \cdot e^{-\frac{Q}{RT}} \cdot \left(\frac{\sigma_{eff}}{\sigma^*}\right)^n + C \cdot \left(\frac{\sigma_{eff}}{\sigma^*}\right)^2 \qquad \text{(Eq. 5-4)}$$

where R=8.3143·10^{-3} KJ/(mol·K) is the universal gas constant, T = temperature (K), σ_{eff} = deviatoric stress (MPa) and σ^* = reference stress (1.0 MPa). The material parameters A = structural factor (0.18 1/d), A_1=2.3·10^{-4} 1/d, A_2=2.1·10^6 1/d, n = stress exponent (5.0), Q = activation energy (54.0 kJ/mol), Q_1= 42 kJ/mol, Q_2 = 113.4 kJ/mol, and C = 1.976·10^{-7} 1/d [Hunsche et al. 2003] have been determined in laboratory creep tests. For details of the creep behavior of different salt layers see [Liu et al. 2017].

Based on extensive lab test series on rock salt, the dilatant behavior of rock salt has been considered using a dilatancy concept (r_V concept) according to [Hunsche et al. 2003]. Here the volumetric dilatancy rate $\dot{\varepsilon}_{dil,vol}$ is correlated to the deviatoric creep rate $\dot{\varepsilon}_{eff}$ via an empirical relation using r_V (depending on σ_{eff} and the minimum compressive stress σ_{min}) (Eq. 5-5):

$$\dot{\varepsilon}_{dil,vol} = r_V \cdot \dot{\varepsilon}_{eff} \qquad \text{(Eq. 5-5)}$$

If the deviatoric stress σ_{eff} exceeds a boundary stress $\sigma_{eff,Dil}$, the factor r_V is positive and dilatancy will occur (Eq. 5-6):

$$r_V = a \cdot \left|\frac{\langle \sigma_{eff} - \sigma_{eff,Dil} \rangle}{|\sigma_{min} - \sigma_{eff}/3|}\right|^{m'} \qquad \text{(Eq. 5-6)}$$

where σ_{min} is the minimum principal compressive stress (negative value), while $\sigma_{min} = \sigma_3$ and $\sigma_1 < \sigma_2 < \sigma_3$. $\langle \dots \rangle$ is the Föppl symbol and means $\langle x \rangle = MAX(0, x)$.

The dilatancy boundary only can be displayed in the following implicit form (Eq. 5-7):

$$\sigma_{min} = \frac{1}{3} \cdot \sigma_{\text{eff,Dil}} - \sigma^* \cdot \left(\frac{\sigma_{\text{eff,Dil}}}{b'}\right)^{1/c} \qquad \text{(Eq. 5-7)}$$

With empirical parameters a = 0.8165 MPa, b'= 3.2 MPa, c = 0.78 and m' = 2.0.

In the THM-modeling performed at IfG, a special elasto-visco-plastic constitutive model for rock salts is employed which allows a realistic description of hardening, softening and dilatancy processes of saliferous and non-saliferous sediments [Minkley & Mühlbauer 2007]. In addition, an adhesive shear model for bedding planes and grain boundaries is used. Both constitutive models are implemented into the numerical codes UDEC and 3DEC as user defined models. The elasto-visco-plastic constitutive model is based on standard models of continuum mechanics and can describe both ductile and brittle material behavior using a generalized non-linear Mohr-Coulomb envelope as failure criterion:

$$\sigma_1^{Yield} = \sigma_D + N_\phi \cdot \sigma_3 \qquad \text{(Eq. 5-8)}$$

Here, σ_1^{Yield} is the major principal stress at yield and σ_3 denotes the minor principal stress. The friction function is:

$$N_\phi = 1 + \frac{\sigma_{Max} - \sigma_D}{\sigma_\phi + \sigma_3} \qquad \text{(Eq. 5-9)}$$

The maximum stress difference at failure can then be expressed as

$$\sigma_{Diff}^{Yield} = \sigma_1^{Yield} - \sigma_3 = \sigma_D + \frac{\sigma_{Max} - \sigma_D}{\sigma_\phi + \sigma_3} \cdot \sigma_3 \qquad \text{(Eq. 5-10)}$$

The parameters of the yield function are the uniaxial compressive strength σ_D, the maximum effective strength σ_{Max} and a curvature parameter σ_ϕ. To incorporate hardening and softening (e.g. dilatancy, failure and residual strength), σ_D, σ_{Max} and σ_ϕ are functions of the plastic shear deformation ε_P, which results from a non-associated plastic potential including volume increase, i.e. dilatancy, due to shear loading. Details of the formulation can be found in [Minkley & Mühlbauer 2007].

This approach also applies a different formula than BGR uses to describe the steady-state creep rate based on a sinh-relation (Eq. 10),

$$\dot{\epsilon}_{eff}^{creep} = \frac{\sigma_{eff}}{3\eta_0} \cdot e^{-\frac{Q}{RT}} \cdot \sinh(m \cdot \sigma_{eff}^n) \qquad \text{(Eq. 5-11)}$$

Where η_0 = viscosity (MPa·d) and m (MPa^{-n}), n (-) are curvature parameters.

However, this approach was easily fitted to reproduce the creep law BGRa reasonably well, so that the creep behavior was modeled in a very similar way by both institutions. Therefore, the general principle of mutual verification and supplementation is followed, since both constitutive models with their respective parameters should describe the same creep properties as defined by the generic database used for this study.

5.4 Numerical Modeling to analyse Salt Barrier Integrity

To predict the long-term barrier integrity of the flat-bedded salt and the salt pillow, numerical calculations have been carried out by BGR and IfG for the four different repository concepts described in the chapter 4. The results are described in [Liu et al. 2018]]. The vertical borehole disposal option (see chapter 4.4.1) is characterized by a compact thermal source, thus representing the most demanding situation with respect to the barrier integrity evaluation.

Therefore, only the simulation for the vertical borehole disposal option is presented in the following subsections.

5.4.1 THM-coupled 2D Modeling

The discrete-element simulations of the thermo-hydro-mechanical coupled behavior of the bedded salt have been carried out by IfG using 2D models and 3D slice models. Underground openings and structures such as disposal drifts and disposal boreholes are explicitly modelled in these simulations. Using the DEM programs UDEC & 3DEC [ITASCA 2011], [ITASCA 2013], the calculations were performed to analyse the time-dependent development of temperature, deformation and dilatancy of the rock salts as well as the long-term integrity of the salt barrier by investigation of the pressure-driven percolation in the coupled simulations.

- Model description

For the 2D and 3D slice modeling of IfG, appropriate cross sections through the repository and geologic structure have been determined. Compared to the real 3D repository situation, this may lead to a conservative overprediction of the THM-effects due to the introduced thermal load, since the repository is then implicitly considered to extend infinitely into the out-of-plane direction. In return, this simplification allows for the allocation of processing power for the explicit modeling of disposal drifts and waste canisters (including backfilling) as well as the modeling of localized percolation processes into the hydraulic protection layers. The position of the cross-section for the numerical 2D-model for the salt pillow structure corresponds to a cutting plane through the center of the repository perpendicular to its largest expansion.

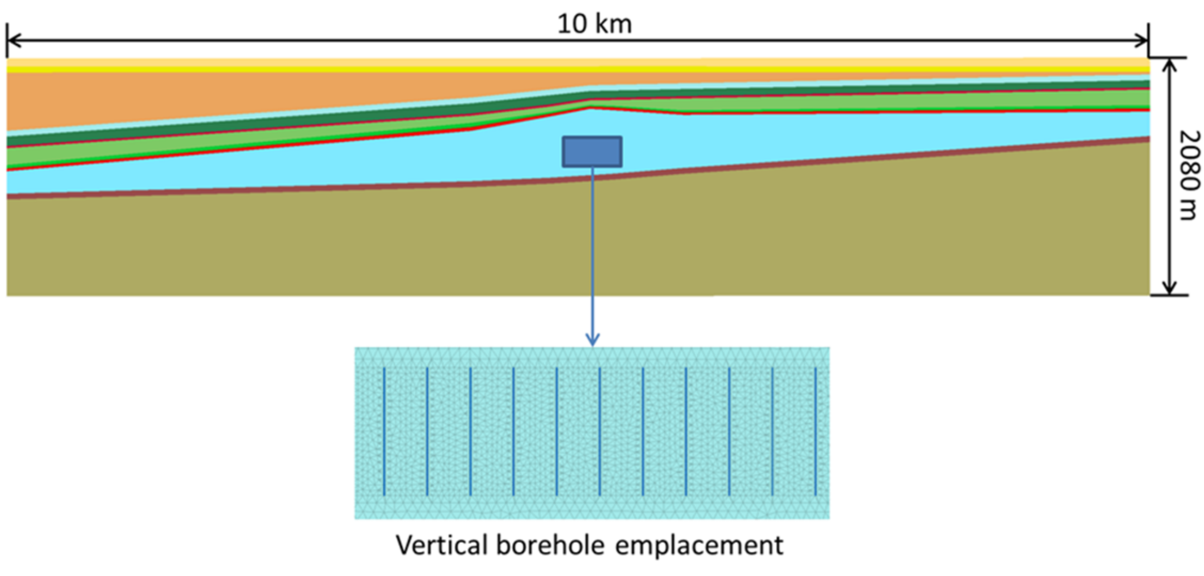


Figure 5-3: Structure of the 2D-model for the emplacement of heat-generating nuclear waste in a salt pillow

The 2D-model has a width of 10 km and a height of 2080 m (Figure 5-3). The 100 m deep boreholes for the vertical borehole disposal option were arranged at a repository depth of 725 m below sea level on a square grid with a respective distance of 33.6 m.

Simulated heat power

Since a 2D-model implies that the modeled geometry extends infinitely in the out-of-plane direction it becomes immediately clear, that the particular geometry of the vertical borehole emplacement is rather unsuitable with respect to this assumption since the boreholes would effectively act as infinitely extended heated plates. Therefore, the 2D-model was actually constructed as a „2.5D“-model, meaning that it actually is a 3D-slice model with a thickness of 16.8 m. With this setup, also the out-of-plane distance between boreholes can be taken into account and therefore the model can be used to investigate near-field temperature and stress developments close to the vertical boreholes. The slice model still implicitly models an infinitely extended repository in the out-of-plane direction, which is why it may conservatively overpredict the thermo-mechanical impact in terms of stress and displacements, depending on the out-of-plane extent of the repository.

The time-dependent heating power of the heat-generating waste canisters was assigned according to Bollingerfehr et al. 2017 with an interim storage period of 57 years. The applied heat sources were validated by recalculating the result of the prior thermomechanical design calculations which defined the borehole distances (s. chapter 4.4.1).

Simulation of percolation processes

In addition to the conventional evaluation of dilatancy and minimum principal stress criterion, the 2D-models were built in such a way, as to allow for the modeling of coupled thermo-hydro-mechanical processes of groundwater percolation into the salt barrier. Preliminary studies had shown that the upper layers of the salt barrier are particularly prone to this effect. Therefore, the layers Na4 and AM3 in the central area above the repository were additionally discretized in deformable Voronoi elements (Figure 5-4).

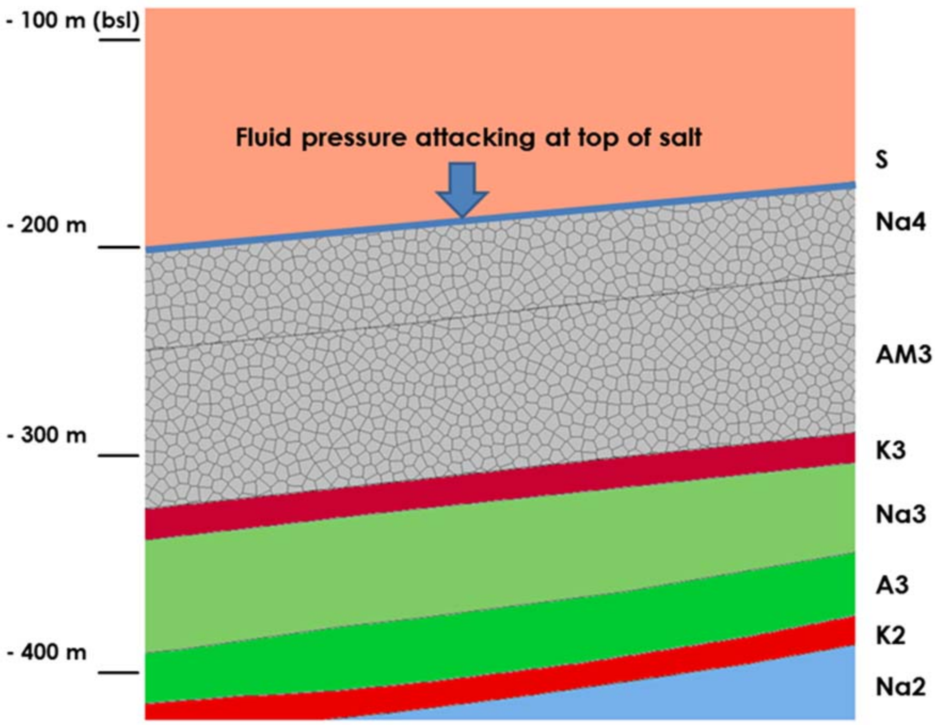


Figure 5-4: Discontinuum-mechanical Voronoi-tesselation of the barrier layers Na4 and AM3

Along the upper edge of the salt barrier a depth-dependent groundwater fluid pressure is acting during the simulation. When the normal stress on the grain boundaries between Voronoi-elements falls below that pressure or when these grain boundaries are mechanically damaged by shear loading, a pressure-driven percolation into the initially impermeable grain boundary network can be initiated. For the long-term assessment no explicit values for fracture widths and contact permeabilities describing the transient pressure development are set. Instead it is conservatively assumed in the quasi-static simulations, that the fluid may instantaneously fill all available opened space along grain boundaries at the stress state for the given point in time.

5.4.2 Results of the THM-coupled 2D Modeling

Upon instantaneous emplacement of all waste canisters, which has been conservatively assumed for the numerical modeling, the thermal loading leads to an increase in temperature, which in turn results in the thermal expansion of the surrounding rock salt. The temperature at the surface of the waste canisters in the center of the emplacement area increases to approx. 185 °C within 280 years after emplacement (Figure 5-5). After a delay of about 300 years, the thermal wave reaches the top of the salt and leads to a maximum temperature increase of 15 °C at 2500 years after emplacement. This temperature change is lower than in the modeling scenarios for the flat-bedded salt due to the larger distance between repository and top of the salt in the salt pillow structure. After reaching their maximum, the temperatures slowly decrease, but the initial temperature field is not reached within the observation period of 10,000 years. There is no noticeable change in temperature at the surface.

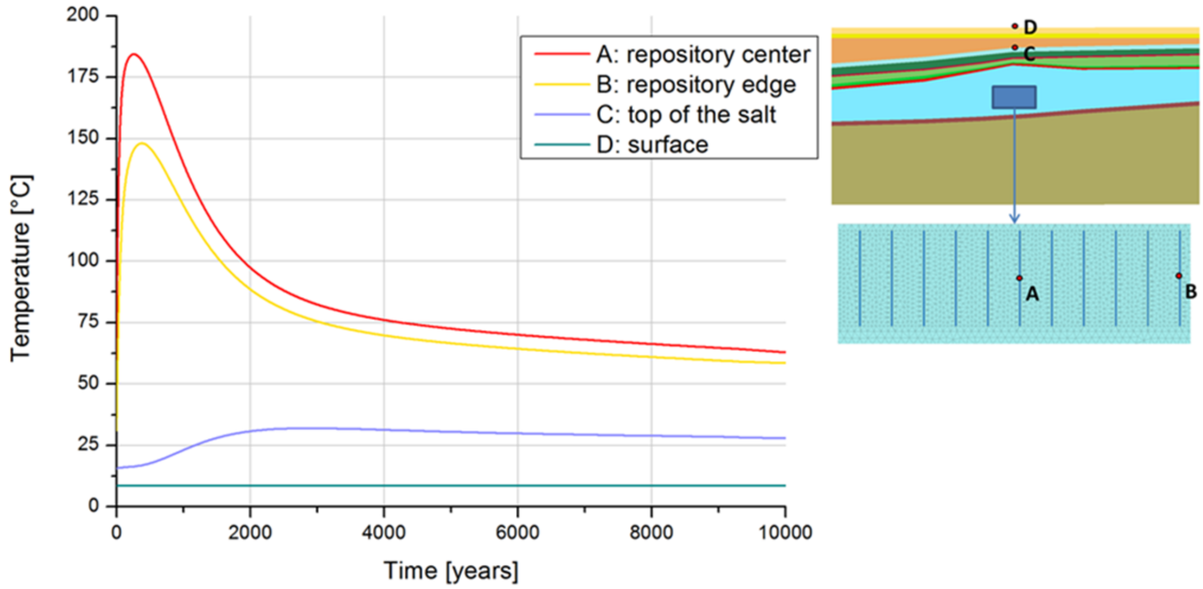


Figure 5-5: **Temperature development in the numerical 2D-modeling of vertical borehole disposal in a salt pillow structure**

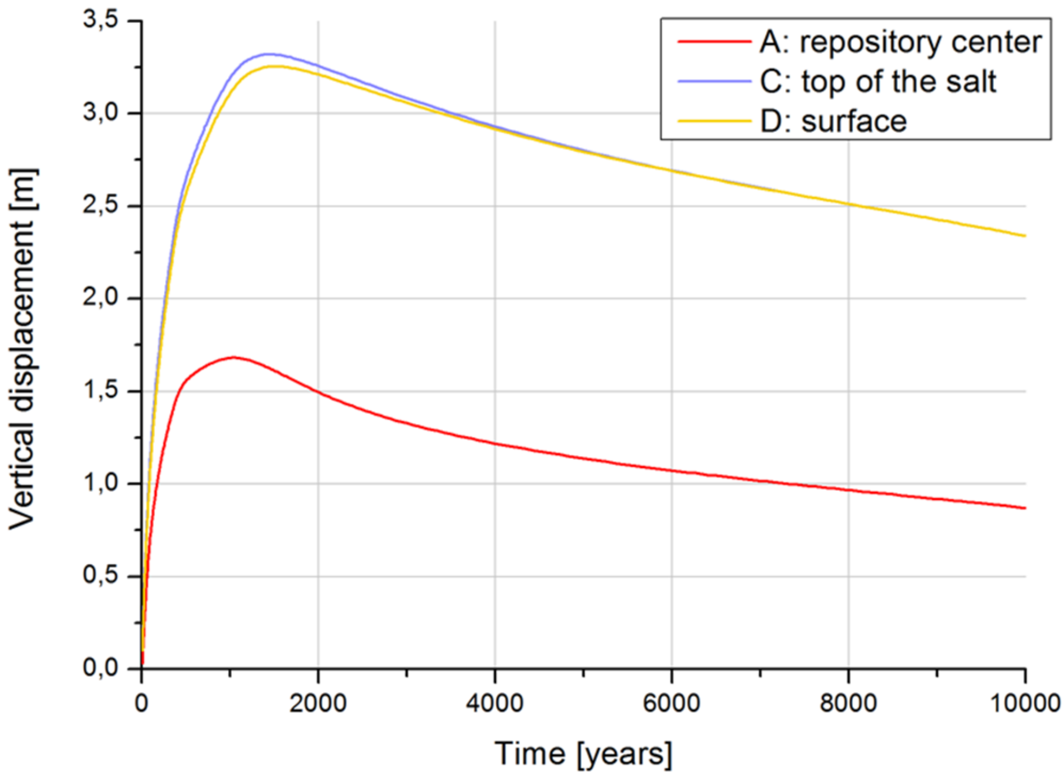


Figure 5-6: **Vertical displacements in the numerical 2D-modeling of vertical borehole disposal in a salt pillow structure**

The thermally induced expansion in the repository horizon initiates an uplift process above the repository (Figure 5-6). The uplift at the surface reaches a maximum vertical displacement of 3.3 m after 1000 years, which occurs more than 700 years after the temperature maximum occurred in and around the repository. The maximum vertical displacement is the largest within all considered disposal options and geologies owing to the fact, that in case of the vertical borehole disposal option the area-specific thermal impact is most pronounced. After reaching the maximum uplift, the vertical displacement slowly decreases again, but – similar to the temperature field – does not reach is initial state within the observation period of 10,000 years.

Due to the thermally induced uplift, the upper part of the salt barrier experiences a reduction of the minimum principle stress (Figure 5-7). This results in a spatially and temporarily limited violation of the minimum principle stress criterion at the top of the salt from approx. 5 to 700 years after emplacement. During this period, the fluid pressure criterion is violated at the top of the rock salt barrier. Moreover, the stresses even reach a tensile regime, leading to localized dilatant damaging. In the numerical model calculations this leads to tensile strains and grain boundary openings, which is why the minimum principle stress σ_{MIN} does not fall below the value of the assigned long-term tensile strength of $\sigma_T = 0$. The area of dilatant damage however only affects a subset of the violation area of the minimum principle stress criterion, which at its largest extend is violated up to 60 m from the top of the salt into the barrier. This leaves a thickness of undisturbed and undamaged salt barrier of over 500 m above the repository at every given time during the simulation.

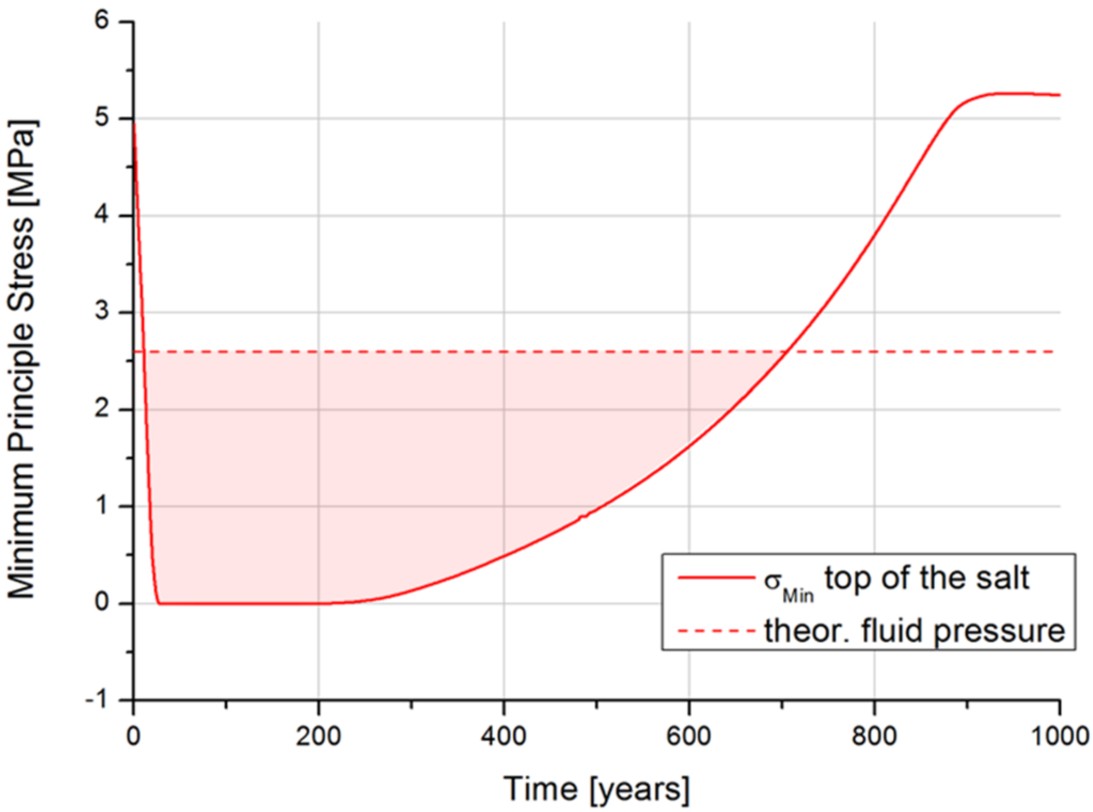


Figure 5-7: Development of minimum principle stress at the top of the salt in comparison with the theoretically attacking fluid pressure in the numerical 2D-modeling of vertical borehole disposal in a salt pillow structure

In the thermo-hydro-mechanically coupled simulations, we can explicitly model the fluid flow into the salt barrier, when the attacking fluid pressure compensates the normal stresses on grain boundaries. Since the uplift induced by the thermal expansion leads to a reduction of horizontal stresses (minor principal stress) at the top of the salt, we observe predominantly vertically aligned pressure driven flow paths reaching into the upper 50 – 60 meters of the salt barrier, which agrees well with the areas of violation of the minimum stress criterion (Figure 5-8). In general, the minimum principal stress is always the conservative envelope of the percolation area, since it does not take the orientation of the stress tensor in account. If for example the vertical stresses would have been the ones reduced in a similar area, we would not have observed any fluid flow into the barrier, even though the minimal stress criterion would have predicted a violation zone.

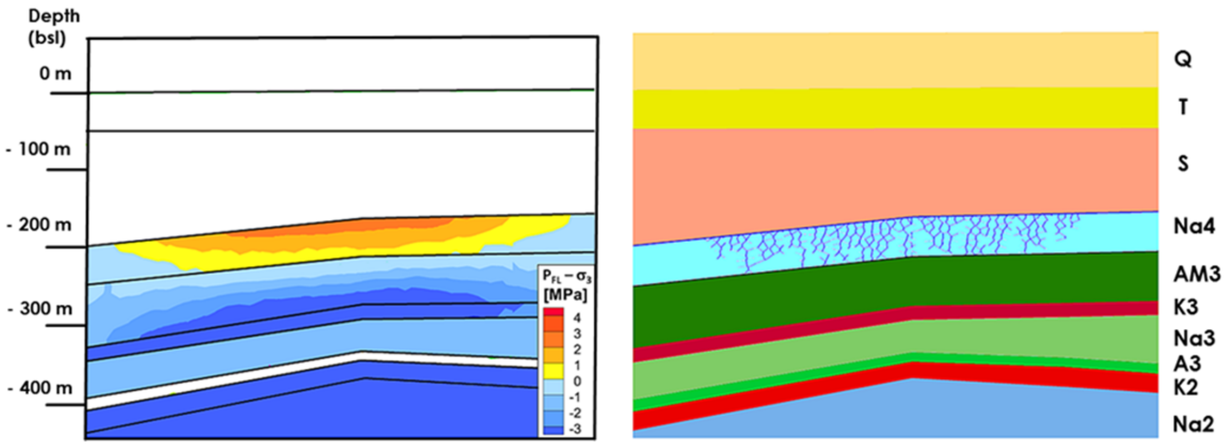


Figure 5-8: **Comparison of violation area of the minimum principle stress criterion (left) and the area, where pressure-driven percolation occured in the coupled thermo-hydro-mechanical calculations (right, dark blue structure) for vertical borehole disposal in a salt pillow structure**

5.4.3 TM-coupled 3D Modeling

The FEM simulations of the thermo-mechanical behavior of the bedded salt have been carried out by BGR using 3D models. Since the analysis focused on the far-field area of the salt structure, underground openings such as shafts, disposal drifts and disposal boreholes were not taken into account in the models. The calculations were performed using the FEM program JIFE [Faust et al. 2016] for a model time period of 10,000 years to analyse the time-dependent development of temperature, deformation and dilatancy of the rock salts as well as the long-term integrity of the salt barrier.

Model description

Figure 5-9 shows the numerical 3D modeling of the salt pillow including dimensions of the model, section cuts of finite element meshes and descriptions of the geological homogenous layers. The length, width and height of the 3D model are 5336 m, 3323 m and 3574 m, respectively. The top of the model was the ground surface. The waste disposal area was located in the salt layer NA2, 798.5 m below the ground surface.

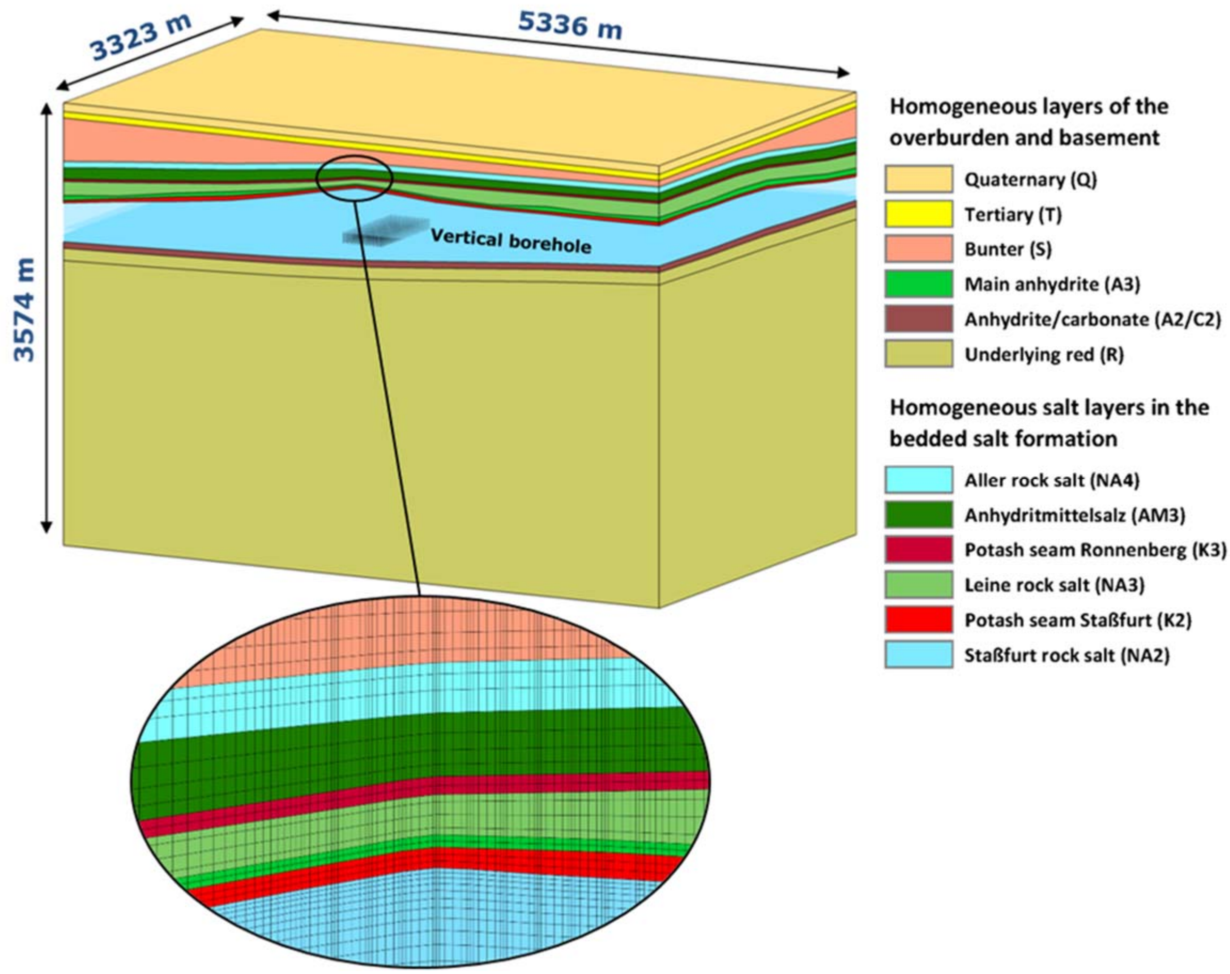


Figure 5-9: Numerical 3D modeling (far-field model) of the salt pillow

Initial and boundary conditions

Based on the annual average temperatures in northern Germany, an initial temperature of 282 K was assigned to the ground surface. By considering a heat transfer coefficient of 8.7 W/($m^2 \cdot$ K), a thermal convection took place at the ground surface over time [Nipp 1988]. An initial temperature field and the fixed temperature at the bottom of the 3D model were calculated by using a gradient of 3 K/100 m.

The primary stress state in the rock mass was assumed to be an isotropic overburden pressure, which was calculated by integration of 2.2 kg/dm^3 density. The front side of the model was a mirror boundary condition. The other sides and the bottom were defined with a sliding boundary condition over time, i.e. no displacement in the normal direction.

Simulated heat power

In order to simulate the heat source of the heat-generating radioactive waste in the numerical 3D modeling of the vertical borehole disposal option, the heat power was described by the equation (Eq. 5-12). Figure 5-10 shows a simplified arrangement of the vertical disposal boreholes in the salt pillow that was used in the model. For the reason of symmetry of the repository only half of the emplacement area could be considered. 11 parallel vertical heat sources at 33.6 m distance were modeled in the emplacement area. The length and height of the heat source were 823.2 m and 87.1 m, respectively. In each heat source a total number of $25 \cdot 15 = 275$ casks (BSK-V) were considered.

$$P_{BSK/area}(t)\left[\frac{kW}{m^2}\right] = \frac{n \cdot P_{BSK}(t)[kW]}{A\left[m^2\right]} = \frac{25 \cdot 15 \cdot P_{BSK}(t)[kW]}{823.2\,[m] \cdot 87.1\,[m]} = \frac{P_{BSK}(t)[kW]}{191.2\,[m^2]} \qquad \text{(Eq. 5-12)}$$

Where $P_{BSK/area}(t)$ is the time-dependent heat power of each vertical heat source, $P_{BSK}(t)$ is the heat power of a single cask, n is the number of the emplaced casks in the vertical area and A is the area size.

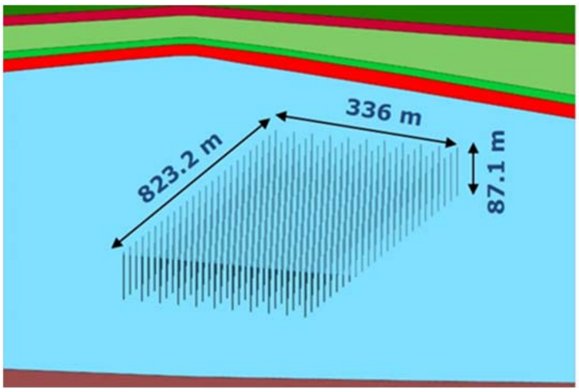


Figure 5-10: **Simplified arrangement of the vertical disposal boreholes in the salt pillow**

5.4.4 Results of 3D Modeling

Due to the thermal loading of HLW waste, the temperature of the rock mass, especially surrounding the emplacement area, raises obviously. As depicted in the temperature-time diagram in Figure 5-11, the center of the emplacement area (point A) reaches a maximum temperature of 147°C after 214 years. The temperature at the emplacement area’s upper edge (point B) reaches a maximum of 129°C at 285 years after waste disposal. The temperature rise diminishes with growing distance from the thermal sources. At the top of the salt barrier (point C), the temperature increases by approximately 10°C. There is no obvious temperature change on the ground surface (point D).

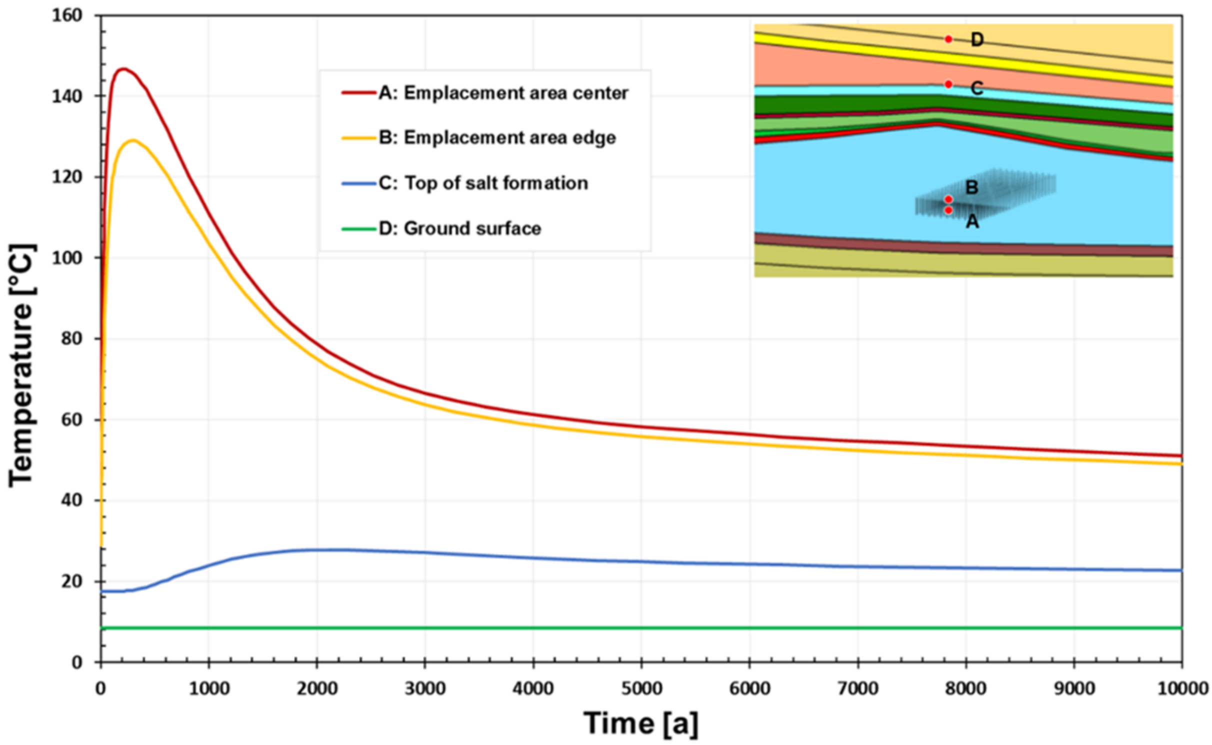


Figure 5-11: Time history of calculated temperatures (3D modeling of the vertical borehole disposal in the salt pillow)

Thermally induced deformation, especially thermal expansion of the rock salts, leads to a vertical displacement of the rocks above the emplacement area. Figure 5-12 shows the calculated vertical displacement at the ground surface, at the top of the salt barrier and at the emplacement area center. The surface uplift is a delayed reaction to the increase in temperature within the repository. Therefore the maximum surface uplift is observed 690 years after the maximum temperature peak. A maximum uplift of 2.4 meters at the top of the salt barrier occurs at 908 years after waste disposal. The maximum uplift at the ground surface after 1000 years and at the emplacement area center after 679 years are 2.2 and 1.3 meters, respectively.

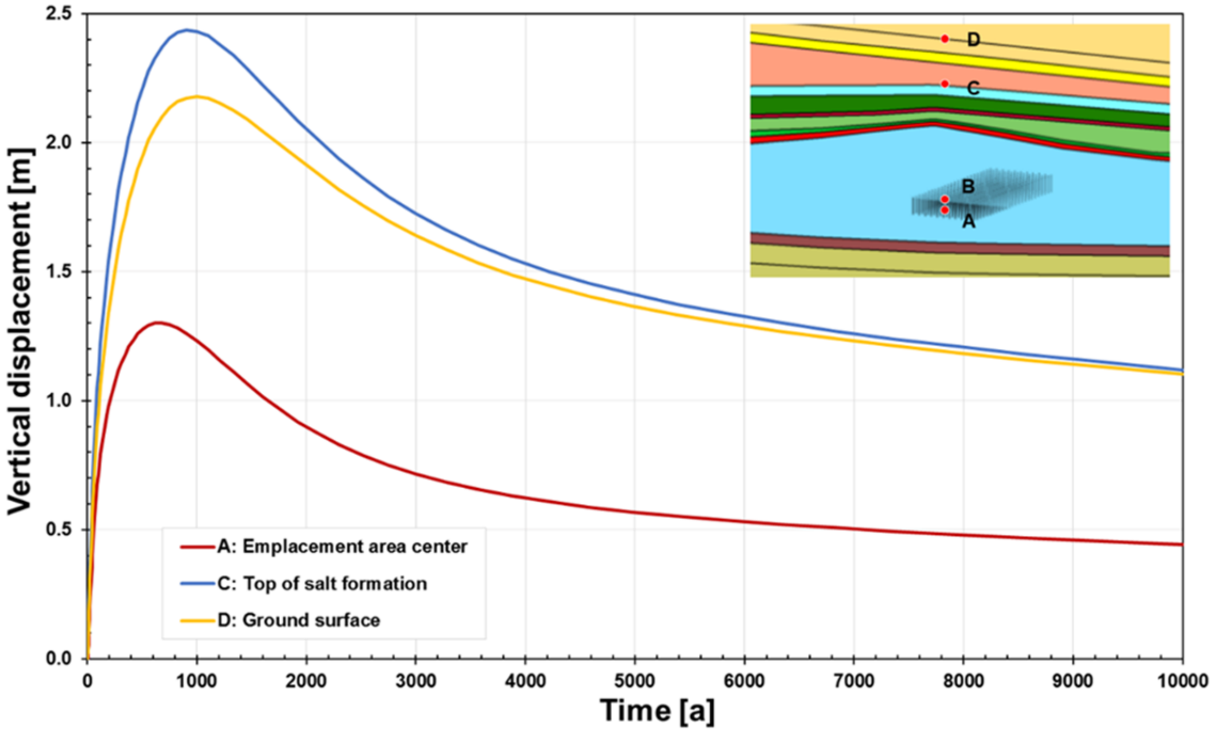


Figure 5-12: Time history of calculated vertical displacement (3D modeling of the vertical borehole disposal in the salt pillow)

To analyse the integrity of the salt barrier, numerical results are evaluated regarding the dilatancy criterion and the fluid pressure criterion, respectively.

As depicted in Figure 5-13, frac-risked zones (yellow, orange and red) are determined at the salt surface and within the layer AM3. The fluid pressure criterion is violated up to 50 meters from the top into the salt barrier for around 400 years. At all times, at least 520 meters intact salt barrier remains.

As depicted in Figure 5-14, dilatant rock zones (red) occur at the top of the salt barrier during the first 20-82 years after waste emplacement. These zones reach up to 50 m from the top into the salt barrier. In the model calculation it was assumed, that dilatancy remains constant once it has formed (a healing model approach was conservatively not considered). Therefore, the calculated dilatancy remains until the end of the calculation, even though healing would be expected to occur with time. In any case, the model calculation showed that throughout the time at least 520 m barrier is not affected.”

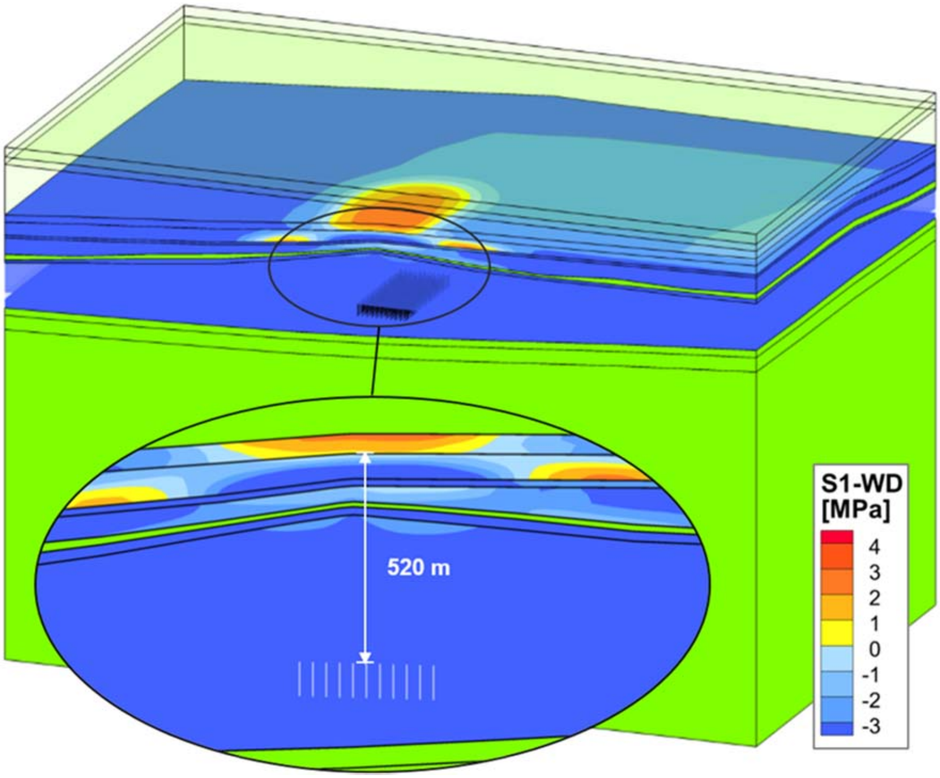


Figure 5-13: **Hypothetical frac-risked zones in the salt barrier (yellow, orange) for the vertical borehole disposal in a salt pillow, 82 years after emplacement. (Overburden layers are shown transparently)**

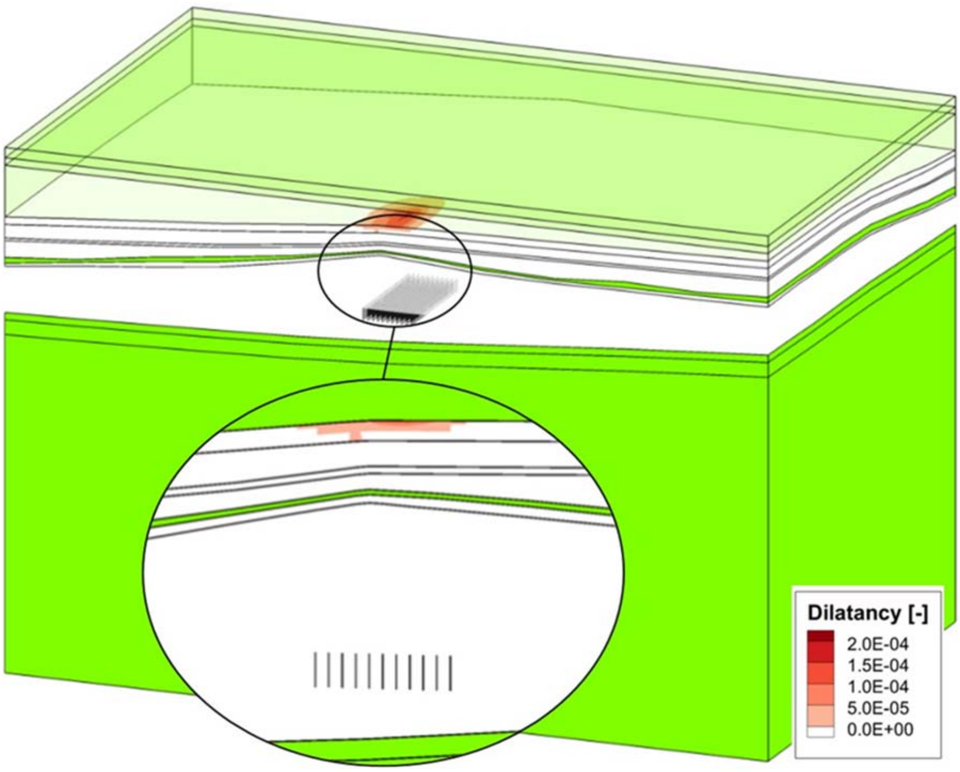


Figure 5-14: **Hypothetical dilatant zones in the salt barrier (red) for the vertical borehole disposal in a salt pillow, 82 years after emplacement. (Overburden layers are shown transparently)**

5.5 Conclusions from the Numerical Modeling of Barrier Integrity

Generally, based on two generic geological models and two different repository concepts for each model, the numerical analyses have been carried out to evaluate the impact of the heat-generating radioactive waste on the long-term barrier integrity of the bedded salt. The results of the THM-coupled 2D modeling by IfG using the DEM programs UDEC & 3DEC and the TM-coupled 3D modeling by BGR using the FEM program JIFE are in good agreement.

Both in the modeling of the flat-bedded salt and the salt pillow, the results of the numerical calculations show the effect of thermal expansion. As a result of the deformation, the horizontal stresses at the top of the salt barrier were reduced and the fluid pressure criterion was locally violated in an up to 60 meter thick zone. According to the reduction of horizontal stress, the pressure-driven fluid percolation in the THM-coupled modeling acts in a vertically aligned direction with a penetration depth similar to the violation depth of the minimum principle stress criterion analysed in the continuum mechanical analyses. However, this effect of criteria violation is only associated with the thermal pulse occurring in the first 2000 years and will diminish with time due to salt creep.

It is crucial that the integrity of a large part of the salt barrier (at least 300 meters thick) is not affected during the simulated observation period of 10,000 years after which the thermal pulse of the emplaced heat-generating radioactive waste will have passed off. At any time there are no continuous migration paths between the top of the salt barrier and the emplacement areas.

In general, the integrity analysis of the geological barrier by different numerical approaches, model dimensions and constitutive models has yielded comparable results, which substantiates their predictive capabilities.

6 Analysis of Radiological Consequences

Within the KOSINA project, a radiological safety indicator was calculated for different computation cases and scenarios for the drift disposal option, the horizontal borehole disposal option, and the vertical borehole disposal option (see chapter 4.2), respectively. No analysis of radiological consequences was carried out for the direct disposal of transport and storage casks. This disposal option resembles the drift disposal option of POLLUX® casks with a design temperature of 200 °C concerning relevant properties, like amount and type of radioactive waste per unit area. Therefore, provided that disposal acceptability of the casks can be demonstrated no significant differences are expected between these two disposal options with respect to radiological consequences. By means of computational flow and transport modelling of the repository mine (near field) the radiological consequences were investigated in detail (biosphere model). Examples of the modelling results for the reference case of the drift disposal option are given here, demonstrating the capabilities of the model. Neither the transport of radionuclides in the gas phase nor the consequences of chemotoxic waste were considered in R&D project KOSINA. In a licensing procedure, both aspects have to be addressed according to the Safety Requirements [BMU 2010].

According to the Safety Requirements it suffices to model only the release of radioactive contaminants from the CRZ, if this release does not exceed a certain limit which is considered to be negligible. This approach is called “simplified radiological long-term statement”. It ensures that only very small amounts of contaminants may be released. Radiological safety indicators shall be calculated using an established generic exposure model under certain assumptions.

6.1 Approach and Methods

6.1.1 Calculation of Radiological Safety Indicators

The safety demonstration concept (see chapter 0) proposes to assess radiological safety of the various disposal options by two indicators:

- an effective dose occurring additionally in the biosphere, and
- a radiological indicator, which is based on the release of radionuclides from the CRZ.

The calculations were mainly performed deterministically, i.e. with fixed values assigned to all input parameters and the consequences being calculated in one run. Additionally, probabilistic calculations were applied to the drift disposal option using Monte-Carlo simulation method.

To implement the specifications in the Safety Requirements for a radiological indicator the concept of so-called RGI was developed in R&D project ISIBEL [Buhmann et al. 2010a]. The RGI is calculated by assuming that the total radionuclide flux released yearly from the CRZ is diluted in a water volume which corresponds to the annual water requirement for nutritional purposes of a group of 10 persons. The calculation does not consider how the radionuclides are transported from the boundary of the CRZ to the water body used by the group.

To determine the radiological consequences of the radionuclide concentration in the water body, a biosphere model equivalent to the calculation of the effective dose in the biosphere is applied. The calculated exposures are normalized in order to highlight the fact that this radiological safety indicator should not be mistaken for a prediction of future exposures.

The RGI is calculated as follows

$$RGI = \frac{10 \cdot \frac{\sum_i S_i \cdot DKF_i}{W}}{K_{RGI}}, \qquad \text{(Eq. 6-1)}$$

where S_i represents the total yearly flux of a particular radionuclide *i* released from the CRZ, and DKF_i corresponds to the associated dose conversion factor. The annual water requirement W of a group of ten persons is set to 5000 m³. The evaluation criterion K_{RGI} is 0.1 mSv/yr according to the Safety Requirements [BMU 2010].

In R&D project KOSINA, only the radionuclide release from the CRZ in the liquid phase was assessed. The RGI concept can easily be expanded to assess both the radionuclide release from the CRZ via gaseous and liquid pathways, respectively. At the moment there are no specifications in the Safety Requirements regarding consideration of the gaseous phase and no generally accepted calculational scheme for 2-phase flow exists.

6.1.2 Containment of Radionuclides in the CRZ

The assessment of the containment is based on the simplified radiological statement described above. The qualitative and quantitative evaluation of fluid and radionuclide transport processes yields a staged assessment (Figure 6-1).

Complete containment is regarded as the most stringent form of containment and this is achieved if there is no contact between intruding solution and the waste and when no radionuclides are released into the gaseous phase, or when no radionuclides are released from the CRZ (stage 1 in Figure 6-1). If radionuclides are released from the CRZ, safe containment has to be demonstrated. For this purpose the RGI is applied.

The calculation of radiological consequences results in RGI values which indicate whether the released radionuclides cause any significant harm for human health. If RGI is below 1, safe containment of the radionuclides within the CRZ is demonstrated (stage 2). If it is above 1, the radionuclide release from CRZ is not insignificant (stage 3). This does not mean that the repository system is not safe, but further investigations, especially the calculation of transport in the overburden and additional effective dose in the biosphere, are required in order to identify whether the consequences of the analysed scenario can be considered to meet the criteria of the Safety Requirements. If not (stage 4), the defined repository system is not suitable.

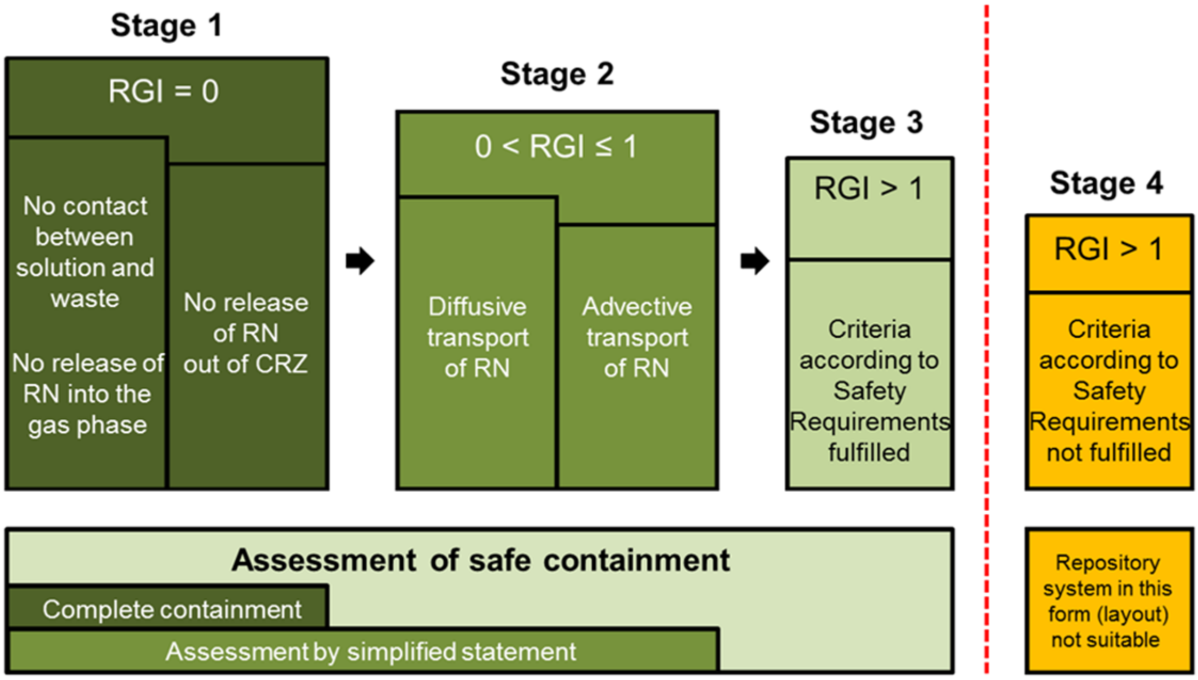


Figure 6-1: Staged approach for the long-term safety assessment

6.2 Modelling the Radionuclide Release in the Liquid Phase

6.2.1 Model Introduction

The numerical simulations for the long-term performance assessment were performed by the integrated code package RepoTREND (Transport and REtention of Non-decaying and Decaying contaminants in final REPOsitory [Reiche 2016]). For repositories in rock salt formations it provides functionalities for simulating the release of contaminants and their transport through the repository (near-field model), release and transport of radionuclides in the overburden (far-field model) as well as the estimation of the radiological consequences for man and environment (biosphere model. Modules for performing and evaluating probabilistic calculations by Monte-Carlo simulation are included as well.

Corrosion of casks, contaminant mobilization from the waste matrices, contaminant retardation, gas generation, advective-diffusive transport of contaminants as well as creep closure of mine openings are taken into account. Important parameter uncertainties (particularly regarding compaction of crushed salt and advective and diffusive transport at low porosities in crushed salt) were handled by parameter variations and probabilistic calculations. Preliminary test cases enabled stepwise and iterative optimization of the repository design. To obtain additional information on the robustness of the system “What-If” cases were also included in the performance assessment.

A major aspect in the safety concept (chapter 2) is that “during compaction, the porosity and permeability of the crushed salt decrease until, in the long term, it has barrier properties comparable to rock salt”. In the model calculations, however, it is conservatively assumed that this long-term behaviour of compacted crushed salt cannot be demonstrated and thus a remaining connected pore space in the very low porous medium is assumed. This pore space allows diffusive and only negligible advective transport of contaminants.

6.2.2 Computation Cases

Deterministic calculations were carried out for generic repositories in bedded salt formations for two geological settings utilising three different repository concepts: drift disposal and horizontal borehole disposal in flat-bedded salt formations, as well as vertical borehole disposal in salt pillows. The objective was to adopt the RGI concept and evaluate its applicability to repositories in bedded salt formations. The concept has already successfully been applied in the preliminary safety case for the Gorleben site (VSG project, [Larue et al. 2013]).

In the following, results are shown for selected computation cases. A detailed description of all of the computation cases and a comprehensive overview of the results is given in [Kindlein et al. 2018]. As an overview, the following calculations have been performed in the deterministic analysis of consequences:

- Analysis of consequences: base case scenario
- Preliminary test cases:
  - Shaft seal length (various lengths)
  - Access drift length (various lengths)
  - Initial moisture content in access drifts
- Variants of base case scenario:
  - Reduced diffusion (coefficient reduced by a factor of 10)
  - Reduced convergence (rate decreased by a factor of 10)
  - Discretisation (higher and lower internal spatial discretisation of segments)
  - Accelerated mobilisation (increased mobilisation rates)
  - Early cask failure
- What-If cases:
  - No failure of geotechnical barriers
  - Instant failure of geotechnical barriers
  - Inventory: no direct disposal of spent nuclear fuel elements

6.2.3 Results of Deterministic Calculations

The base case scenario for the drift disposal option serves as illustrative example for the general approach. In order to numerically model the repository, the original mine layout was transferred into a segmented model structure by means of aggregation of areas. The mine layout for drift disposal option as well as the derived aggregated model areas (framed) is depicted in Figure 6-2.

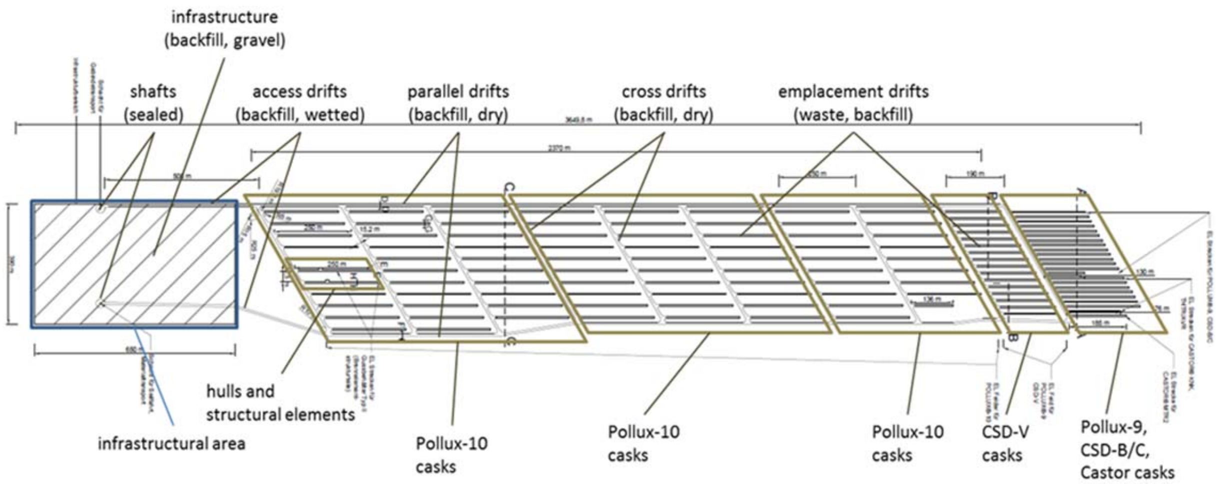


Figure 6-2: **Mine layout for drift disposal option**

The simulation period covers the demonstration period of 1 million years. An operational emplacement period lasting from 2050 till 2080 is considered by simulating sequential backfilling of the mine. The modelled repository structure includes shaft seals of 100 m length, sealing of the access drifts with wetted crushed salt and concrete barriers, an infrastructure area that is backfilled with highly porous gravel, and crushed salt backfill in emplacement areas and all remaining mine openings. A failure of all geotechnical seals (concrete) after 50,000 years is presumed, modelled by an instantaneous increase of permeability and eventually resulting in continuous brine intrusion and radionuclide mobilization.

The modelling results of the radiological safety indicator RGI over time for the base case scenario are shown in Figure 6-3. The calculations indicate that inflowing brine slowly reaches the emplacement areas after the designed functional time of the shaft and drift seals (50,000 years) eventually leading to practically no release of radionuclides from the CRZ in the demonstration period. The calculated RGI is well below 10^{-7} for radionuclide release in the liquid phase in 1 million years, pointing towards an almost complete containment of radioactive substances within the CRZ throughout the regulatory stipulated demonstration period. Because the RGI is still increasing after the end of that time frame, the future RGI evolution is additionally shown.

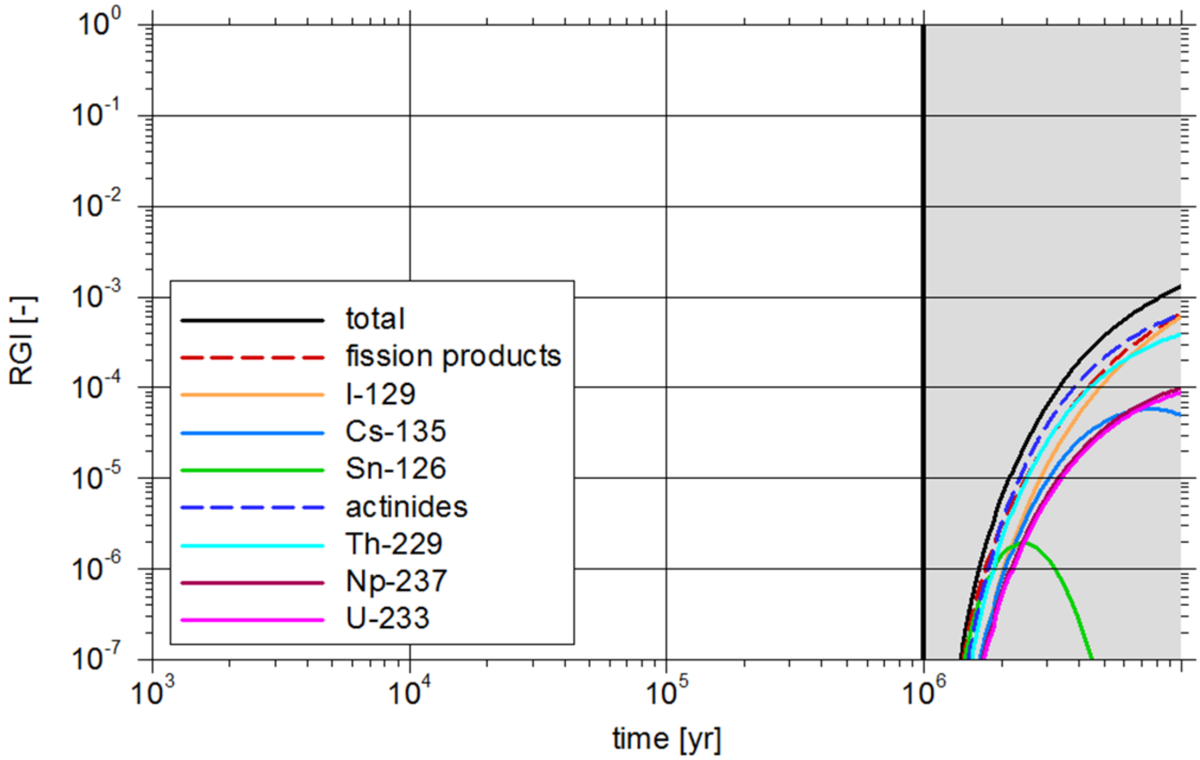


Figure 6-3: **Radiological consequences (RGI) for base case scenario of drift disposal option**

Due to the long period of release by diffusion, the main contributions to RGI are from long-lived radionuclides, such as I-129 or Th-229. In the case of Sn-126 (half life $2.345 \cdot 10^5$ years) the decrease in RGI over long times is caused by radioactive decay.

Supplementary to the analysis of base case scenarios extensive case studies were performed. These model calculations included preliminary test cases, where design parameters were tested in advance of the final repository layout, parameter variations for sensitivity studies, as well as What-If cases, in order to gain better understanding about the particular processes affecting the evolution of the modelled repository system.

Exemplarily, parameter variations for the diffusion and compaction processes illustrate that with reduced diffusion coefficients the calculated RGI rapidly decrease (Figure 6-4) whereas with a lower convergence rate of the rock salt resulting in a slower compaction rate of the crushed salt backfill the RGI slightly increases (Figure 6-5). For these variants the diffusion coefficient and the compaction rates were altered by one order of magnitude each. The results show clearly that transport of radionuclides towards the drift seals is dominated by diffusion and is thus very slow. The advective part of the transport is comparatively small since convergence processes have ultimately ceased by the time intruding brine reaches the waste forms and thus no driving force for advective transport exists (neglecting gas production as assumed for the calculations).

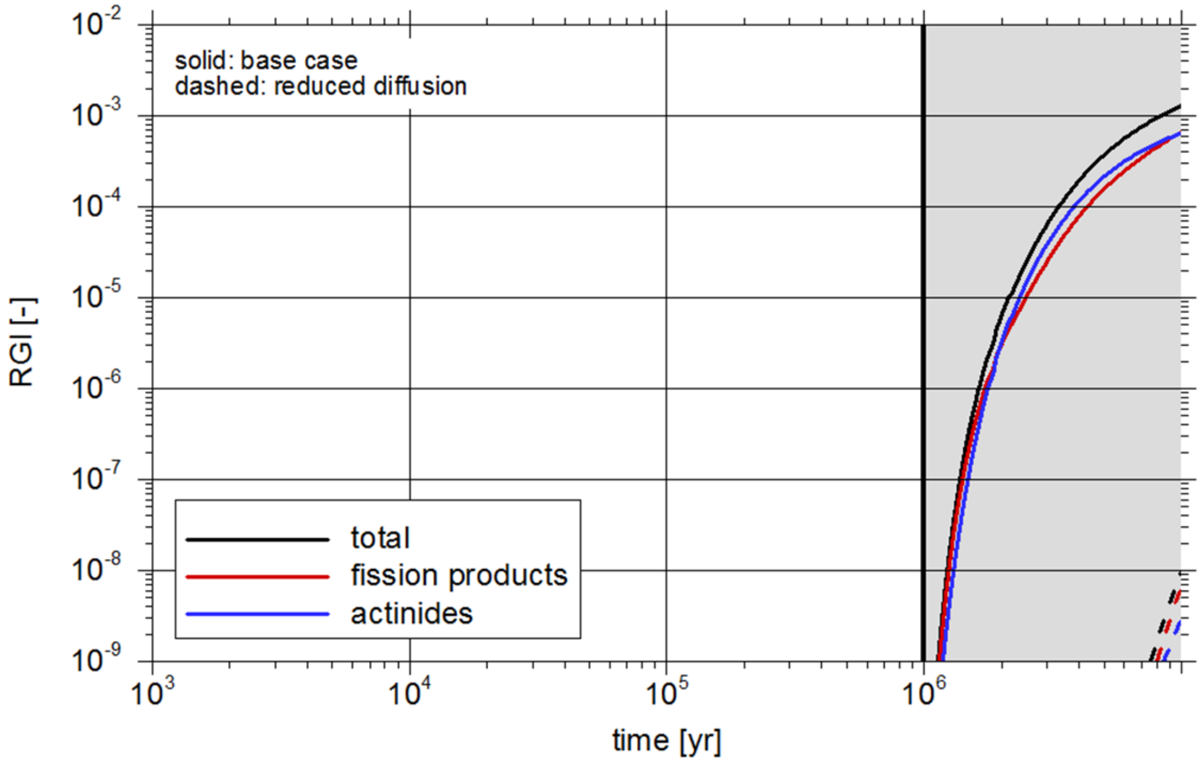


Figure 6-4: **Radiological consequences (RGI) for case study "reduced diffusion" of drift disposal option**
The vertical axis is shifted by 2 orders of magnitude compared to other figures.

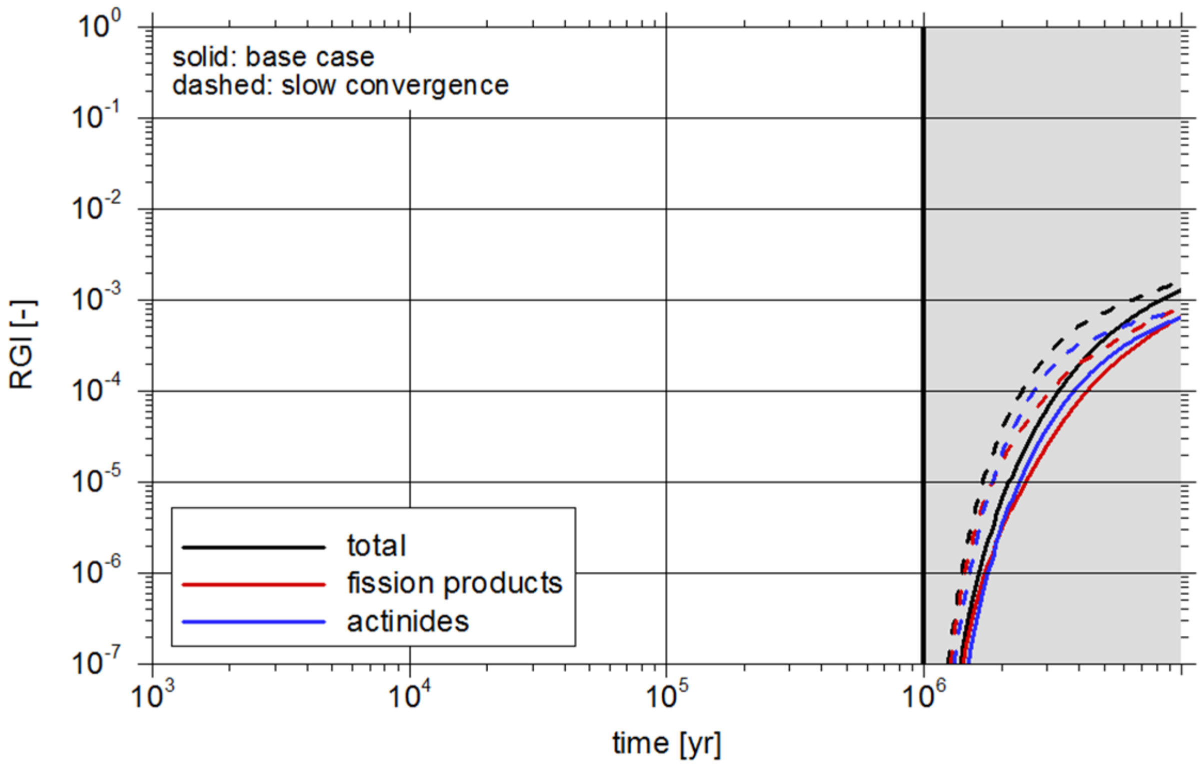


Figure 6-5: **Radiological consequences (RGI) for case study "slow convergence" of drift disposal option**

In summary it can be stated that the analysis of radiological consequences for the base case scenarios, test cases, variants and What-If cases regarding a radionuclide release in the liquid phase covers a wide range of potential system evolutions and parameter distributions, and is based on very detailed and profound process knowledge. All calculations show RGI values several orders of magnitude below the criteria set out in the Safety Requirements occurring only beyond 1 million years, pointing towards an almost complete containment of radioactive substances within the CRZ throughout the demonstration period. For a radionuclide release from the CRZ in the liquid phase, all calculations illustrate that radionuclide transport within the CRZ is not affected by advection. The radionuclides are transported mainly by diffusive processes determining the calculated consequences. The diffusive transport is quite slow and a significant release is calculated only for times well beyond the demonstration period of 1 million years, see Figure 6-4 and Figure 6-5.

As stated in chapter 2, compacted crushed salt is expected in the safety concept to have barrier properties comparable to rock salt but the calculations conservatively assume that a connected pore space remains. Thus diffusive transport is overestimated in the calculations. To reduce conservatism in modelling diffusive transport, more information is required regarding radionuclide diffusion in compacted crushed salt. The results demonstrate the importance of a comprehensive and profound understanding of transport processes in backfill material. Especially for material with low porosity (e.g. compacted crushed salt) R&D projects have been performed in the past to elucidate the transport processes and to establish parameter values, e.g. [Flügge et al. 2016]. So far, all experiments in the low porosity range have yielded somewhat ambiguous results due to problems in adjusting the porosity values aimed at and an imperfect knowledge of the actual pore structure at these porosity values, respectively. Long-term safety assessments should continue to use the diffusion coefficient in free water to consider diffusion of radionuclides in the pore water of compacted crushed salt as long as no additional results are obtained from experiments.

6.2.4 Results of the Probabilistic Analysis

In addition to deterministic calculations probabilistic calculations were carried out for the drift disposal option applying a Monte-Carlo method. The results were analysed regarding uncertainty and sensitivity. Two calculation cases were investigated: a reference case[6] with realistic values for the probable evolution of the repository system as defined by the Safety Requirements and a hypothetical case with less probable characteristics of all varied parameters, which is used to implement the largest possible set of system evolutions. In the reference case 1,000 runs[7], and in the hypothetical case 2,000 runs were generated and calculated. The probabilistic calculations were carried out using the codes RepoSTAR [Becker 2016] and RepoSUN of the code package RepoTREND [Reiche 2016].

6 The term „reference case“ was introduced in [Buhmann et al 2016] and refers to probable evolutions of the repository system. It comprises reference values as in the base case (this term is used for deterministic calculations, see chapter 6.2.3) and the bandwidth of these parameters.

7 A run is a deterministic calculation with a set of parameter values from the statistical random sample. This set is also called “realisation”.

For both probabilistic calculation cases uncertainty analyses were carried out with two methods of statistical evaluations:

- Temporal evolution of statistical parameters concerning the RGI values (mean, median, 0.05 quantile, 0.95 quantile, maximum and minimum).
- Histogram of the relative frequency distribution of the RGI values.

Since in both computation cases, due to slow diffusive release, the absolute maximum of RGI only occurs after the end of the demonstration period, the presented time period in the figures was extended to 10^7 years to better understand the system development. If the absolute maximum is not reached even after 10^7 years, the maximum value reached up to that point is given and statistically evaluated.

Figure 6-6 and Figure 6-7 show the temporal evolutions of the statistical parameters of the reference case and the hypothetical case over a period of 10 million years. Due to the slow diffusive transport, the curves rise until the end of the period shown. It is expected for both cases that the maximum values of all calculated maxima of the RGI will be reached after a few tens of million years and to be slightly above 0.1. The highest values of the maximum RGI values occur in the hypothetical case as expected. The bandwidth between minimum and maximum RGI values is also much larger than for the reference case. Specifically, a difference of only a factor of about 25 occurs between the minimum and maximum values in the reference case, while for the hypothetical case a distance between these values of more than 6 orders of magnitude results. With the hypothetical case, maximum values above 10^{-7} are observed after about $1.5 \cdot 10^5$ years, in the reference case about $4 \cdot 10^5$ years later. This is attributed to the different statistical distributions and bandwidths of the parameter values used for both calculation cases.

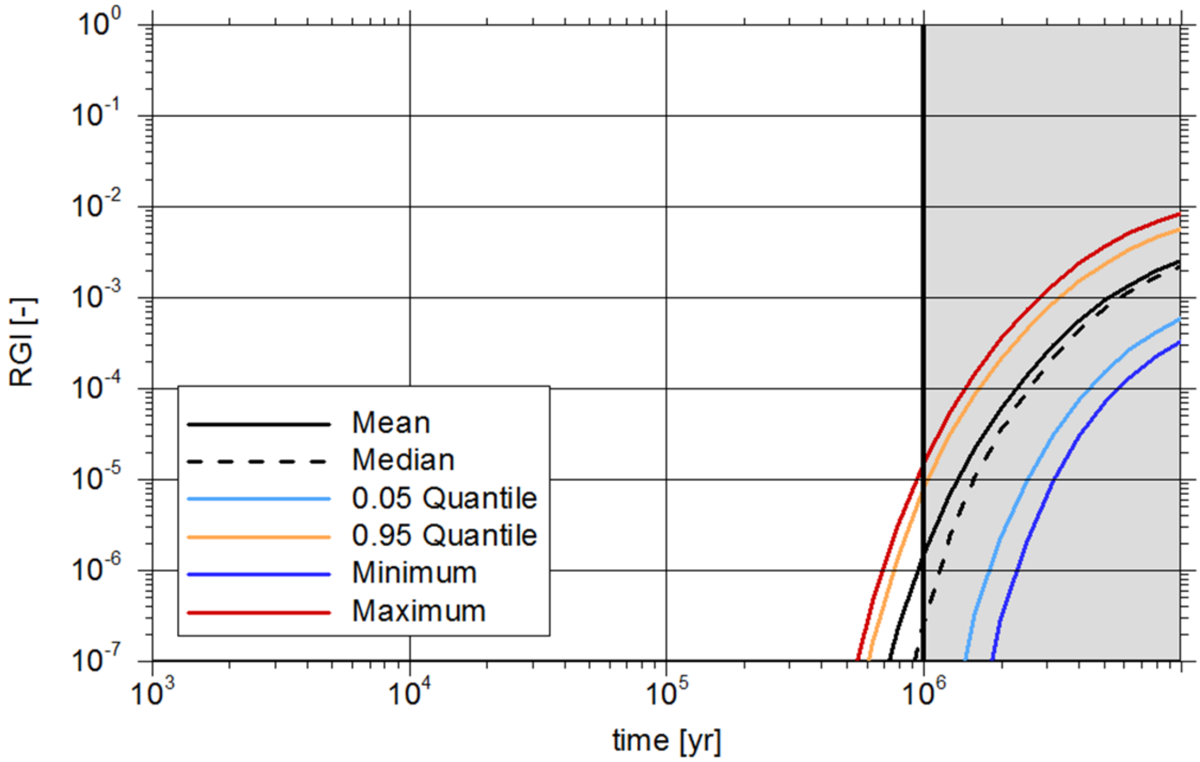


Figure 6-6: Radiological consequences (RGI) for probabilistic study "reference case" of drift disposal option

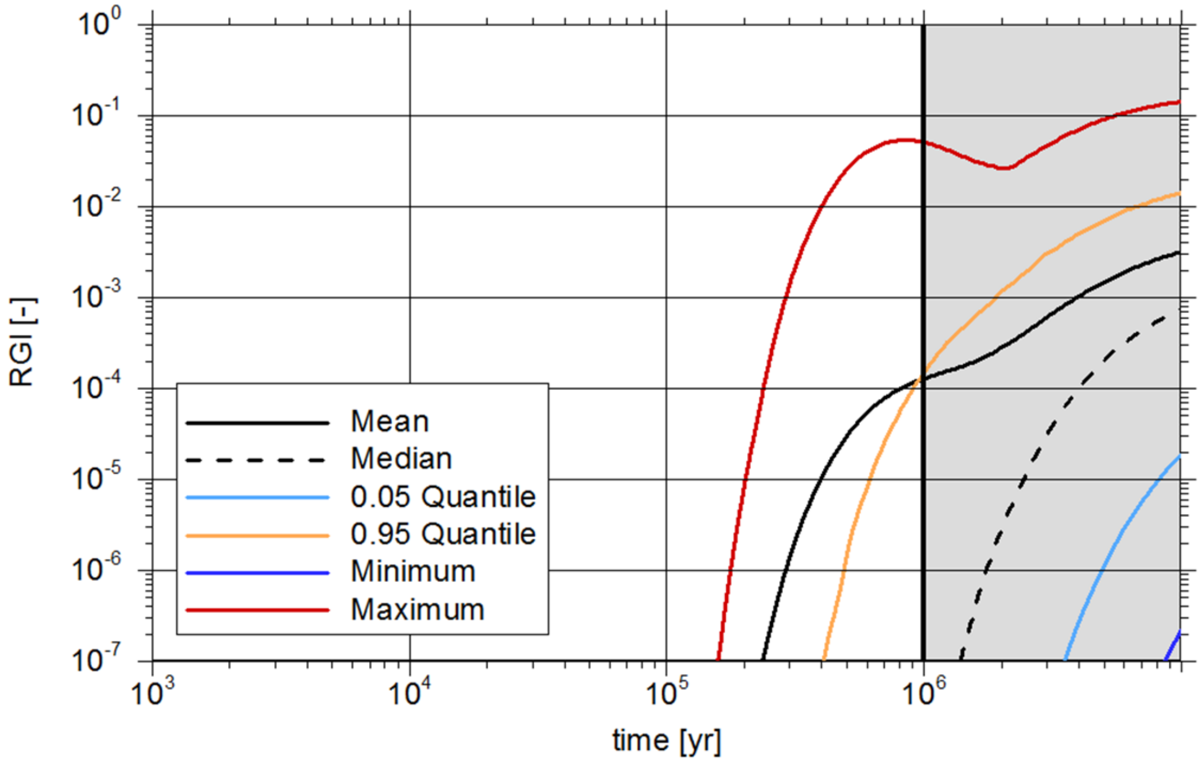


Figure 6-7: Radiological consequences (RGI) for probabilistic study "hypothetical case" of drift disposal option

The results of the hypothetical case allow the assessment of the ambiguous transition range between less probable and improbable evolutions of the system. In this case, many realisations (evolutions) are taken into account that certainly must not be evaluated with the assessment criteria of the Safety Requirements.

Since the calculated RGI values of all calculation runs (1000 for reference case and 2000 for hypothetical case, respectively) are below 1, the safe containment regarding the release of radionuclides is demonstrated. Consequently, the results show that the safety criteria are always met, even despite the large and sometimes "unrealistic" bandwidth of the parameters in the hypothetical case.

In sensitivity analyses the relevance of the above mentioned processes "diffusion" and "convergence" was confirmed. In general, the sensitivity of a parameter reflects the contribution of the parameter uncertainty bandwidth to the uncertainty bandwidth of the calculated model output. As an example, Figure 6-8 shows the sensitivity of four parameters. The more the curves deviate from the diagonal the higher is the sensitivity of the calculated model output, i.e. the RGI value, against the respective parameter [Spießl 2017]. The most sensitive parameter is the diffusion coefficient as indicated by the largest deviation from the linear behaviour, followed by the final porosity, which is an indicator for the convergence process.

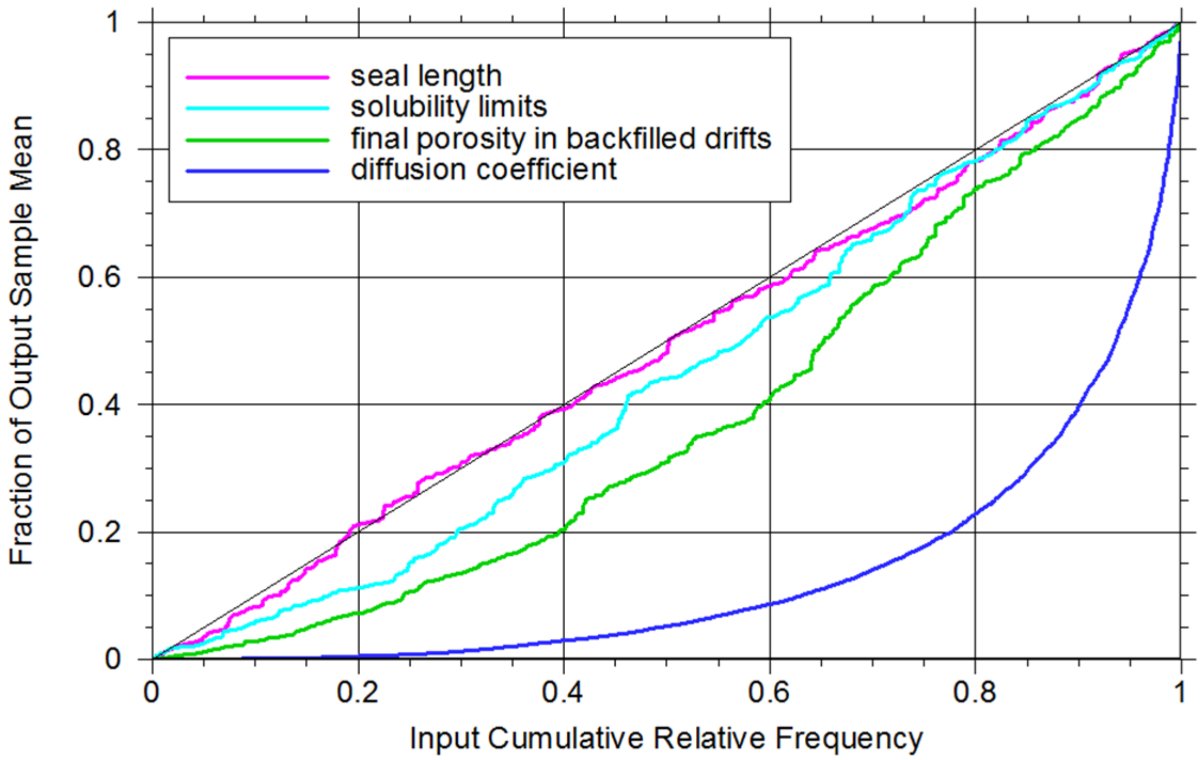


Figure 6-8: **Contribution of independent variables to sample mean (CSM), hypothetical-case**

6.3 Conclusions from the Analysis of Radiological Consequences

As a result of the numerical investigations it can be stated that geotechnical barriers along with the long-term sealing effect of compacted crushed salt backfill reduce radiological consequences to negligible values during the demonstration period of 1 million years and beyond. The potential radionuclide releases from the repository that are from the CRZ, are mainly controlled by diffusion and only occur at very late times beyond demonstration period. Reduced convergence rates may increase or add an advective portion but only to a very limited extent. With the aid of preliminary test cases it could be demonstrated that optimization of the repository design based on numerical analysis of the consequences is possible and beneficial. Computational case studies with parameter variations as well as the examination of What-If cases are useful and necessary for process analysis as well as for identifying sensitive model parameters. Probabilistic calculations are useful and necessary tools for the investigation of parameter und model uncertainties, mainly in the reference case.

Using current state of the art in science and technology, the safety and the demonstration concept have been successfully applied to the geological situation represented by typical bedded salt formations that can be found in Germany. The results provide evidence that a safe HLW repository in a bedded salt formation with a suitable geological structure is feasible and that its long-term safety can be demonstrated according to the state of the art in science and technology. This statement depends, however, on several generic assumptions which will have to be confirmed by comprehensive site-specific investigations.

7 Unresolved Issues and R&D Needs

Reflecting the achieved results of the KOSINA project a few unresolved issues appeared and a need for initiating R&D activities deems to be apparent. These activities are related to the general knowledge about bedded salt formations, the improvement of models and tools, the reduction of uncertainties, and to the better understanding of proof of integrity of geotechnical barriers. Furthermore, the conceptual designs in particular for the disposal option *emplacement in horizontal boreholes* should be improved.

Activities related to the geological situation comprise the following aspects:

- The differences between bedded and domal salt need deeper understanding and the lithological knowledge about bedded salt formations should be extended.
  - Reliable data about the initial water content of rock salt are needed, because it is relevant for salt creep and for the compaction behaviour of crushed salt, if excess water from the host rock salt has access to the mine workings.
  - The possible differences in rock mechanical properties for bedded and domal salt need further investigation, e.g. reliable approaches and parameters for salt creep at low deviatoric stresses.
  - The relevance of lithological or textural discontinuities in the salt mass, e.g. embedded anhydrite (beds or intercalations) and/or clay layers has to be proven with respect to potential preferential lateral pathways of fluids or as local mechanical weakness planes due to textural anisotropy effects.
- The occurrence of thick stratigraphic salt clay layers (up to some tens meter) within the hanging salt sequences above the repository has consequences, e.g. for the design of shaft sealing systems. In addition, the potential advantages of intercalated salt clay layers as additional geological (clay-based) barrier have to be proven regarding the safety concept ("geological multi-barrier system").
- Geophysical methods and tools for non-destructive detection of inhomogeneities (e.g. fluid-filled cavities, local rock disturbances) need to be refined.

The models and tools applied in the safety case of a repository in flat-bedded salt must be improved and the existing uncertainties should be reduced:

- Regulatory requirements:
  - It should be clarified, whether the simplified radiological statement according to the Safety Requirements [BMU 2010] is sufficient for the safety case, or whether the transport in the overburden should always be assessed additionally.
  - In the present study, the containment-providing rock zone (CRZ) was determined by a stepwise approach. It should be clarified, whether the implementer is obliged to define it prior to establishing the safety case.
  - The calculation scheme for the index RGI is still in discussion, because no detailed description in the Safety Requirements is available up to now. The question arises, whether only individuals older than 17 years should be considered or a more representative person group?

  - The dose conversion factors (DCF) need revision and the biosphere model should be updated.

- Models and tools for analyses of consequences (transport modelling):
  - Transport of contaminants is mainly calculated as flow in the liquid phase. Models and tools for two-phase flow exist, but need further improvement for application, especially for transport in the gas phase.
  - The transport behaviour of compacted crushed salt at very low porosities should be resolved: are there connected pores (flow paths) or not?
  - The results of the model calculations have been presented for model times larger than the demonstration period. As KOSINA is an R&D project, this procedure seems to be appropriate. Is must be defined, whether releases after the end of the demonstration period should be discussed in a safety report or not.

- Models and tools for analyses of consequences (demonstration of barrier integrity):
  - The simulation tools for percolation processes in salt should be further developed.
  - Further developments towards a THM-coupled 3D modelling are necessary.
  - The dilatancy concept needs to be discussed regarding its demonstration approaches, for instance the role of the dilatancy boundary. Alternatively, damage in the rock mass can be locally quantified by qualified numerical tools (e.g. as developed in the WEIMOS-project [WEIMOS 2016] and assessed regarding its consequences for the rock permeability.
  - The simulation of convergence of openings and compaction processes of crushed salt including impact of humidity, etc. within geomechanical codes needs improvement regarding the two-porosity range.
  - Consideration of discontinuities in the salt mass (e.g. main anhydrite z3HA as stiff inclusion) or in the overburden (e.g. Bunter with joints in different scales).

The proof of integrity of geotechnical barriers needs improved understanding and investigations of the following:

- Proof of lifetime of technical barriers, i.e. integrity of the geotechnical barriers, based on developments of appropriate demonstration methods and experimental determinations of qualified material parameter sets
  - for shaft seal integrity,
  - for drift seal integrity, especially depending on the individual properties of different construction materials, e.g. MgO-concrete or hydraulic concrete (in particular: proof of limitation of shrinking cracks and/or cracks during hydration of phases, material law development)
- The long-term behavior of crushed salt needs further experimental investigations and improvements of material laws regarding a reliable decision: are the remaining pore spaces connected or not?
- Investigations on the use of molten salt for special applications as backfill and sealing material

- Experimental studies on the temperature dependence of the dilatancy boundary of rock salt

Some of the repository designs have been developed within the KOSINA project and need improvement, in particular the disposal option *emplacement in horizontal boreholes*. The following topics were identified:

- More detailed planning of the components and the processes for emplacing waste packages into horizontal boreholes (emplacement device, interfaces between pushing element and waste package/dummies, functionality of tank rollers over decades, etc.)
- Safety issues: failure of borehole liners, failure of components during operation processes and measures to ensure safety, durability of tight contact between transfer cask and borehole mouth lock, etc.
- A plan or measures regarding radiological protection during operation and potential retrieval processes should be developed.

It is recommended to transfer these identified R&D needs to the responsible funding organizations for fundamental R&D activities as well as to the implementer with regard to the availability of results in due time for the ongoing site selection process.

8 Summary

According to the German Site Selection Act for a repository for heat-generating radioactive waste and spent nuclear fuel [StandAG 2017] the repository site shall be identified that best ensures the repository safety for a demonstration period of one million years. Owing to the geological situation in Germany, several potential host rocks (salt, claystone and crystalline rocks) are to be considered in a science-based comparative procedure. As a prerequisite it is necessary to develop at least generic repository concepts as well as suitable safety and demonstration concepts for repositories in all potential host rocks (rock salt, claystone and crystalline rock).

A reference repository design in salt domes was developed in the early 1980s. Comparable investigations for generic repositories in claystone or crystalline rock as host rock formations were launched in the early 2000s. Bedded salt formations, however, were not yet considered as host rock for the disposal of radioactive wastes. For this reason, the R&D project KOSINA was launched in summer 2015 and funded by BMWi represented by the Project Management Agency Karlsruhe. KOSINA is a German acronym for "Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept". Thus, the KOSINA project serves to investigate the technical feasibility and the long-term safety of a generic repository in bedded salt formations. The work programme comprised: a compilation of basic data and design requirements, the development of generic geological models and compilation of adequate material parameters, a safety and demonstration concept, demonstration of integrity of geological barriers, repository designs for four different disposal options, analysis of radiological consequences, investigation of operational safety, and eventually a summary of the results in a synthesis report.

The results of the first working step – the compilation of basic data (e.g. type and amount of waste) and design requirements as well as a first draft of a safety and demonstration concept – were published in an interim report in December 2015 [Bertrams et al. 2015].

Subsequently, the safety and demonstration concept was detailed. Based on the safety principles set out in the Safety Requirements, the site properties and existing knowledge concerning the processes that could impair the safety of the repository, the following guiding principles have been derived:

- The radioactive waste must be contained as much as possible in the CRZ.
- The containment shall be effective immediately post-closure. Containment must be ensured by the repository system permanently and maintenance-free.
- The immediate and permanent containment shall be accomplished by preventing or limiting intrusion of brine to the wastes.

In the same way as the safety concept, the safety demonstration concept is based on concepts developed and refined in the projects ISIBEL and VSG. According to these concepts the decisive elements are:

- demonstration of integrity of the geological barrier
- demonstration of integrity of the geotechnical barriers
- scenario analyses
- evaluation of release scenarios

While operational safety has been investigated in detail, other elements of the safety demonstration concept, such as demonstration of subcriticality, non-radiological protection targets and human intrusion are just mentioned.

Prior to the start of repository design work, representative geological 3D models for both flat-bedded salt formations and salt pillows were developed. The statutory criteria defined in the Site Selection Act [StandAG 2017] were not foreseeable when the KOSINA project began in 2015. Consequently, geological criteria were used that were up for discussion at that time for site selection (see [AkEnd 2002], [Krull et al. 2004], [Hammer et al. 2009]). For flat-bedded salt formations an approx. 8.8 km long generic geological cross-section was generated based on available knowledge on flat-bedded evaporitic horizons in Germany. The cross-section represents a characteristic geological situation in regions with flat-bedded rock salt successions of Zechstein age in Germany. The thickness of the rock salt succession in the Staßfurt Formation selected as the emplacement horizon varies in the "flat-bedded" model between 160 m in the western part of the model area and 290 m in the eastern part. For the "salt pillow" type an approx. 12.5 km long reference profile was derived which shows a characteristic salt pillow structure of the Zechstein rock salt succession in Germany. The geological model units are identical with the reference profile for the "flat-bedded" model type. The thickness of the Staßfurt Formation rock salt succession selected as the emplacement horizon is up to 600 m in the centre of the salt pillow.

Based on detailed information about the types and amounts of radioactive waste [Bertrams et al. 2015], the two generic geologic models "flat-bedded salt" and "salt pillow" as well as the safety and demonstration concept repository designs were developed for four considered disposal options (two different disposal options for each of the two geological models). Another design basis were national regulations, ordinances, and safety requirements, in particular that all repository designs had to meet the retrievability requirement of waste packages at any time during the operational period of the repository. The repository mine layouts were developed on basis of the aforementioned data and on the results of thermal calculations providing the geometric distribution of waste package, the borehole and drift spacing with respect to the design temperature. Transport and emplacement technology was adjusted to the appropriate disposal option and eventually backfilling and sealing measures were designed to meet the goals of the safety concept. While knowledge for the disposal options "drift disposal of POLLUX® casks" and "vertical borehole disposal " are quite advanced it became obvious that there still is a need for further R&D with regard to the disposal options "horizontal borehole disposal" and "direct disposal of transport and storage casks". In particular the "horizontal borehole disposal option" needs further engineering of safety-relevant technical components and processes. Regarding operational safety, the level of knowledge for the individual analyses of operational disturbances varies. This is mainly due to the fact that demonstration tests were carried out for the "drift disposal of POLLUX® casks" and the "vertical borehole disposal", but only rough concepts are available for the other two disposal options.

The impact of the heat-generating radioactive waste on the long-term barrier integrity of the rock salt was analysed numerically for all four disposal options. The results of the THM-coupled 2D modeling by IfG using the DEM codes UDEC & 3DEC and the TM-coupled 3D modeling by BGR using the FEM code JIFE are in good agreement. Both in the modeling of the flat-bedded salt and the salt pillow, the results of the numerical calculations show the effect of thermal expansion of the rock salt. As a result of the deformation, the horizontal stresses at the top of the salt barrier were reduced and the fluid pressure criterion was locally violated in an up to 60 meter thick zone. According to the reduction of horizontal stress, the pressure-driven fluid percolation in the THM-coupled modeling acts in a vertically aligned direction with a penetration depth similar to the violation depth of the minimum principle stress criterion analysed in continuum mechanical analyses. However, the violation of the integrity criteria is only associated with the thermal pulse occurring in the first 2000 years after emplacement of the radioactive waste. It is crucial that the integrity of the CRZ and a large part of the overlaying rock salt (at least 300 meters thick) is not affected during the simulated observation period of 10,000 years after which the thermal pulse of the emplaced heat-generating radioactive waste will have passed off. At any time there are no continuous migration paths between the top of the salt barrier and the emplacement areas. In general, the integrity analysis of the geological barrier by different numerical approaches, model dimensions and constitutive models has yielded comparable results, which substantiates their predictive capabilities.

The results of the numerical investigations of radiological consequences for the four disposal options demonstrate that radionuclides remain securely contained within the containment-providing rock zone during the demonstration period and beyond. Geotechnical barriers along with the long-term sealing effect of compacted crushed salt backfill will reduce radionuclide release from the containment-providing rock zone to negligible values. The potential radionuclide releases from the CRZ are mainly controlled by diffusion and only occur beyond the demonstration period. Reduced convergence rates may increase radionuclide releases or add an advective portion but only to a very limited extent. With the aid of preliminary test cases it was shown that optimization of the repository design based on numerical analysis of the consequences is possible and beneficial. Computational case studies with parameter variations as well as the examination of What-If cases are useful and necessary for process analysis as well as for identifying sensitive model parameters. Probabilistic calculations are useful and necessary tools for the investigation of parameter und model uncertainties, mainly in the reference case. Using current state of the art in science and technology, the safety and the demonstration concept have been successfully applied to the geological situation represented by typical bedded salt formations that can be found in Germany. The results provide evidence that a safe HLW repository in a bedded salt formation with a suitable geological structure is feasible and that its long-term safety can be demonstrated according to the state of the art in science and technology. This statement depends, however, on several generic assumptions which will have to be confirmed by comprehensive site-specific investigations. However, a bedded rock salt formation offers only minor restrictions on the horizontal expansion of a repository. Thus, a large distance between the emplaced waste and the shafts offers advantages for long-term safety, namely in the form of a delay in both solution access to the waste and solution migration from the waste to the surface.

Reflecting the achievements of the KOSINA project, finally unresolved issues and identified needs for additional R&D were compiled. It was distinguished between R&D needs linked to a more detailed understanding of bedded salt formations, to improvements of models and tools, to a reduction of uncertainties, to a better understanding of proof of integrity of geotechnical barriers and to the improvement of conceptual repository designs in particular for the disposal option emplacement in horizontal boreholes.

9 Abbreviations

2D/3D	two/three dimensional
3DEC	Three-dimensional Distinct Element Code
approx.	approximate(ly)
bgl	Below ground level
BSK	Fuel rod canister (Brennstabkokille)
bsl	Below sea level (German equivalent: “Unter NN”)
BWR	Boling water reactor
CRZ	Containment-providing rock zone
CSM	Contribution of independent variables to sample mean
CSD-B	Colis standard des déchets boues
CSD-C	Colis des déchets compactés
CSD-V	Colis des déchets vitrifiés
DCF	Dose conversion factor
DEM	Discrete Element Method
DIN	Deutsches Institut für Normung (German Institute for Standardization)
ELVIS	Emplacement device in drifts
FEM	Finite Element Method
HLW	High-level waste
IAEA	International atomic energy agency
ICRP	International Commission on Radiological Protection
InSpEE	Informationssystem Salzstrukturen: Planungsgrundlagen, Auswahlkriterie und Potenzialabschätzung für die Errichtung von Salzkavernen zur Speicherung von erneuerbaren Energien (Wasserstoff und Druckluft) (Information system salt structures: planning basis, selection criteria and estimation of the potential for the construction of salt caverns for the storage of renewable energies (hydrogen and compressed air))
ISIBEL	Überprüfung und Bewertung des Instrumentariums für eine sicherheitliche Bewertung von Endlagern für HAW (Evaluation of methods and tools to develop safety concepts and to demonstrate safety for an HLW repository in salt)
JIFE	Java application for Interactive nonlinear Finite-Element-analysis in Multi-Physics
MOX	Mixed oxide
MTHM	Metric tons heavy metal
NPP	Nuclear power plant
PWR	Pressure water reactor
R&D	Research and development
RGI	Radiologischer Geringfügigkeitsindex (index of marginal radiological impact)
RN	Radionuclide
STEV	Drift transport and emplacement device
STW	Shaft transport wagon

THM	Thermo-hydro-mechanical
TM	Thermomechanical
TSC	Transport and storage cask
UDEC	Universal Distinct Element Code
UO_2	Uranium oxide
WWER	Russian pressure water reactor
Yr	Year(s)

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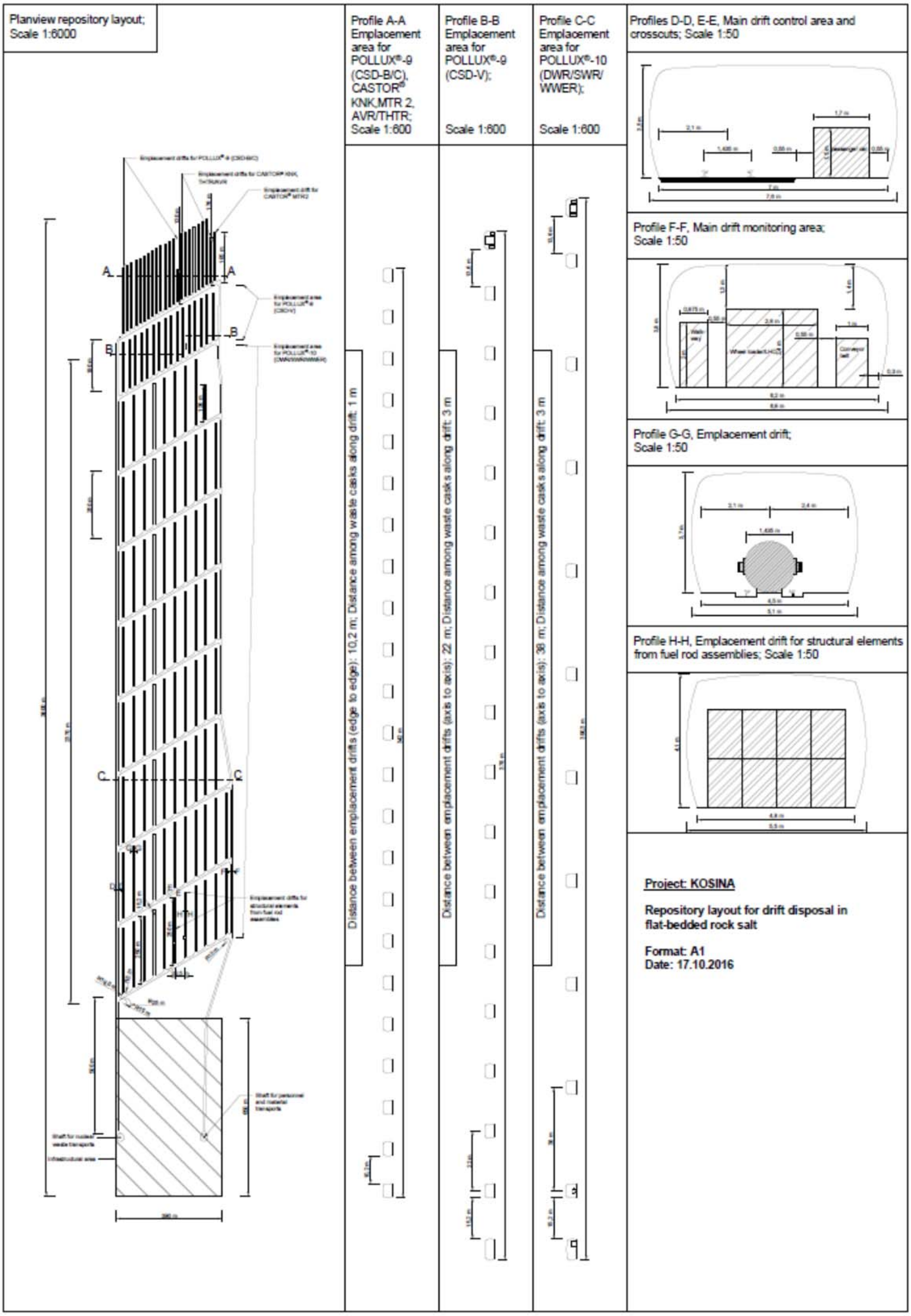
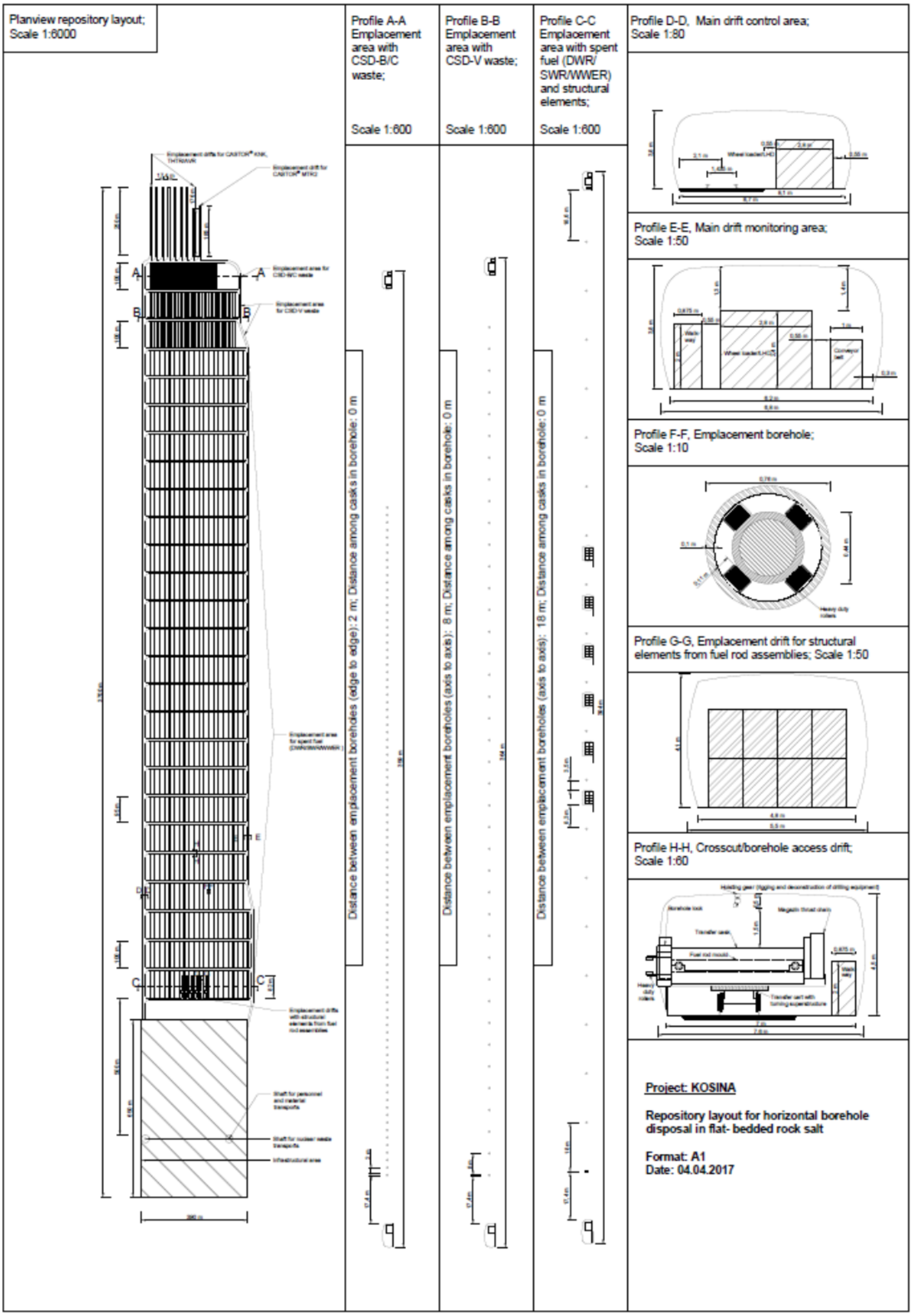
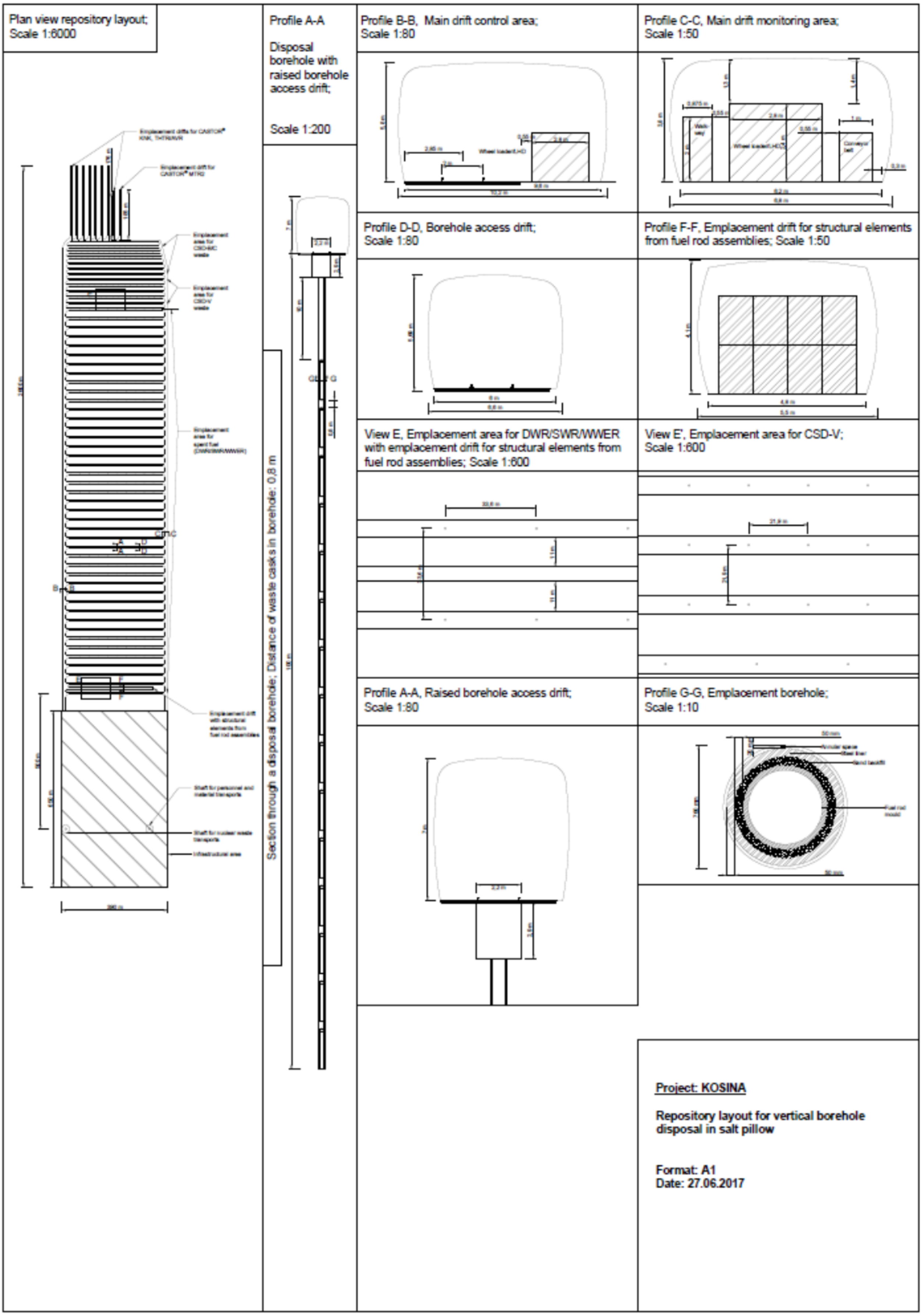
Appendix 1: Mine layout for disposal option drift emplacement



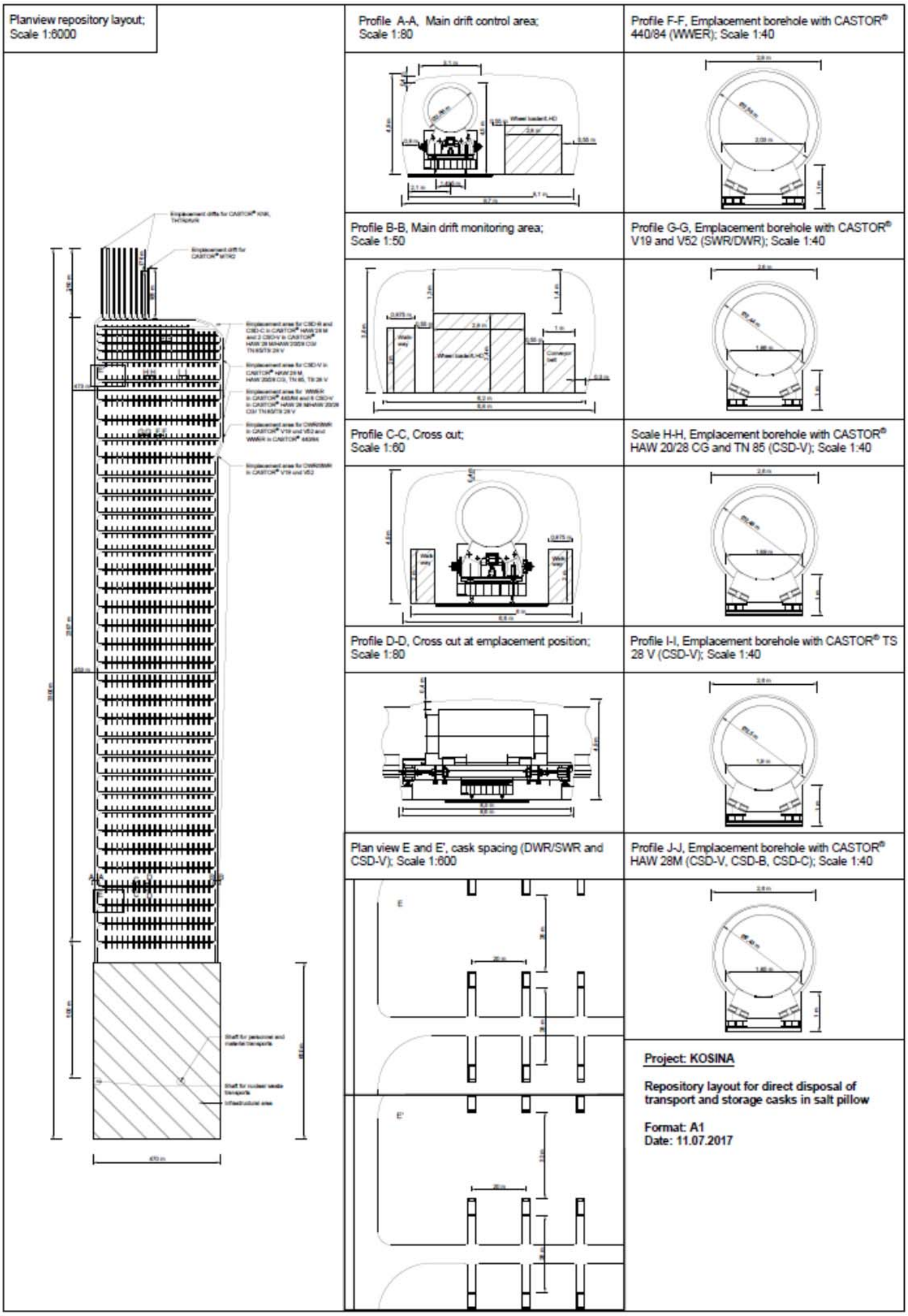
Appendix 2: Mine layout for disposal option horizontal borehole disposal



Appendix 3: Mine layout for disposal option vertical borehole disposal



Appendix 4: Mine layout for disposal option direct disposal of TSC



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