

Studies Relating to Human Intrusion into a Repository

Report Pertaining to
Work Package 11

Preliminary Safety Case of the
Gorleben Site (VSG)

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Preliminary Safety Case of the
Gorleben Site (VSG)

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Remark:

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The authors are responsible for the content of the report.

Preliminary remark – changed objective of the VSG project (as at: December 2012)

The Preliminary Safety Case of the Gorleben Site (VSG) is a research project of Gesellschaft für Anlagen- und Reaktorsicherheit (GRS). GRS has taken over the scientific and organisational management of the project that is funded by the Federal Ministry and deals with the major part of the work packages itself.

Original Objectives

In its original concept, the VSG project pursued three major objectives. The first objective was to prepare a systematic summary of the state of knowledge relating to Gorleben. On this basis, a preliminary suitability prognosis was to be made as a second objective. This prognosis was to provide an answer to the question of how and, if so, under what conditions a repository for heat-generating radioactive waste could be operated at the Gorleben site. The preliminary character of such a prognosis follows inevitably i.a. from the circumstance that a final statement on suitability is only possible following a complete underground exploration, which is not the case at Gorleben. Finally, the third objective of the VSG was to identify any further need for research and development, i.e. the site-specific and site-independent issues that remain to be clarified.

Adapted objectives

When the project was already underway, broad political consensus was reached that the site for a future repository for heat-generating radioactive waste should be found by way of comparing different sites within the framework of a multistage selection procedure. It follows from this fundamental decision that the question of the suitability of a site can in future only be answered by comparing it with other sites. „Suitable“ in this sense will be the site that fulfils various fundamental and comparative criteria and which, regarding safety, therefore shows itself to be the best site compared to others. As these criteria have not yet been defined to this date, it is not possible to make a preliminary prognosis as part of the VSG of the suitability of the Gorleben site as understood in this way.

Against this background, GRS – by mutual agreement with the Federal Environment Ministry (BMU) as sponsor of the VSG – adapted the objectives of the project to the changed boundary conditions. While the systematic summary of the state of knowledge relating to Gorleben and the identification of the future need for research and development remained as objectives of the VSG, the changes concerned the following points:

- The originally intended provisional prognosis of the suitability of the Gorleben site will no longer be pursued. What will be examined will be whether the repository concepts developed in the VSG project in combination with the geological barrier at the Gorleben site or with respect to a comparable site regarding the geological situation are suitable from today's point of view to fulfil the requirements of the BMU's Safety Criteria.
- The objectives of the project so far will be supplemented by an analysis of the question of which methodological approaches of the VSG may reasonably be used in a future site selection procedure for a comparison of repository sites. Irrespective of the concrete structuring of the future site selection procedure, it is already foreseeable today that during the course of such a procedure, it will be necessary again and again to systematically summarise and assess the state of knowledge regarding the different sites up to a certain step of the procedure.
- Moreover, the project is to examine beyond the original objectives which of the technical concepts developed as part of the VSG for the emplacement of the radioactive waste and for closing the repository mine may be transferred to repository systems at sites with different geological conditions.

Adapted project planning

Due to the decision of May 2011 to phase out nuclear power, the prognosis of the total amount of heat-generating radioactive waste has changed considerably compared with what was assumed at the start of the project in the summer of 2010. This led to the fact that a considerable part of the concept developments and model calculations performed until May 2011 had to be carried out again with the new data and that some sub-reports that had already been complete had to be replaced by revised versions. This additional effort and the above-mentioned supplements regarding the objectives of the VSG meant that it was not possible to conclude the project – as originally intended – at the end of 2012 but at the end of March 2013 instead.

Project partners

Since specialist knowledge from different disciplines is needed for working on the VSG, various partners are involved in the project apart from GRS. Among these are: Dr. Bruno Baltes, the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe - BGR), DBE TECHNOLOGY GmbH, the Institute of Mineral and Waste Processing, Waste Disposal and Geomechanics (Institut für Aufbereitung, Deponietechnik und Geomechanik) of Clausthal University of Technology (TU Clausthal), the Institute for Rock Mechanics (Institut für Gebirgsmechanik GmbH - IfG), the Institute for Safety Technology (Institut für Sicherheitstechnologie - ISTec), the Karlsruhe Institute of Technology/Institute for Nuclear Waste Disposal (Karlsruher Institut für Technologie/Institut für Nukleare Entsorgung - KIT/INE), international nuclear safety engineering GmbH (nse; several institutes of RWTH Aachen) as well as the Institute for Atmospheric and Environmental Sciences (Institut für Atmosphäre und Umwelt - IAU) of Frankfurt University.

Work packages

The overview of the work packages (WP) of the Preliminary Safety Case of the Gorleben Site (VSG) comprises the following:

- WP 1: Project co-ordination
- WP 2: Geoscientific site characterisation and long-term prediction
- WP 3: Waste specification and volume
- WP 4: Safety and demonstration concept
- WP 5: Repository concept
- WP 6: Repository design and optimisation
- WP 7: Catalogue of FEPs
- WP 8: Development of scenarios
- WP 9: Integrity analyses
- WP 10: Analysis of release scenarios
- WP 11: Assessment of human intrusion
- WP 12: Assessment of operational safety
- WP 13: Assessment of the results
- WP 14: Recommendations

Key Words:

Actions, Case distinction, Cavern, Exploratory drilling, Human intrusion, Optimisation, Repository, Salt mine

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1 Introduction

The question of the long-term safety of a repository system is inseparably linked with the intensive technical examination of the possible future evolution of the site and the repository system e. g. as a result of climatic, geologic, waste-related and repository-related processes. Here, the possible evolutions to be considered are those that have the potential to have a negative impact on the intended, furthest-possible, immediate, and lasting isolation of the radioactive waste in a defined area around the underground workings of the repository mine in salt rock, which is referred to as the containment-providing rock zone (CPRZ).

This is why on the basis of a systematic analysis of relevant influencing factors, a limited number of conclusive future representations are developed. This is done with the help of the scenario development. The aim is the identification, detailed description and selection of possible scenarios regarding the future evolution of the repository, all of which is necessary for a reliable assessment of the safety of a repository following its closure. Scenarios illustrate imaginable future evolutions of a repository system. They can only be plausible for a certain period of time into the future and can only refer to a part of the repository system. The entirety of all scenarios derived in the scenario development is to cover the uncertainties regarding the actual future evolution of the repository system /BEU 12/.

An exceptional position in scenario development is taken by the possible developments brought on by human activity at the site. With regard to the evolution of a repository, actions such as human intrusion into the CPRZ have to be considered in particular, that have the potential of jeopardising the isolation of the radioactive waste. On this topic, the "Scenario Development" working group has published the position paper on the "Consideration of human intrusion into a repository for radioactive waste in deep geological formations" /BEU 08/.

The regulatory framework conditions regarding human impacts on a repository system are anchored in the Safety Requirements of the BMU /BMU 10/ and form the working basis for the studies that have been carried out.

This report looks into the subject matter of "Future human actions in the post-closure phase of a repository for heat-generating radioactive waste". The foundations for

working on and dealing with the subject within the framework of the Project "Preliminary Safety Case for the Gorleben Site" (VSG) are explained (Chapter 2), the human activities relevant for a repository from today's point of view identified and described (Chapter 3), the scenarios on the basis of human activity to be considered in terms of the objective mentioned above specified and analysed (Chapter 4), and possibilities and limitations of optimisation measures shown up and assessed (Chapter 5).

2 Fundamentals

2.1 Definitions and regulatory provisions

The Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste /BMU 10/ demand the consideration of future human actions. Due to the enormous spectrum of possible human actions that is beyond any scientific prognosis, the consideration of future human actions requires a restriction to activities to be dealt with in the safety case by previously specified assumptions. Here, the corresponding provisions of the Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste /BMU 10/, especially those in Subsection 5.2, have to be taken into account:

"Optimisation of the final repository with regard to reliable isolation of the radioactive materials in the final repository from future human activities shall be carried out as a secondary priority to the aforementioned optimisation targets. As future human activities cannot be forecasted, a variety of reference scenarios for unintentional human penetration of the final repository, based on common human activities at the present time, shall be analysed. Within the context of such optimisation, the aim shall also be to reduce the probability of occurrence and its radiological effects on the general public."

For a better understanding and placement of the deliberations of this report, essential technical terms and their definitions are listed and explained in the following. Here, definitions already specified in /BEU 08/ will also be used.

Future human actions

With a view to the effects of future human actions on the barrier system of the repository, a difference is made between activities that modify the site situation and thus possibly also the effectiveness of the barriers and those activities that destroy or bypass directly the barrier system of the CPRZ.

Pertaining to the first-mentioned group of activities, which modify the site situation and thus possibly also the effectiveness of the barriers, are e. g. the construction of a barrage, the digging of a tunnel or the construction of a groundwater catchment plant. The consequence of such activities for the containment capacity of the repository

system is considered to be extremely slight due to the fact that their effects are restricted to near-surface areas. Such activities can often be put on the same level as influences and effects from natural developments occurring on or near the earth's surface.

The activities that destroy or bypass directly the barrier system of the repository are understood as human intrusion. Examples of such activities are deep drillings, solution mining in salt rock, or the construction of extraction mines in direct vicinity of the repository. In the further course of this study, the focus will – in line with the Safety Requirements /BMU 10/ - be exclusively on activities relating to human intrusion.

Human intrusion

"Human Intrusion" (HI) is understood as all human activities after the closure of a repository mine that will directly damage the barriers within the backfilled and sealed underground workings of the mine and/or the CPRZ. A difference is made between actions that are carried out with knowledge of the repository and its hazard potential and those that are carried out inadvertently after this knowledge has been lost.

Deliberate human intrusion

Deliberate human intrusion is characterised by the fact that society has knowledge of the repository and its hazard potential. Internationally, there is wide-spread consensus /EUR 11/ that the consequences of any deliberately performed activities are the responsibility of the acting society. Hence, future generations need not be protected from their own decisions that have been made in the knowledge of the possible consequences of their actions.

Inadvertent human intrusion

Inadvertent human intrusion is characterised by the fact that the knowledge of the repository and its hazard potential and the knowledge of the hazard potential of the waste emplaced has been lost.

Predictability

In Subsection 5.2 of the Safety Requirements it says that it is not possible to predict future human actions (see page 3). Internationally, there is consensus that there is no scientific basis for a reliable prediction of human society, its ways of acting and its

technological skills over a period beyond a few generations /EUR 11/. The long-term development of human society defies a scientific systematic treatment.

To deal with these uncertainties, the VSG project, in line with /BMU 10/ and the methods applies in other countries, assumes behaviour patterns of society and the state of the art in science and technology to be those of the local situation of today and applies them as stylised HI scenarios as a basis for the assessment.¹

According to the safety and verification concept /MÖN 11/, stylised scenarios generally play an important role in the handling of uncertainties that concern developments that are hardly or not at all predictable. Such uncertainties cannot be dealt with within the framework of a systematic scenario development. By using stylised scenarios, a method of how these uncertainties are handled is specified in a comprehensible manner.

HI scenarios

Evolutions of the repository system with regard to human intrusion cannot be derived systematically as part of a scenario development due to the lacking scientific basis. Hence, HI scenarios (see above) have to be specified on the basis of regulatory requirements, such as with regard to the consideration of today's societal conditions and the current state of the art in science and technology. The HI scenarios have to be oriented on concrete repository concepts and site conditions.

Current common human activity

According to Subsection 5.2 of the Safety Requirements, only current common human activity is to be considered as a basis. This means that in the consideration of human activity, today's local practices and technologies have to be regarded. This requirement is to stop any speculation about future skills and technical possibilities. Moreover, the derivation of optimisation measures regarding speculative or unreal technical applications makes little sense.

¹ In /BMU 10/, the term 'reference scenarios' is used for an inadvertent human intrusion. In the VSG project, the term 'HI scenarios' is used throughout instead in order to avoid confusion with the reference scenarios that have been derived in the VSG project as part of the systematic scenario development /BEU 12/.

Primary optimisation targets

The Safety Requirements consider it an iterative tasks to develop the repository concept and the repository design step by step with consideration of predefined optimisation targets. The Safety Requirements mention the following optimisation targets, which are referred to as "primary" optimisation targets in this report for the purpose of distinguishing them from the general optimisation targets /BMU 10/:

- Radiation protection for the operating phase
- Long-term safety
- Operational safety of the final repository
- Reliability and quality of long-term waste containment
- Safety management
- Technical and financial feasibility

The optimisation of the repository regarding future human actions with adverse effects on its safety is to be of lower priority with respect to these primary optimisation targets. The Safety Requirements do not explain the relevance of the lower priority in further detail, so that the further procedure is specified by the following interpretation:

Optimisation measures regarding the isolation of the radioactive waste from the biosphere with consideration of future human actions must not be in conflict with the above-mentioned primary optimisation targets. For example, it has to be checked whether the intended measures regarding human activity may initiate or favour processes or create circumstances that will have a negative effect on long-term safety. If necessary, the measure concerned will then have to be modified or dispensed with.

General HI optimisation targets

Subsection 5.2 of the Safety Requirements concludes with the specification of optimisation targets to be striven for as a result of the analysis of HI scenarios. Two general targets are defined, relating to the reduction of

- the probability of human intrusion and
- the radiological effects on the general public.

2.2 Approach

On the basis of the above-mentioned provisions, the following approach was pursued for the studies of inadvertent human intrusion into a repository for heat-generating radioactive waste (Fig. 2.1):

1. In a first step, human activities as practiced today in the local area of the site and showing a potential of intrusion into the repository with regard to the associated technologies or courses of action and the planned depth of the repository were identified.

For the aim to derive optimisation measures in connection with future human actions it is essential to know about current common human activities with respect to their practical execution and application. For this purpose, information and facts were compiled, and corresponding experts were interviewed where necessary to clarify open issues.

2. Once the necessary information and knowledge about current common human activities from 1) had been obtained, different possible cases were considered. This case differentiation takes different locations for e. g. vertical drillings, which could thus affect different areas of the repository system, into account.
3. Taking the case differentiation made in 2) into account, the possibly resulting impacts on the repository were discussed.
4. This step, which also takes the case differentiation into account, included the study of to what extent – based on the courses of action of the human activities – there is a chance that any existing irregularities or anomalies caused by the repository and the radioactive waste emplaced are perceived or detected. In this context, the evolution of the repository over time has to be taken into account.
5. Such cases that may have safety-related implications for the repository and as a result of the discussion of cases of a possible perception of anomalies caused by the repository and the waste, the HI scenarios for further study were defined.

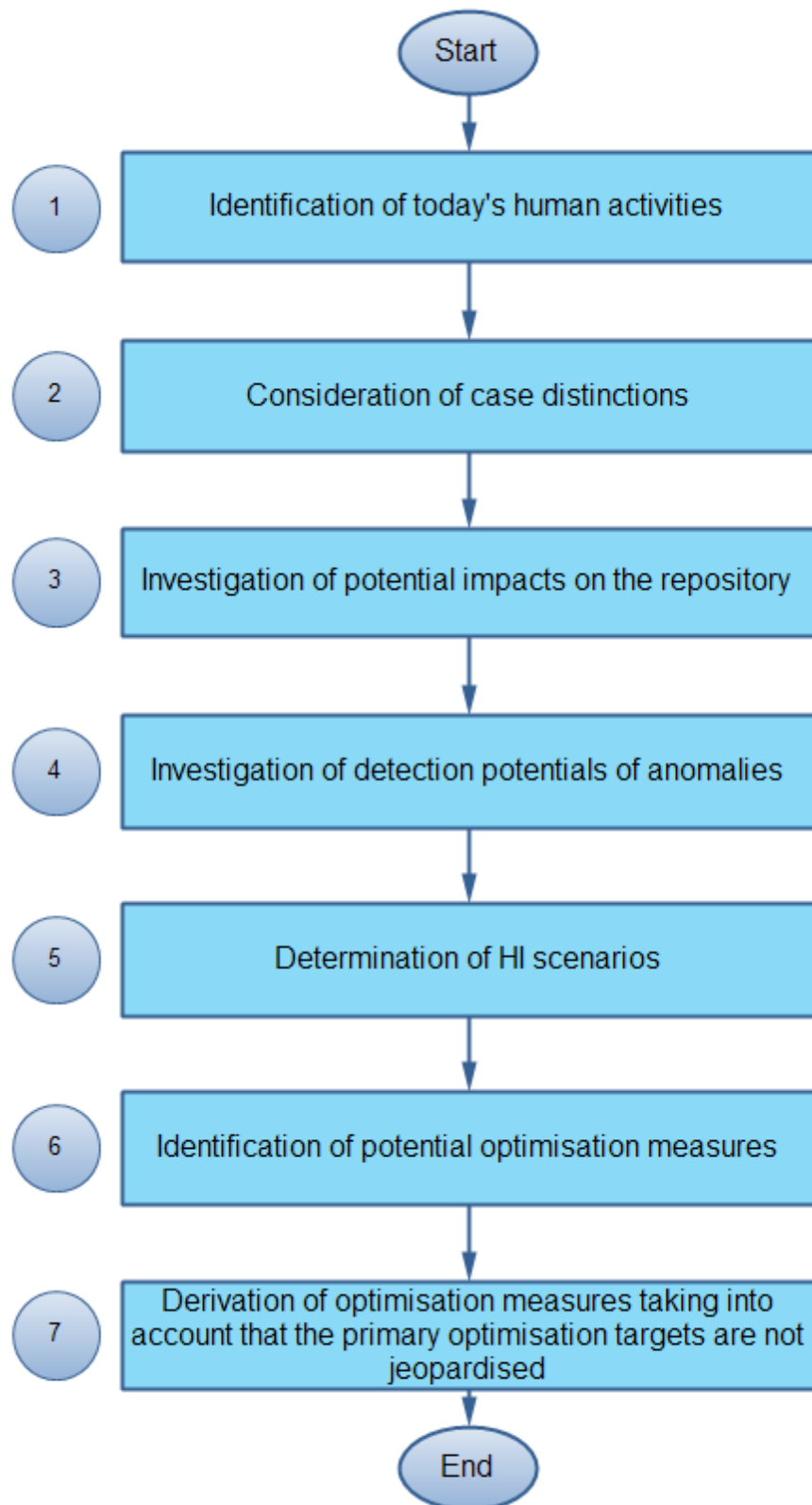


Fig. 2.1 Representation of the working steps performed with respect to the study of human activities

6. In this step, possible optimisation measures were identified for the defined scenarios; these measures are in particular aimed at the required optimisation targets of reducing the probability of human intrusion and the radiological effects on the general public.
7. The possible optimisation measures identified in the preceding step were finally discussed under the aspect of their feasibility and possible conflicts with primary optimisation targets. If there is a possibility of a quantitative assessment of the HI scenario before and after the consideration of countermeasures, the corresponding case has to be modelled and analysed.

The following specifications for the further work were made:

- a) HI scenarios and the resulting consequences are not to be discussed in connection with less probable alternative scenarios from systematic scenario development, nor are they to be combined with them.
- b) Only the north-eastern wing of the repository with the heat-generating waste shall be considered.
- c) HI scenarios have to be considered in connection with variant B1 (emplacement of heat-generating radioactive waste in self-shielding repository casks in horizontal drifts). Furthermore, variant C (emplacement of all heat-generating radioactive waste in deep, vertical boreholes) is to be considered in terms of a differential consideration /BOL 11/, /BOL 12/.
- d) Any inadvertent human activity at the site is to be assumed no earlier than 500 years after the closure of the repository.
- e) Consequences of inadvertent human intrusion into a repository are not to be measured on radiological limits.

To a) As the HI scenarios cannot be systematically derived within the framework of scenario development due to the missing scientific basis, it is not rational to combine them with scenarios from scenario development /BEU 12/ with the aim to derive possible optimisation measures. Due to their own nature, the stylised HI scenarios therefore have to be dealt with separately from the alternative evolutions that have been identified by scenario development. The HI scenarios are guided by the repository concepts and the natural conditions at the Gorleben site. A quantitative

analysis of HI scenarios is based on the assumption of a probable evolution of the site and the repository system.

To b) The Safety Requirements have to be applied to heat-generating waste. An optimisation of the repository against future human actions is not necessary for the waste with negligible heat generation in the south-western wing of the repository, but would be desirable for a comprehensive assessment. Since, however, a plausible quantification of the waste flow is hardly possible with the knowledge available today, any emplacement concepts and consequences (e. g. gas formation) are highly speculative. A discussion of optimisation measures against human intrusion is therefore postponed due to the current state of knowledge regarding the amount and composition of the waste with negligible heat generation.

To c) Apart from the combination of variants A and B1, variants C and B2 (emplacement of all heat-generating waste in transport and storage casks in horizontal boreholes) are considered /BOL 12/. As for variant A, it has to be pointed out that this concept is an option and that an optimisation can only be of an exploratory character due to the presently insufficient state of information and knowledge about the corresponding waste (type, content, amount) and to the, therefore, relatively rough design of the waste packages and the emplacement areas at this stage. Variant A is not considered according to b). Due to the consideration merely of different transport and storage casks, variant B2 only differs slightly from variant B1 and has no or only insignificant effects on the optimisation regarding human intrusion. For the reasons mentioned above, only variants B1 and C are considered here.

To d) Regarding the time-frame of future human actions it is assumed that for the phase immediately following the closure of the repository, no inadvertent human actions at the site that may lead to a degradation of the barriers have to be considered. The reason for this is that the knowledge about the site and its associated hazard potential will not be instantaneously lost and that measures have to be taken in line with the Safety Requirements (/BMU 10/, Subsections 9.7 and 10.2) that allow the long-term preservation of knowledge. This long-term preservation of knowledge is, however, limited due to the unpredictability of human acting. Analogous to the recommendations of the "Scenario development" Working Group /BEU 08/, a period of 500 years following the closure of the repository is basically assumed for the knowledge to be preserved. Within this specified period, inadvertent human activities at the site need not be considered. The mentioned period is oriented on the time-span of

current documentation practice, e. g. in German mining archives that are still in use and consulted today.

To e) As for how to deal with any possible consequences, the "Scenario development" Working Group /BEU 08/ is of the opinion that by deciding in favour of a concept of concentrating and isolating the radioactive waste in a repository, one inevitably has to accept the possibility that in the event of someone intruding into the repository, the acting persons could suffer extensive radiation exposure. Moreover, the consequences associated with human intrusion cannot be quantified with any meaning due to the unpredictability of the assumptions to be taken and boundary conditions to be applied. For those reasons, the Working Group considers it not useful to measure the consequences for the intruding person or group of persons on radiological limits.

This opinion is in line with the Safety Requirements in that according to Subsection 6.5 /BMU 10/, no limit for acceptable risks or acceptable radiation exposure levels has been defined in connection with developments as a result of an inadvertent intrusion.

3 Future human actions

Future human actions can be divided into actions that cause a local, regional or global change. Human actions of a trans-regional origin or which have a global effect, e. g. anthropogenic greenhouse gas emissions, and which then have an indirect influence on the repository system via consequential processes and resulting mechanisms (e. g. the flooding of the site associated with a transgression) are not considered within the framework of this report. Although such actions are not directly dealt with in the scenario development (/BEU 12/), they are implicitly considered by the consideration of the process "global climatic changes" in the scenario development. Hence in the following, only those actions will be considered that have local or regional implications.

3.1 Human actions and practices in the repository region

A look back into the past shows that human actions have taken place at the site as well as in the closer vicinity that have also affected deep areas underground.

Records from the borehole register /LBG 11a/ (Hanover geological data centre: Nibis map server) confirm that in the past a number of boreholes have been sunk in the site region. These drillings served e. g. for the extraction of crude oil or natural gas reservoirs and for the exploration of the hydrogeological, geological and geothermal situation. The drilling depths ranged between a few metres up to several 100 m.

Apart from the drillings, further imaginable actions in connection with salt domes can be mentioned, such as the excavation of caverns and building of mines, which did not, however, take place in the past. Based on the analysis of earlier human actions in the site region and with respect to salt domes that may reach down into the depth of a repository, so-called basic actions can be derived for the further treatment of the issue (**Fig. 3.1**).

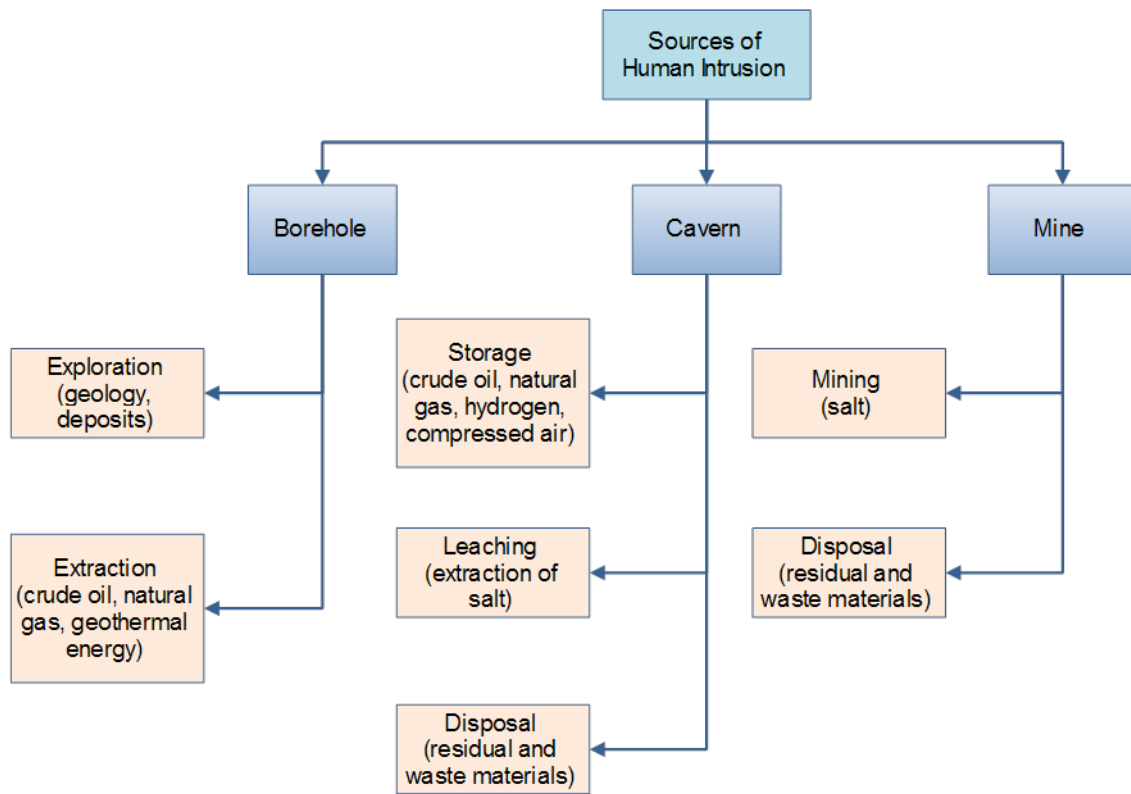


Fig. 3.1 Schematic diagram of basic actions

These basic actions form the basis of the further treatment of HI scenarios as they have the potential to affect the planned area of depth of the repository and hence to damage the barriers. In the following chapters, the individual basic actions "Drilling of a borehole", "Creation of a cavern" and "Construction of a mine" and the associated sequences of action are addressed. Described are the individual development phases of the basic actions such as prospection, planning and construction as well as operation and decommissioning. It has to be noted that the drillings are attributed a special importance as the leaching of caverns or the construction of a mine will also be preceded by a test or exploratory drilling.

3.2 Regulatory basis

Within the framework of the development of safety requirements, GRS began establishing and documenting (in /BAL 05/) the state of the art in science and technology regarding the above-mentioned basic actions. The regulatory basis is referred to in /BAL 05/. The legal framework for the basic actions and thus also for the exploratory drillings is provided by the Federal Mining Act (BBergG) /BBG 09/ and the

Deposits Act /LAG 34/. Mining law as well as deposits law are the responsibility of the federal Länder, who regulate official supervision and compliance by corresponding Länder-specific ordinances. For example, the different Länder have decreed corresponding Deposits Ordinances and range of Mining Ordinances, i. a. the Mining Ordinance for Drilling, Deep Storages and the Extraction of Natural Resources by Drilling. Due to Länder-specific regulations, it may be that further laws, such as the Water Act of Lower Saxony, have to be taken into account. Furthermore, the Environmental Information Act regulates i. a. the right of free access to the information regarding the environment that is available to the authorities. Apart from the acts and ordinances, there also exist a number of Länder-specific guidelines, such as the "Guideline of the Chief Mining Authority of Clausthal-Zellerfeld Relating to the Backfilling of Abandoned Boreholes" /OCZ 98/, which have to be considered accordingly.

Within the framework of the analyses of the basic actions, which are based on today's current human actions and techniques, not only the work sequences but also the regulatory basis must be taken into account. This regulatory basis provides information e. g. about the scope of examinations that have to be carried out or documents that have to be submitted to the competent authority prior to any undertaking, such as the excavation of a cavern. Furthermore, regulatory requirements are put up, like e. g. how a borehole has to be sealed and a cavern has to be decommissioned. In the further analysis of the basic actions, it is assumed that all applicable regulations are observed.

3.3 Drilling of a borehole

The borehole database of Lower Saxony /LBG 11a/ comprises the results of drillings from 170 years of geological exploration. It provides information on more than 280,000 drillings with approx. 1.9 million data sets on the individual strata found by boring. The deepest drilling recorded in the register reaches down to 7,000 m below sea level. The depths of the drillings depend on the prospection target. As can be seen from the database of the Lower Saxony State Office for Mining, Energy and Geology (LBEG), the largest part of the boreholes are sunk with the aim to explore the hydrogeological or geotechnical conditions. Their final depths are less than 100 m. In contrast, the depths of boreholes sunk for hydrocarbon exploration in the environment of salt domes are between some 100 m and some 1,000 m.

The frequency of test drillings and exploratory drillings depends on the potential presence of natural resources in a region. In northern Germany, intensive drilling activity has been recorded in the past for the exploration of hydrocarbon deposits (natural gas/crude oil). The depth areas of the crude oil deposits range between 1,000 m and 2,500 m and of natural gas between 3,000 m and 5,000 m. In the case of a corresponding exploratory drilling, the planned depth area of a repository for radioactive waste of approx. 900 m would be exceeded. The LBEG database contains data sheets of more than 30,000 drillings for hydrocarbon exploration purposes /LBG 11b/. Apart from title data, other data on special subject groups such as geological profiles, cored intervals (areas of a drilling for which cores exist), carrier rock or the like have been registered. An overview of the drilled deep boreholes since 1840 is given in Fig. 3.2. Generally, a decrease in drilling activity can be observed /BMWI 04/.

More and more often, boreholes are also sunk for exploiting geothermal energy. As regards the depth at which geothermal energy is exploited, a rough distinction can be made between three types of utilisation:

- a) utilisation of surface-near groundwater or geothermal energy (heat pumps)
- b) utilisation of geothermal energy by means of geothermal probes
- c) plants for geothermal electricity production.

The utilisation mentioned under a) concerns depths of several 10 m and are therefore irrelevant for the further considerations.

The exploitation of geothermal energy by means of geothermal probes takes place at depths of several 100 m, in rare cases beyond 1,000 m. Owing to their good thermal conductivity a preferred utilisation of salt structures cannot be excluded. Hence this form of geothermal energy exploitation can generally be considered for the derivation of HI scenarios. However, these installations are closed systems, with a working agent (liquid, direct-expansion evaporator) circulating in a closed coaxial pipe. A solution of salt rock or the influx of contaminated brine into the geothermal probe is therefore excluded. What is decisive for a potential degradation is therefore not so much the operation of such a plant but rather more its construction, i. e. the drilling of a borehole with the intention of expanding it later on for geothermal energy exploitation. This case,

however, corresponds to the normal working process of "Drilling of an exploratory borehole".

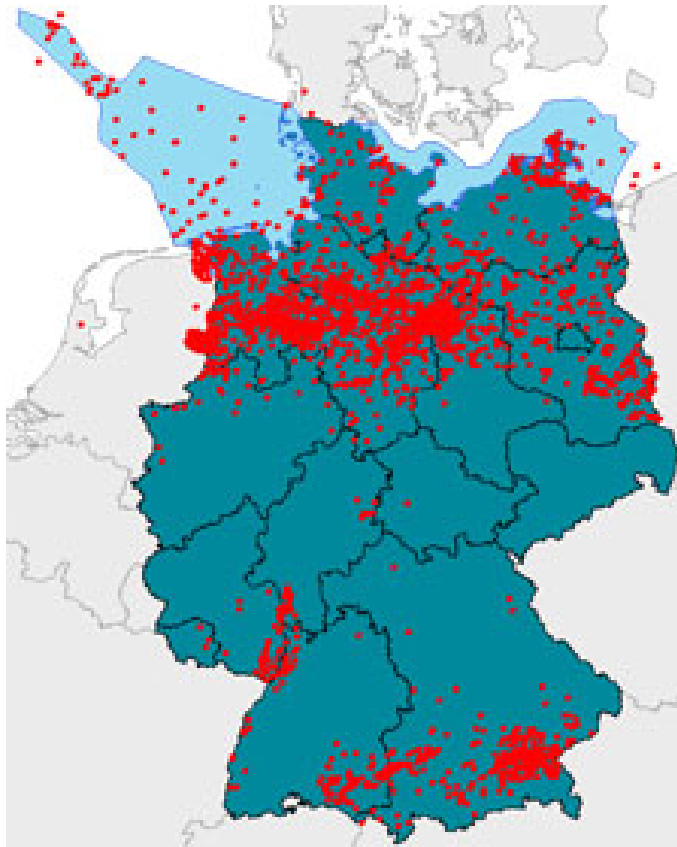


Fig. 3.2 Representation of deep drilling sites for hydrocarbon exploration (Source: /LBG 11b/, red dots indicate locations for deep drillings)²

Geothermal energy plants for electricity generation utilise depths of several 1,000 m as they are reliant on water temperatures of at least 100 °C. It is generally imaginable that if the plant is erected at a relatively early stage (up to 1,000 years after the sealing of the repository), the heat anomaly generated in this location by the repository might possibly be preferably used as a source of geothermal energy even above the typical depth area mentioned above. What is also conceivable is that the detection of a hot-spot, representing an anomaly, would entail further examinations. Any resulting

² Due to the disproportional representation of the drilling sites, no relation of the drilled-on surface areas can be derived from the illustration.

reactions or conclusions as well as the initiation of measures either for or against a geothermal plant cannot be derived. However, geothermal plants are operated as Hot Dry Rock systems – if no hydrothermal aquifer can be utilised at the Gorleben site. In a Hot Dry Rock System, the heat transfer medium (water, CO₂) is forced through an injection borehole at high pressure above the lithostatic pressure of the corresponding depth into low-permeable rock formations to break up flow paths (so-called hydraulic fracturing or "Hydro Frac" method). This increases the permeability of the rock. The heat transfer medium is conveyed back to the surface via a second production well. Owing to the operating mode as an open system, the exploitation of geothermal energy in salt formations is out of the question as there is a risk of incalculable leaching in the salt rock.

For the above-mentioned reasons, this form of utilisation of geothermal energy can be reduced to the case of "Sinking of an exploratory borehole" (which would later on be expanded to an injection borehole) with regard to the derivation of HI scenarios. The following remarks on the state of the art in science and technology therefore refer solely to the sinking of an exploratory borehole.

3.3.1 General

Boreholes that serve for the search for new deep deposits are referred to as exploratory boreholes. Their main purpose is the so-called prospection, i. e. the exploration of the geological conditions and the deposit itself, but also the preparation of the extraction or mining e. g. of hydrocarbons, salt, groundwater or geothermal energy.

The depths of the boreholes depend on the objective of the prospection. For example, the largest parts of the boreholes with the aim to explore hydrogeological conditions are drilled with final depths of less than 100 m. In contrast, the depths of boreholes sunk for hydrocarbon exploration in the environment of salt domes are between some 100 m and some 1,000 m.

The drillings can be vertical, horizontal or even kinking. Available drilling modes are hammering, rotary or oscillating methods. The method most frequently applied in deep drilling technology is the rotary method in which the drill bit together with the drill pipe is set in rotary motion by a top drive (see Fig. 3.3).



Fig. 3.3 Lateral and front view of a drill bit tool roll used for the rotary method (Source: FRE³)

A further drilling method is that of turbine drilling, in which the driving turbine is situated right above the drill bit (down hole). This method is used above all for deflection drillings.

The technique used more and more often for exploratory drilling is "slim hole drilling". Here, by choosing a smaller diameter, the time and material needed for the drilling is reduced, and drilling costs are thus lowered. Once a decision in favour of extraction or production has been taken, the exploratory borehole is cut around with a drill with a larger diameter.

Furthermore, the horizontal drilling techniques used for the exploitation of crude-oil and natural-gas deposits are increasingly used. Also successfully tested and more and more frequently used is the horizontal drilling technique in combination with the "frac" technique. Here, cracks are generated in a low-permeable deposit by means of high pressures, allowing a higher gas or oil flow and thus an increased production.

³ Division of Mining Engineering, Mineral Processing and Recycling (FRE) of RWTH Aachen University (2004), photos from geothermics drilling Project Super C

3.3.2 Prospection and planning

The technical measures to be taken before, during and after the drilling of a borehole are defined in the so-called drilling operations plan and in the drilling programme specified by the client or laid down in laws, ordinances and guidelines. The drilling operations plan contains instructions, general conditions and information about the execution of the drilling such as boring site, start of boring, property, circulation, drilling method, monitoring installation etc. In the drilling programme, further-reaching instructions regarding the sequence of the drilling work are specified. The clients, who come mainly from the oil and gas industry as well as from the area of mining, generally use a range of competent service providers such as geological experts, drilling companies and laboratories for carrying out their intended projects in the exploration, operational and conclusive phase. A first step towards finding suitable areas is the classification of geological maps and geological outcrops above ground as well as the search for deep drillings that have already been performed. Additionally, aerial photographs are taken and the ground of the thus marked-off regions is assessed.

For the preparatory exploration of the geological conditions of the underground, different geophysical measuring methods are often applied. What is a problem is that the depth-dependent characteristics of the rock can only be determined indirectly, so that inversion procedures will always have to be applied for the derivation of e. g. the sequence of geological strata. This can result in considerable uncertainties in the interpretation of the measured phenomena. In the following, some essential methods used prior to the execution of an exploratory drilling, such as earth-magnetic, gravimetric, geo-electric and thermal measurements as well as seismic methods are briefly described /BEN 85/, /KNÖ 05/, /MIL 84/, /MIL 85/, /MIL 87/:

By means of earth-magnetic measurements, anomalies in the natural magnetic field of the earth can be identified and their manifestation in form and depth determined.

Similar to geomagnetics, gravimetrics is a potential measure in which changes in the gravity field of the earth are measured by using gravimeters or pendulums. The different gravitational acceleration intensities in different locations allow (by means of terrain reduction) making a statement on the distribution of the masses in the earth's crust and on the density of the rock, by which way it is e. g. possible to locate salt domes.

By means of geo-electric measuring methods, the potential distribution, which is governed by the conductivity structures underground, is measured. This allows the calculation of the spatial distribution, which in turn allows conclusions with regard to the geological situation.

The measuring principle of thermal measurements aims at deviations from the heat flow of the earth. With increasing depth, there is a linear increase of the temperature due to a constant geothermal gradient. Any deviations from this gradient suggest changes in the rock with consideration of specific thermal conductivities.

An important current geophysical method is the seismic method and especially the further developed 3D seismic interpretation method, which is marked by its accuracy of the underground structure that meets the requirements of the task. The measuring principle is based on reflected oscillations that are recorded by geophones and transformed into electric impulses, which are digitally recorded. The oscillations are induced by blasting operations, vibrations or air pulses (in water). Depending on the type of rock, the oscillations propagate through the underground at various different speeds and are reflected or deflected at the boundary surfaces. Due to the comprehensive documentation, it is possible to represent the underground structure only after preparation and further processing by means of computerised tools.

3.3.3 Operation

To secure the walls borehole wall during the drilling process, a drilling fluid (at least an aqueous clay or barite solution) is pumped through the drill pipe, rising together with the drill cuttings to the surface again via the annular gap. Steel pipes can be cemented into the borehole as long-term protection against a collapse.

During the phase of sinking the borehole, a number of accompanying examinations and monitoring operations are carried out. These range from the geological-mineralogical analysis of the drill cuttings conveyed above ground or, in the case of core drillings, of the extracted drill cores, the drilling fluid, the drilling process, the borehole or the borehole wall and the drilling equipment such as the drill bit, drive and drill pipe. Any arising circulation losses are recorded. The extraction of the drill cores is specified in the drilling operations plan. Instead of core extraction, televiewer methods

(optical and acoustic) are often also applied. The exact determination of the chemical and mineral composition of the core specimen takes place in the laboratory.

Depending on the kind of prospection, a range of further geophysical parameters such as temperature, resistance, natural radioactivity, conductivity, density, porosity etc. are recorded in the borehole by means of borehole probes (gamma log, neutron log, sonic log etc.) /FRI 99/. The recording of measured curves (logs) is done by lowering special probes into the borehole and subsequent recording and measuring various different parameters while steadily moving the measuring instrument upwards back to the surface. Here, a distinction can be made between passive and active methods, with the passive methods reacting to natural phenomena (the magnetic field, the rock's own electrical potential or the natural radioactivity) and the active methods being characterised by the generation of signals (seismic waves, nuclear particles, electrical currents). Besides the classic method of logging described above, the "logging while drilling" (LWD) method has been developed in recent years, allowing measurements directly during the drilling process.

Apart from the measurements relating to the borehole environment, data of the borehole geometry and the properties of the drilling fluid are also recorded. An overview of the individual measuring methods and the parameters measured with them is given in Fig. 3.4. The Fig. 3.5 contains an overview of the different possible uses of different geophysical procedures in connection with the determination of geological characteristics and conditions concerning the structure of the underground. This report will not go into a description of the individual measuring principles. Reference is made rather more to the extensive technical literature on this topic, as e. g. /FRI 99/, /MIL 84/, /MIL 85/, /MIL 87/.

Additional to the geophysical measurements, the wear of the drilling equipment, especially of the drill bit, is continuously checked. The monitoring of the advance of the drill would indicate any increased wear or a change in the sequence of strata.

The drill cuttings arising during drilling is initially stored at the drilling site and later disposed of irrespective of what kind of drilling fluid has been used. As in the case of the drill cuttings, any liquids arising are collected at the drilling site and are eventually disposed of.

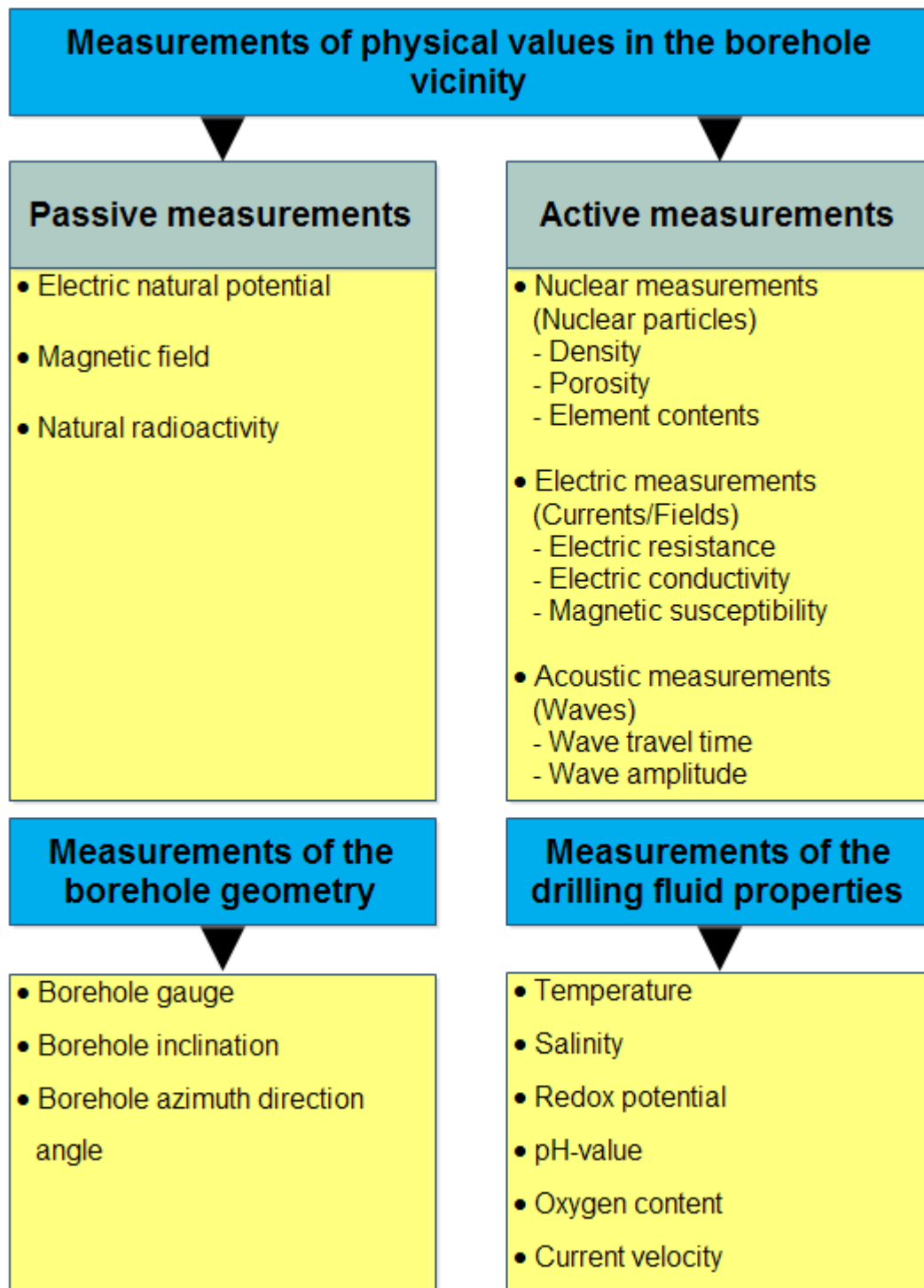


Fig. 3.4 Overview of the different measurements in a borehole
(based on /KNÖ 05/)

| Reference | General geology | | | | | Deposits geology | | Geo-chemistry | | Petrophysics | | | | | | Seismics | | |
|--|---------------------|--------------------|-----------|---------------------------|---------------------------|------------------------|----------|---------------|-------|--------------|----------|--------------|--------------|--------------------------|------------------------|----------|-------------------|--------------------|
| | Lithology (general) | specific lithology | | Mineralogical composition | Stratigraphic Correlation | Deposition environment | Fissures | Overpressure | Educt | Maturity | Porosity | Permeability | Clay content | Salinity formation water | Hydrocarbon saturation | Gas | Interval velocity | Acoustic impedance |
| | | Vulcanite | Evaporite | | | | | | | | | | | | | | | |
| Temperature | | | | | | | | | | | | | | | | | | |
| Gauge | | | | | | | | | | | | | | | | | | |
| Natural potential | | | | | | | | | | | | | | | | | | |
| Electric resistance | | | | | | | | | | | | | | | | | | |
| Gamma Ray | | | | | | | | | | | | | | | | | | |
| Spectral Gamma Ray | | | | | | | | | | | | | | | | | | |
| Sonic | | | | | | | | | | | | | | | | | | |
| Density | | | | | | | | | | | | | | | | | | |
| Photoelectric effect | | | | | | | | | | | | | | | | | | |
| Neutron porosity | | | | | | | | | | | | | | | | | | |
| Dipmeter | | | | | | | | | | | | | | | | | | dip |
| Image Logs | | | | | | | | | | | | | | | | | | dip |
| <div><div></div>(essentially)<div></div>Semi quantitative and<div></div>strong quantitative</div> <div>qualitative usequalitative useuse</div> | | | | | | | | | | | | | | | | | | |

Fig. 3.5 Overview of the different uses of various different geophysical procedures for the determination of certain geological properties (based on /GEO 11/)

3.3.4 Closure

The closure of abandoned boreholes is regulated in the Federal Mining Act and the Deep Drilling Ordinance of the Länder as well as in the corresponding guidelines of the mining authorities (e. g. the "Guideline of the Chief Mining Authority of Clausthal-Zellerfeld Relating to the Backfilling of Abandoned Boreholes" /OCZ 98/). In all cases, it is required that abandoned boreholes be sealed or backfilled by suitable measures, on the one hand to protect the deposits and on the other hand to protect groundwater reservoirs as well as for reasons of stability. Groundwater reservoir and extraction horizons have to be sealed against adjacent strata, and leak-tightness has to be demonstrated by corresponding control measurements.

The "Guideline of the Chief Mining Authority of Clausthal-Zellerfeld Relating to the Backfilling of Abandoned Boreholes" /OCZ 98/ contains the following general requirements for the backfilling of deep boreholes:

- "The borehole has to be backfilled completely. This involves the sealing through the insertion of special backfill in the areas of utilisable crude-oil, natural-gas and salt deposits, of utilisable storage and water horizons as well as of high-pressure horizons with feeders (referred to in summary as deposits in this Guideline), liners, intersections of pipes and annular gaps as well as the pipe shoe of the deepest borehole casing in a partially uncased borehole and the area under the earth's surface."
- "In areas in which problems have arisen during drilling or conveying, the insertion of additional special backfilling sections may be required."
- "The special backfilling sections have to be backfilled with suitable cement or with other suitable solid matters, if necessary in combination with mechanical seals. It has to be ensured by suitable measures that the solid matters will adhere well to the pipe or borehole wall."
- "The materials used for the backfilling of the other sections must not impact the bedrock, the casing, as well as the materials of the special backfilling sections."

/OCZ 98/ requires in particular:

- "Special backfilling sections are only to reach from 50 m below to 50 m above the deposit" (see Fig. 3.6).
- "Perforation sections with feeders are to be isolated by pressure cementing. If for this purpose a permanent cement retainer is used, a length of 20 m above it will suffice for the special backfilling section. If pressure cementing [...] is not or only under difficult conditions possible, a mechanical seal with a special backfilling section of at least 50 m above has to be installed as directly above the perforation as possible."
- "In the case of deep gas drillings, a mechanical seal with a special backfilling section of at least 50 m above [...] may be inserted as a seal that is technically equal to pressure cementing [...]. If mechanical sealing is effected by a plug in the production packer, the leak-tightness of the mechanical seal has to be demonstrated before the insertion of the special backfilling section."

- "It has to be indicated in the backfilling operations plan whether the sealing [...] is to be carried out; deviations from these regulations have to be justified in the operations plan."
- "Notwithstanding, [...] a special full-length backfilling section may be dispensed with within deep salt deposits. At least in the roof and at the bottom, there have to be special backfilling sections of at least 100 m length in the salt and 50 m in the adjoining rock" (see Fig. 3.6).
- "If a borehole is partially uncased, a special backfilling section of at least 100 m or a mechanical seal with a special backfilling section of at least 50 m has to be inserted into the deepest borehole casing from the pipe shoe".

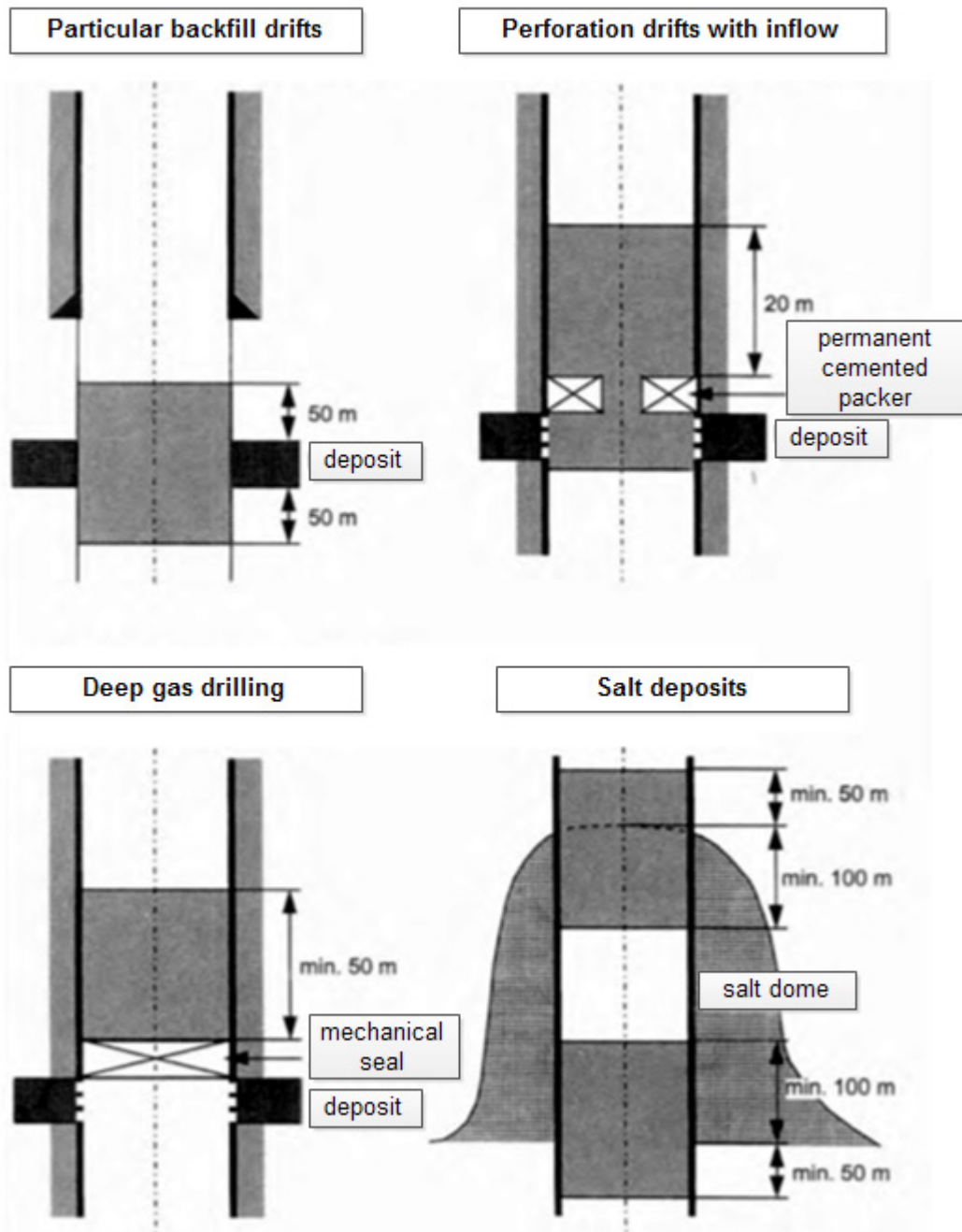


Fig. 3.6 Graphic representation of backfilling sections (according to /OCZ 98/)

Generally, the borehole is backfilled with stably settling material (e. g. crushed rock) or with cement and sealed at the top with a closure plug. In addition, the borehole is secured by a 0.25-m-strong concrete plate located at least 1 m below the surface /OCZ 98/. A borehole that penetrates an aquiclude that separates two groundwater storeys is sealed in such a way that shorting of the two groundwater storeys is

prevented. Furthermore, storage and production horizons have to be sealed off from the adjoining rock strata. Sealing materials are usually different types of cement.

Special production and storage boreholes have to be backfilled and secured by cement bridges /SCH 11/

- at the upper end of the borehole,
- in the area of freshwater aquifers,
- in the area of "plastically sloughing rock salt strata",
- in a reservoir up to the surface formation as well as
- in the area of pipe joint locations.

As an alternative to cement, the use of different types of clay (possibly also polymer-gel materials) is recommended (especially in the case of CO₂ storage drillings due to the susceptibility of cement to corrosion) /SCH 11/. For the further considerations it can be assumed that an abandoned borehole in the area of a salt structure, similar to the requirements of /OCZ 98/, is sealed off at the roof and at the bottom by special backfilling sections that consist either of cement or of sealing cohesive material, such as different types of clay.

3.4 Creation of a cavern

3.4.1 General

In the narrower sense, all cavities artificially created by solution mining in a salt dome, e. g. for salt production or for the storage of crude oil or natural gas, are referred to as caverns. In Germany, there are about 250 such caverns, e. g. near the country's most important crude-oil import port of Wilhelmshaven (Fig. 3.7). The caverns there lie at a depth of more than 1,000 m and serve not only for gas storage also for the storage of the reserves of raw materials required by the Petroleum Stockholding Act to be kept for times of crisis, managed by the Petroleum Stockholding Association. Fig. 3.7 shows the cavern and pore storages that are in use or being planned in Germany.

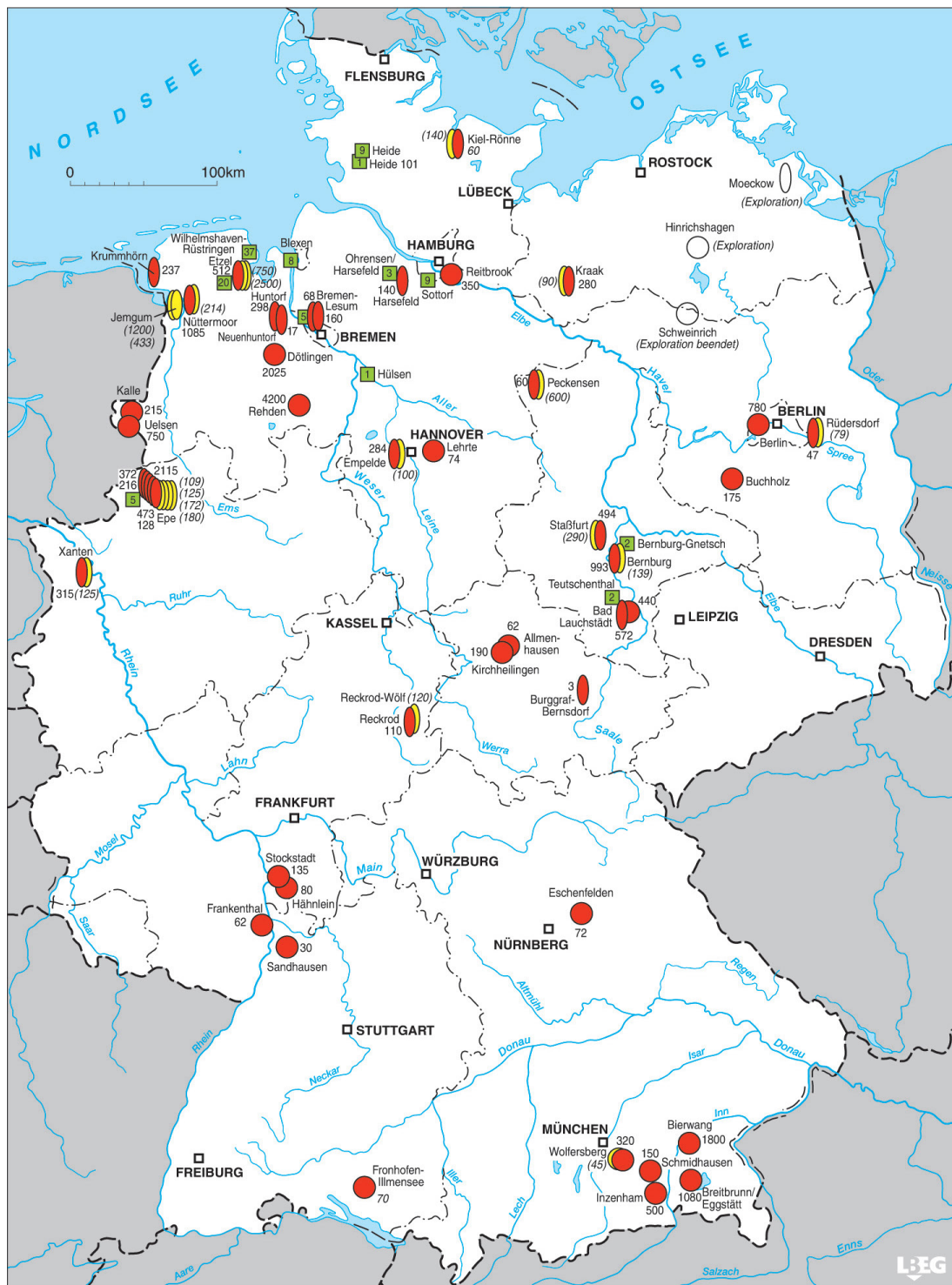


Fig. 3.7 Storage locations in Germany (taken from /SED 09/)

3.4.2 **Prospection**

Based on the geological state of knowledge of a known salt structure, test drillings are performed in the planning phase to examine the suitability of a salt dome as a storage /BAD 01/. If the results are positive, a hexagonal well pattern is defined. Using the results of rock-mechanical calculations, the spacing of wells (usually approx. 250 m – 300 m) is specified. Further examinations are carried out by means of modern seismic methods. For example, shallow seismic is used to describe the contour of the salt dome.

With seismic methods it is possible to examine whether a salt structure has any overhangs. In these structures, the flanks of the salt dome incline downwards towards the centre so that their diameter decreases with increasing depth. Charts showing the maximum contours of salt domes projected to the above-ground surface area can therefore not be equalled to the exploitation potential. In many cases, further project-specific geophysical exploration is necessary in view of the very different states of knowledge /SCÜ 01/.

Smaller salt structures often have a complex inner structure that can be derived from the intensive internal folding of the stratigraphic sequence of the saline strata making up the structure (rock salt, potashes, anhydrite, in the case of Permian salt rock beds also more mighty clay intercalations) and which increase the geological risk of a futile boring site.

On the basis of the state of knowledge about existing cavern fields, further caverns are frequently created. Here, the exploration effort is often much less than in the case of the new creation of caverns in a so-far unused salt dome. However, the leachability of parts of the salt rock at the site of a planned cavern can only be demonstrated by the cavern drilling /SCÜ 01/.

When exploring and choosing a site for creating a cavern in salt, a salt rock that is as homogenous, unexploited and little permeable as possible is striven for since the use of caverns is generally intended for the provision or storage of compressed air, natural gas, hydrogen, methane or liquids (e. g. crude oil). Possible pathways from former mining activities can lead to considerable storage losses and in extreme cases, as a result of uncontrollable leaching during the creation of the cavern, to considerable damage at the surface and must therefore be excluded by all means. This is why today

it is checked in each exploration whether there have been any salt mining activities in the vicinity. For further exploration activities, too, it can be expected that – especially in view of the residual risk resulting from the assumed loss of mining survey data – corresponding studies will be performed to exclude that there has been any former mining activity.

For the creation of caverns, Staßfurt rock salt is the preferred formation as the main salt used here shows great homogeneity and is well predictable regarding its solution behaviour. This is particularly true of areas in which the salt sequence within salt domes shows broad anticline structures without interfoldings of easily soluble potash. In this cavern area there should be no potash as these salts have a solution progression in leaching that is 5 to 7 times higher than that of rock salt and can therefore cause an uncontrolled irregular creation of caverns. Moreover, any non-leachable clay and anhydrite intercalations may negatively affect the structure of the cavern /SCÜ 01/.

3.4.3 Planning and construction

Design and dimensioning

Based on the structure of the salt dome or the geological knowledge available, a boring grid is draped over the future cavern field, showing the locations of the boring sites for the caverns to be created. Only then will any visible activities be carried out. Roads will be built and boring sites established.

Construction

Large drilling equipment as it is also used for the exploration of oil and gas deposits will sink the cavern boreholes down to their final depth within 8 to 10 weeks.

Installation of the borehole casing

During the drilling operations, cemented borehole tubes are inserted for stabilisation of the surface-near strata and as uninterrupted connection to the salt. In preparation of the following leaching operation, the variable pipe sections are also installed with the drilling equipment.

Leaching

Here, the solution capability of the water with respect to salt is utilised. On this basis, the leaching process develops in every cavern. Following the drilling, two variable borehole tubes are inserted into the borehole. Water is then pumped continuously into one of the tubes, while brine is continuously conveyed upwards and discharged through the other tube. On its way to the discharging borehole tube, the water dissolves the borehole wall and hence becomes brine. The shape and size of the cavern is controlled by corresponding positioning of the two variable borehole tubes. The leaching process for creating a cavern of usual dimensions lasts approx. 2 – 4 years. Approx. 7.5 m³ of brine (saturation 90 %) per m³ of cavity volume can be taken as a reference value for the amount of brine produced /KBB 07/.

Monitoring and measuring

The monitoring of the shape of the cavern is done independent of the leaching at specified intervals by inserting measuring probes into the cavern. These probes have rotary and pivotable ultrasonic sensors that move in an orientated and gyration-stabilised manner. The image of the cavity can be monitored on the computer screen during measurements. Here, the contour of the cavern wall as well as the sound signal forms of the ultrasound responses, temperature and sound velocity, pressure, natural gamma radiation as well as the routing of the piping and the positions of the bolted joints are recorded /TRY 01/.

Planning and construction phase

Generally, a distinction has to be made in the planning and construction phase between storage and leaching caverns. Compared with the storage caverns, the leaching caverns usually have larger volumes, reduced safety pillars between the caverns, and larger cross-sections. Normally, the caverns are preferably created by leaching at a depth between 550 m and 2,000 m. Most of the caverns are located deeper than 1.000 m. The usual cavern dimensions are 40 m – 100 m in diameter and up to 600 m in height. Volumes usually range between 500,000 m³ and 1,000,000 m³.

When a cavern is created, safety pillars or safety margins to different objects or geological structures are usually provided. These include in particular the distances to neighbouring caverns, which are the two- to threefold of the cavern diameter. The

safety margins to the flanks of the salt dome are usually 200 m – 300 m, to old mine structures 500 m due to the exploration boreholes that may exist in these cases, and a few tens of metres to potentially permeable rocks and structures (e. g. anhydrite).

3.4.4 Operation

Leaching operation to create a cavern

The desired expansion and geometry, shape and size of the cavern is achieved by alternation between direct and indirect leaching. The undesired leaching of the roof area of a cavern is prevented by regulating a blanket, i. e. a protective fluid or protective gas (e. g. oil or nitrogen) that is lighter than water or brine and also does not dissolve the salt. A system of concentric pipe sections allows the application of two methods:

In the direct leaching method, freshwater or seawater (approx. 100 m³/h) is injected via the inner pipe section, and the brine is discharged through the inner annulus. This way, the cavern develops more quickly in the bottom area. In indirect leaching, the water (approx. 250 – 300 m³/h) is injected via the inner annulus, and the brine is discharged via the inner pipe section. The cavern develops more quickly in the upper area. Here, the depths of the inner pipe section and the inner annulus can be variable /KBB 07/,/KBB 11/.

Depending on the intended use of the cavern, a casing is installed more or less deeply in the salt strata, and the borehole is subsequently cemented. Two concentric circulation pipes are suspended into the borehole and flanged above ground. The leaching process starts with the direct leaching method. Here, freshwater into the deepest spot of the borehole via the lower suspended central pipe (Fig. 3.8). The resulting brine is then simultaneously displaced and conveyed to surface the via the second outer pipe section. During the course of cavern formation, circulation is reversed (indirect leaching method). The freshwater then reaches via the annulus into the outer space of the cavern, slowly becoming saturated on the way downwards, and leaves the borehole vial the lower suspended central pipe.

To control the development of the cavern roofs during the leaching process, a protective liquid, the so-called blanket, is injected through the annulus between

borehole casing and the second borehole casing. Owing to its low density, this blanket positions itself above the freshwater and thus prevents vertical leaching.

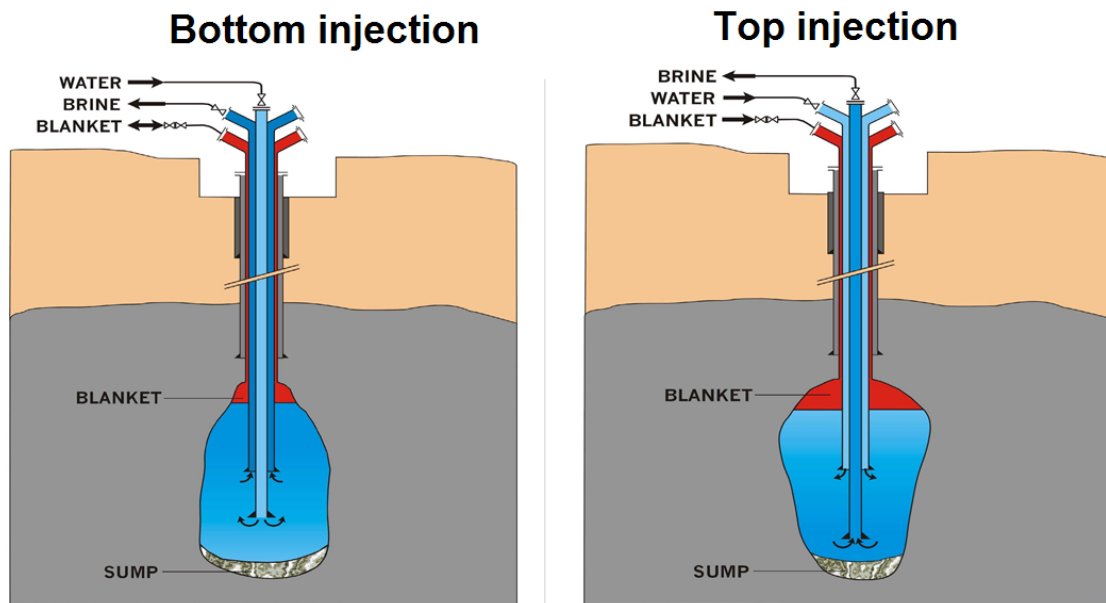


Fig. 3.8 Leaching methods for cavern creation /KBB 11/

With the help of a pipeline system, the brine reaches the processing industry. It serves for the production of soda, washing and cleaning agents as well as plastics. The brine is also used for the production of medical drugs and feedstuffs, preservatives and chemicals for water treatment /KUR 07/.

Emplacement in storage caverns

After leaching, the leaching borehole tubes are withdrawn and replaced with a fill pipe string and an injection pipe string for storage operation. Usual uses in connection with the storage operation of a cavern are the storage of crude oil and natural gas, but the storage of hydrogen and compressed air are also possible uses. In the following, both the storage and the retrieval process are described, using the example of a cavern for the storage of crude oil.

An "empty" cavern will always be filled with brine to prevent high stresses in the rock. With the help of high-pressure pumps, crude oil, for example, is injected through the annulus of the last-cemented borehole casing and the fill pipe into the cavern.

Upon filling of the cavern with crude oil, the brine in the cavern is displaced under pressure and flows via the fill pipe string to the surface, where it is drained off. As the saturated brine cools down on the way up, part of it crystallises and may thus clog up the pipe. In order to prevent this from happening, the brine is diluted. To this end, freshwater is injected into the brine via the injection pipe string.

Retrieval from storage caverns

In the retrieval process, the density difference between the water and the crude oil is used to displace the "light" oil with the "heavy water". The water is injected at low pressure into the cavern via the fill pipe string. The light oil floats on the water and flows to the oil depot, conveyed by the buoyant force. In the course, the water may trigger a leaching process to a limited degree; it will then be saturated with salt before it is discharged into the outlet channel during the next storage process.

Operating phase

From today's point of view, an operating lifetime of the caverns of approx. 100 years is assumed. However, there is no operating experience for such periods available as the use of caverns has only developed over the past 50 years.

Furthermore, the operating phase and the associated work processes depend on the type of use of the cavern. The use of caverns is predominantly aimed at the storage of e. g. crude oil, natural gas, hydrogen and compressed air as well as at the production of salt.

Operational pressures lie below overburden pressure and thus do not lead to fracture or crack formation in the overburden.

Especially due to prevailing favourable rock-mechanical conditions it is possible to realise relatively high operational pressures. For example, natural-gas storage caverns are primarily used for balancing seasonal and daytime peaks in consumption. This type of use places high demands on the availability of storage and retrieval capacities of natural gas. The cavern location in Epe shows e. g. that the individual gas storage caverns can be operated at a maximum inner pressure of up to 250 bar and that therefore correspondingly large volumes of gas can be stored /KUR 07/.

Regulatory requirements by the mining authority as well as requirements by the rock-mechanical conditions at the site regarding the size, shape and extension of the cavern demand monitoring measures, usually in the form of ultrasonic surveying, not only during the leaching phase but also following its conclusion and the final creation of the cavern. Such monitoring takes place at regular intervals to examine any possible changes and ensure the stability of the cavern /TRY 01/.

3.4.5 Closure

Normally, the cavern will be flooded with freshwater or brine or with unsaturated solution. This process is carried out very carefully in order to prevent big temperature differences between brine and overburden, which could cause stress changes at the corresponding depth, and as not to jeopardise the integrity of the closed cavern at a later stage. Alternatively, it is also possible to inject or stow backfill materials (liquid/granular).

Following complete flooding/backfilling and temperature balancing, the borehole is sealed with a plug. Under optimal conditions, independent of the cavity's geometry and depth location, a long-term-stable liquid volume or backfill volume is maintained.

To keep the differential temperature between freshwater or brine and the overburden small, the option of pre-heating the liquid to be injected is also considered. This, however, requires a considerable input of energy due to the necessary amount of liquid.

The development of sealing systems has so far not been concluded yet. Generally, however, the same requirements apply as in the case of the closure of deep boreholes (Chapter 3.3.4). A concrete implementation proposal can e. g. be found in /SCM 06/. According to this proposal, the design of the seal is to be implemented such that it will secure the borehole in a permanently stable and leak-tight manner. This is why each sealing structure is made up of at least two parts: one static load-carrying element and one sealing element. The design proposed in /SCM 06/ is one variant of many different options.

3.5 Construction of a mine

3.5.1 General

In accordance with the different salt bed formations in Germany, today one can find salt beds at depths of between 70 m and more than 1,000 m. The different salt beds formed under arid climatic conditions as they geologically prevailed in central Europe above all in periods of the Permian, Mesozoic and Tertiary eras. Most wide-spread in Germany the salt rock types of the Zechstein subdivision of the Permian. These are cyclical sequences of clays, carbonates, sulphates and chlorides, allowing a distinction of seven major cycles (Z1 to Z7). Other salt beds that are also commercially exploited are located in the area of the Upper Rhine Rift as well as in the alpidic region (Berchtesgaden) (Fig. 3.9). Salt is produced either by mining (dry) or by leaching (wet) of underground salt beds. 14m tonnes of salt are produced annually. Regarding the basic action of "Construction of a mine", only the dry production of rock salt will be considered in the following, as salt production by leaching has already been covered by the basic action of "Creation of a cavern".

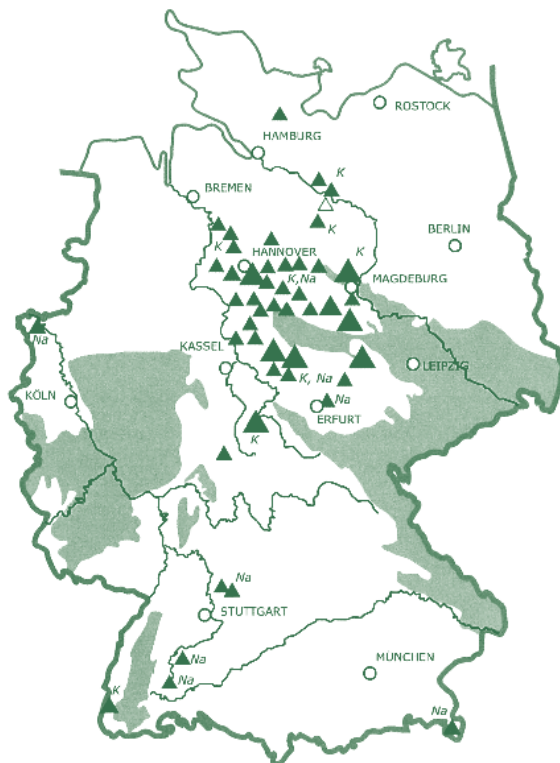


Fig. 3.9 Schematic diagram of the distribution of potash and rock salt production sites in Germany /ZEI 06/

3.5.2 Prospection

In the above-ground exploration of salt beds, the following measurements are usually carried out:

- gravimetric measurements to detect density differences underground that are to resolve the contrast between salt deposit and overburden and adjoining rock,
- geo-electric measurements to detect the salt table with a depth resolution of approx. 200 m – 300 m,
- vibration-seismic measurements with a depth resolution of approx. 800 m – 900 m and
- blasting-seismic measurements with a depth resolution of some 1,000 m.

With the measurements mentioned above, the contour of the salt dome including its rim synclines is measured. Following the measurements carried out from above ground, a decision to sink deep boreholes for further exploration is taken if the results support such action. Here, the definition of a boring grid (e. g. 1 borehole /km²) above the salt dome is common practice, as is the drilling of a borehole into the core of the salt dome. The drillings are effected in the area of the salt rock, usually as core drillings. Regarding the planning, operation and closure of a prospection drilling and the measuring methods used, reference is made to the corresponding explanations with respect to the basic action of "Drilling of a borehole" in Chapter 3.3. In the case of prospection drillings for a salt mine, however, a final depth of 1,500 m is not exceeded since below this depth, profitable mining operation is not possible due to the high ambient temperatures and the convergence as well as due to operational temperature limits, e. g. for electronic systems.

3.5.3 Planning and construction

Following site exploration and the decision to construct a mine, the planning phase includes among a large number of other preparatory work the definition of collars. In line with the requirements of mining law, at least two shafts are planned. In the case of lower mining depths, the construction of a ramp is also possible. Normally, one can assume that the collars for salt mining are chosen central to the salt bed. Apart from the mentioned practical and safety-related aspects, it is above all also the prevailing

site conditions that play an essential role. For example, topographic and infrastructural boundary conditions or existing protected areas or targets can have an influence on the choice of where the collars are to be located.

Before a shaft is sunk, an advance borehole is drilled at the centre of the intended shaft cross-section. Except for the first metres, this advance drilling is executed as a core drilling. Apart from the geological identification of the drill core, the advance drilling can also identify the position and course of the drilling by the possible use of a multi-shot probe. At all events, however, there will be a deviation survey and an examination regarding wet spots or water influx spots.

If the results of the examinations and the advance drilling are positive, the shafts will be sunk. Their final depths depend on a number of factors, i. a. the salt table, the definition of a protective layer of approx. 200 m – 300 m and the type of salt (potash or rock salt). As already mentioned above, however, the focus nowadays is on rock salt alone. What generally applies, though, is the fact that for financial reasons, as shallow salt mining as possible is striven for. The tentative cost of creating a shaft for example has been indicated as approx. 10,000 €/m. Apart from that, with increasing operating lifetime of the mine, there will by nature be clearly higher costs e. g. for the transport of the salt mined at greater depths compared to shallow mining. For the above-mentioned reasons, a mine will as a general rule be developed and exploited from the upper down to the lower-lying strata.

3.5.4 Operation

To produce salt by mining, at least two shafts are sunk for exploiting the salt bed, i. a. for safety-related reasons (second escape route); these shafts will then be linked with each other underground by drifts. From here, salt production is by drilling and blasting or by using cutting techniques.

When mining salt, safety margins have to be provided according to §224 ABVO (General Mining Ordinance, 1996). For example, a distance of 150 m has to be maintained to the flanks of the salt dome. A safety margin to the shafts has not been defined explicitly, but here, too, sufficient distances (shaft safety pillars) are kept to ensure stability of the shaft.

Salt mining is mainly guided by the existing homogenous structures of the salt deposits and the above-mentioned safety margins. Mining operations are controlled in dependence of geophysical measurements accompanying operation.

In German salt mines, the blasting technique is the predominant mining method. As preparation, boreholes of approx. 7 m length are sunk into the salt and filled with blasting charges. For drilling the blast holes, electro-hydraulic drill jumbos are used. The explosive (usually ammonium nitrate explosive) is inserted in loose form into the boreholes with the help of blasting explosive charging machines operating with compressed air and is electrically detonated there.

At each detonation, more than 400 t of salt arise. The broken-up rock salt is moved away either by diesel-driven front-loader dump trucks with vehicle load capacities up to 18 t or by electrohydraulic excavators in combination with skip loaders with vehicle load capacities up to 50 t. The rock salt is crushed below ground and then transported via conveyer belts to the hoisting shaft.

If cutting techniques are applied, electrohydraulic heading machines equipped with two or four cutting rotors (so-called continuous miners) and cutting chains.

The mined rock salt is processed mechanically by fracturing, grinding et al. and prepared this way for further processing. Samples are taken and analysed in the laboratory for quality assurance. The analysis methods usually used for the quality assurance of salt are applied. These include e. g. the optical examination for impurities as well as the determination of the NaCl content and of the other mineral contents. The standard examinations do not, however, include tests for radioactivity.

3.5.5 Closure

For the closure of salt mines, wet closure is usually the chosen method, with the mine being flooded (mandatory in Lower Saxony) and the shafts being closed by complex seals. Hydraulic short-circuits of groundwater storeys have to be prevented in the area of the aquicludes by suitable measures (e. g. by using cements or clays). Apart from wet closure, there is also the option of dry closure of a salt mine /KIß 08/. One such example is the former potash mine at Salzdetfurth, where corresponding shaft seals

prevent an influx of brine into the mine. The chambers were backfilled, while the drifts remained open /WIL 08/.

4 Identification of scenarios of human intrusion into the repository

As mentioned above, the Safety Requirements demand the study of human intrusion into a repository by means of stylised scenarios (HI scenarios). The stylised scenarios make no claim of being comprehensively complete as regards safety for all possible cases of human intrusion. Taking into account the current state of the art in science and technology and current human actions, they rather more identify typical human actions at the site that show a potential of intrusion into the repository. In this context, the spectrum of derived HI scenarios should be reasonably limited /BEU 09/, /BEU 10/.

For the identification of HI scenarios for the Gorleben site, the basic actions described in Chapter 1 are applied and their intrusion potential into the repository is analysed. To do so, the indicators for a possible detection of the repository or of the anomalies induced by the repository and the waste are determined.

For the study of the basic actions, case distinctions are necessary that consider the different possible intrusion locations and types of utilisation of the respective actions. Furthermore, case distinctions are made that take the historical evolution of the repository system into account. Different starting points of the basic activity are taken in to account in the analyses of the cases. In addition, the underlying assumption is that the knowledge about the Gorleben repository site has been lost 500 years after the closure of the repository.

Those cases which under the assumption of today's methods and technologies show a potential of an intrusion and hence of possible consequences form the underlying set for the HI scenarios to be defined. Here, it is not absolutely necessary that each case of the underlying set be considered as HI scenario. For example, enveloping cases or cases that are similar due to their development can be used as representative cases for HI scenarios.

With the aid of the basic actions, the chances of detecting anomalies or unusual features are discussed. This discussion is taken into account in the formulation of the HI scenarios. It also gives some indication of possible starting points for optimisation measures.

Although a repository in deep geological formations in its post-closure phase does not offer any visible clue at the surface to its presence, like e. g. a building structure, it will still leave to posterity some traces in the form of e. g. abnormal or unexpected ambient features deep underground. Such anomalies linked with a repository for heat-generating radioactive waste are:

- porosity, permeability and density differences, brought about by drifting and backfilling,
- direct radioactive radiation in the immediate vicinity of the waste packages,
- increase of temperature in the area of the heat-generating waste over approx. 1,000 years, and
- presence of material such as casks, die-casts, concrete, radioactive waste etc. that is foreign to the formation.

It has to be pointed out, however, that above-mentioned anomalies – except for the last one – are limited in time and that the first two are less clearly marked. For example, if drifts have been backfilled with salt breeze, the porosity, permeability and density differences are only detectable with difficulty in the environment of the surrounding solid rock salt due to the small diameter of the drift. In addition, the properties of the salt breeze backfill will soon assimilate to those of the solid rock salt as a result of the convergence processes, so that for periods of less than 1,000 years /BEU 12/ the mentioned differences will no longer be present or perceivable. As regards with direct radioactive radiation, only gamma radiation is relevant, which should only be detectable as an anomaly in direct vicinity of the waste packages. Moreover, gamma activity decreases considerably after a few hundred years already.

In this context the question arises to what extent such anomalies can be detected at all in connection with the preliminary examinations, technical sequences and processes associated with the basic actions.

In the following, the basic actions will be examined according to the method described above.

4.1 Exploratory borehole

For the Gorleben site, the basic action of "Drilling of a borehole" is assumed. Depending on the location of the boring site, this involves the possibility of an intrusion into the CPRZ. As for drilling actions outside the CPRZ area, influences on the CPRZ are not assumed, or they are covered in their effects by the scenario of the direct drilling into the CPRZ. They will therefore be not considered any further. The intrusion into the CPRZ, on the other hand, does have safety-related implications and is pursued further.

4.1.1 Detection of a repository during above-ground examinations

Exploratory drillings are seen to take place mainly in connection with the prospection of oil, gas and salt deposits. Furthermore, exploratory drillings are linked with the creation of caverns and mines, with geothermal energy production, and with storage uses. It has to be pointed out, however, that exploratory boreholes are also sunk for scientific purposes.

The search for suitable locations for the exploitation of natural resources and for geothermal energy production as well as the utilisation of the storage capacity of certain types of rock is associated with a high financial risk and effort. To minimise the risk, comprehensive surveys with the aim of delimiting areas of potential exploitation or storage sites are carried out before a decision to sink an exploratory borehole is made.

A first step towards finding suitable boring sites is the evaluation of geological records, maps and geological outcrops above ground as well as the study of the bore logs of already performed deep drillings. As an accompanying measure, aerial photographs are also evaluated. For the identification of favourable underground structures, different geophysical methods are used that have been described in Chapter 3.3.2.

In discussions with experts from industry (see Annexes A.1, A.2 and A.3) and the authorities about the chance of a detection of the repository it was found that the salt structure including the rim synclines would be identified by the measures mentioned. The repository and especially the casks, however, would not be detected as anthropogenic anomaly due to the great depth and the associated signal attenuation by the overlying strata.

4.1.2 Detection of a repository during the drilling of a borehole

In the following, the question of a possible detection of anomalies in connection with the sinking of an exploratory borehole is discussed. Here, a case distinction has to be made for the further treatment of the issue of whether the detection probability of the repository is high or which optimisation measures exist to increase the detection probability. From the large number of potential intrusion locations into the CPRZ, six different options can essentially be derived with regard to the resulting consequences. These are graphically represented in Fig. 4.1. The cases mainly differ from each other in whether a storage cask has been bored into, whether the borehole runs through the repository in direct proximity of the waste, whether the borehole runs through the CPRZ without touching any elements of the former mine (e. g. drifts). In principle, all the cases described can occur, but the determination of a relative frequency of the cases with consideration of different area ratios of casks, emplacement drifts, drifts without waste storage casks and areas outside drifts is dispensed with. Owing to the lacking possibility of making predictions, all cases have to be considered as equal with regard to their occurrence.

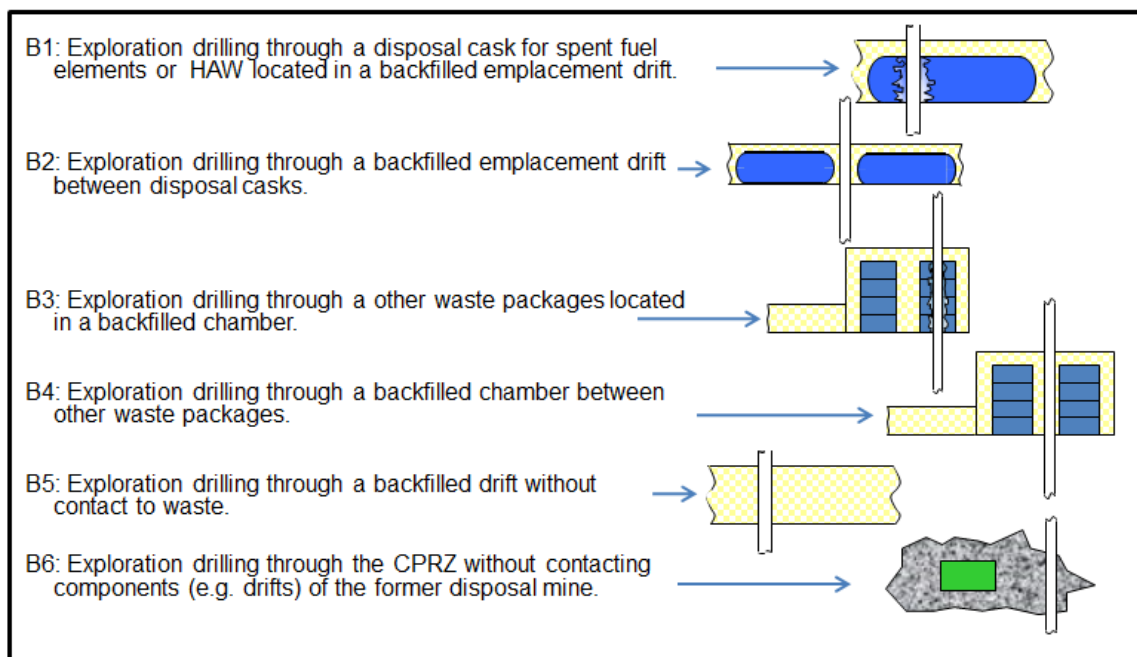


Fig. 4.1 Case distinctions (B1 to B6) for the basic action of "Drilling of a borehole"

Case distinction

In the further work towards answering the general questions of the possible detection of anomalies, talks were held with experts from the industry and the authority to identify the state of the art in science and technology in connection with the execution of exploratory drillings (Chapter 3.3).

The results of the meeting with the representatives of mining companies, which were recorded in an agreed memo, are given in Annex A.1. In the following, the essential statements on the detection probability of the unusual features brought about by the repository are presented.

From these expert discussions, the following indicators have emerged that can be used for the identification of unusual features:

1. high wear of the drilling equipment (cutter head, drill bit), deflection of the advance of the drill as a result of hitting a waste container,
2. loss of drilling fluid,
3. unusual features of the drill cuttings, in drill cores or in the drilling fluid,
4. physical anomalies in the borehole environment (density, porosity, temperature, natural radioactivity, etc.) and
5. examination of the borehole geometry (clear width, inclination, etc.).

In the following, the essential statements of the discussion regarding the detection of unusual features are used and applied to the different cases.

To 1. If one assumes largely intact, thick-walled POLLUX casks (Case B1, Fig. 4.1), the drill bit will either be rendered useless or strongly deflected when hitting on a cask wall made of steel that is thicker than 2 cm. In any case, the advance of the drill will be interrupted or considerably reduced. Both would immediately be registered and give rise to corresponding examinations (see above list item 4, as the case may be also 3.). This case does not apply in the event of an encounter of thin-walled casks for radioactive waste with negligible heat generation (B3). Here, an accelerated advance of the drill may rather more indicate the presence of less dense material of increased porosity (see above list item 2.).

To 2. In addition to an accelerated advance of the drill, the intersection of a layer of increased porosity generally also involves a greater loss of drilling fluid. In the case of a backfilled emplacement drift or chamber (B2, B4, B5), the detection probability of the anomaly is estimated to be low due to the loss of drilling fluid since at the point I time $t > 500$ years, the compaction of the backfill is far advanced. Here, analogous to the above-mentioned 3D seismic interpretation method, it also applies that the detection probability is further reduced with advancing convergence of the emplacement area. The drilling into an emplacement drift only in the backfilled area, i. e. between the casks (B2, B4), would probably go unnoticed if backfill material of similar type as well as similar density and porosity as the surrounding rock is used.

To 3. When sinking a borehole, the eroded drill cuttings are regularly examined by geologists on site. Any material of a foreign kind, as it would be encountered when drilling into waste containers (B1, B3) or technical structures with dissimilar materials, would be noticed with great certainty, and the indications of an anomaly or anthropogenic activities would be perceived. The same applies to the drill cores extracted for further examinations (here, too the penetration of not fully compacted backfill (B2, B4) would be noticed). Any dissimilar material in the drill cores originating from a repository would most probably be detected, and investigations into their origin would be initiated. The drill cuttings accumulated at the boring site is taken to a dump. Upon arrival at the dump, samples are taken, and the mineralogical composition is analysed in the laboratory. The identification of any so far undetected contaminated material is considered to be highly likely. The same is true of the disposal of the drilling fluid.

To 4. Unusual features caused by the presence of a repository are e. g. temperature development, gamma radiation, density changes. For example, if there were any ionising radiation, this would be identified by the gamma log, which is part of the standard measurements, once the borehole has reached the direct vicinity of the casks. Also, temperatures that are increased compared with the normal ambient temperature, which would be caused by the heat-generating waste, would be noticed if the point in time is less than 1,000 years after the closure of the repository. Other methods belonging to the standard, such as density log, sonic log and resistance log can also contribute to the detection of anomalies or unusual features. It can be assumed that anomalies in cases B1 to B4 will be detected as a result of the unusual features noticed in the exploratory borehole.

In case B6, in which the borehole is sunk without touching on any elements of the former mine, it can be assumed that no anomaly indicating a repository will be detected as the emplacement drifts are located at too long a distance for being detected by geophysical measurements and as there will also be no other indications of the existence of any anthropogenic influences (e. g. increased porosity in backfilled drifts).

To 5. While a borehole is sunk, the inclination is recorded in the process. In case B1, it is assumed that presuming the container is intact, the drill will be deflected. This unusual feature would certainly be noticed. In case B3, also presuming containers or waste packages that would represent a resistance, a deflection of the drill cannot be excluded. However, due to the low strength of the container wall and the assumed early failure of the containers due to the convergence of the rock salt, any associated unusual feature will only be slight or latently present for a phase that is relatively short compared with the safety demonstration period.

4.1.3 Derivation of a stylised scenario regarding the basic action "Drilling of a borehole"

Based on the analyses of the drilling and examination activities in connection with an exploratory drilling, one can state that if a waste container is damaged by the drill and the gamma log is subsequently evaluated, the repository will be detected by those acting as an anomaly and potential hazard. The same will be true if the drill merely touches on the containers. The registration of the temperature anomaly is limited to a period of approx. 1,000 years. A similar time-span applies to the recognition of the backfill due to its higher porosity (drilling fluid loss, density difference) in the emplacement areas compared with the intact salt rock.

In summary, a stylised scenario "Exploratory drilling" can be derived:

A cased exploratory borehole is sunk through the Gorleben salt structure, lying within the CPRZ and not leading to the detection of the repository.

The stylised scenario "Exploratory drilling" is also part of the analysis of the other basic actions (Chapters 4.2 and 4.3). The further discussion of the HI scenario is oriented on cases B1 to B6.

In any future prospection for hydrocarbons, exploratory drillings that will be sunk into the Rotliegend below the salt dome are imaginable. In the area of the salt structure, an extension of the borehole is necessary to counteract an undesired closing of the borehole through the convergence of the salt. Here, the salt will tightly envelop the casing on the outside. A release of radionuclides from the repository during the time of production drilling would thus be prevented. Even if one assumes that during the course of the closure of the borehole the casing were to be withdrawn, according to /OCZ 98/ the borehole would still have to be backfilled at the bottom and in the roof of the salt structure along special backfilling sections measuring at least 100 m in the salt and 50 m in the adjoining rock (Chapter 3.3.4). Hence, no releases over longer periods and with considerable effects need to be assumed, neither during the operation nor after the closure of the borehole. Safety-relevant scenarios thus only ensue for the phase of the sinking of the output well.

4.2 Cavern

For the Gorleben site, the basic action of "Creation of a cavern" is taken into account. Depending on the boring site, planned depth and dimensions of a cavern, an effect on the CPRZ is possible. Depending on the kind of use (e. g. storage and salt production) of the cavern, the influence on the repository system may vary.

If a cavern were planned for disposing of residual or waste materials or for the final disposal of radioactive or hazardous chemical waste, it can be assumed that there would be a comprehensive examination of the site during which a repository established in the past would be discovered. This kind of cavern use is therefore not considered any further.

In addition, it is quite usual that several caverns are created at single site. For the purpose of this study, this circumstance is not relevant as the consideration of just one or several caverns will not yield any different possible optimisation measures. Hence, only one cavern is assumed in the following.

With the basic action to be examined here, there are generally two possible ways of intruding into the CPRZ. One is the drilling of prospection boreholes prior to site exploration. If the exploratory drillings have not resulted in the identification of the repository as an anomaly, there is the other possibility that intrusion into the CPRZ

might take place during the course of the leaching of the cavern. As the safety-relevant aspects in connection with a human intrusion into the repository system by exploratory drilling have already been comprehensively dealt with in Chapter 4.1, the further deliberations will mainly deal with the aspect of human intrusion into the CPRZ by the creation, operation and closure of a cavern within the Gorleben salt structure.

4.2.1 Detection of a repository during above-ground examinations

The statements made in Chapter 4.1.1 about the chance that the repository is detected during above-ground examinations apply analogously to examinations of suitable cavern sites. For the study of the geological structures, standard gravimetric, geo-electric and seismic measurements are performed prior to the creation of caverns (cf. Chapter 3.4.2).

4.2.2 Detection of a repository during the creation and operation of a cavern

In the further course of this study, the question of the intrusion potential and a possible detection during the creation and operation of a cavern as a result of the anomalies or unusual features induced by the repository is discussed. As regards the clarification of the issues, case distinctions have to be made. Regarding the impact on the CPRZ, different basic types can be distinguished; these are shown in a diagram in Fig. 4.2. Essentially, the cases differ by whether the creation of the cavern could affect the CPRZ either directly (cases C1 – C3) or indirectly (case C4).

Case distinctions

Although in **case C1** the cavern lies outside the CPRZ, the feeder pipe of the cavern penetrates the CPRZ. This case is similar to cases B2, B5 or B6 regarding the sinking of an exploratory borehole (see Chapter 4.1.2 and Fig. 4.1). Due to this analogy, this case is covered by the established HI scenario relating to exploratory drillings as well as by cases C2 to C4 below. A special consideration of case C1 is therefore not necessary.

Case C2 describes the creation of a cavern that crosses the entire CPRZ in vertical direction. Owing to the usual dimensions of caverns and the planned variant B1⁴ /BOL 11/ this could also affect several emplacement fields.

Case C3 is similar to case C2. Here, however, the cavern does not penetrate the entire CPRZ in vertical direction but intersects the CPRZ in parts without touching the emplacement fields. From the point of view of possible resulting consequences, case C3 is covered by case C2.

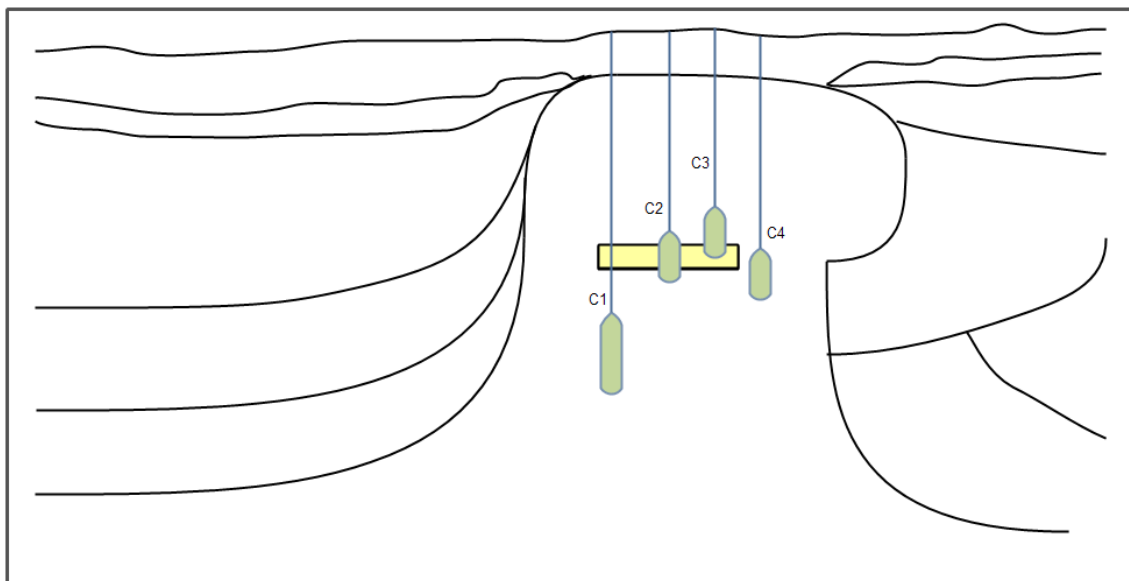


Fig. 4.2 Case distinctions (C1 to C4) for the basic action "Creation of a cavern" (yellow area symbolises the CPRZ)

In **Case C4** there will be no direct safety-related consequences for the repository system as the CPRZ remains untouched. However, the wider host rock in the environment of the CPRZ, which represents a further barrier, will be affected by the leaching process for cavern creation. The flooding of the cavern with freshwater or unsaturated brine that is usually performed during its closure leads furthermore to a considerable presence of solution in the environment of the CPRZ. Moreover, it is imaginable that there may be a link between the CPRZ and the cavern due to circumstances related to the cavern's creation, operation or closure. Since from a

⁴ Variant B1 (emplacement of heat-generating radioactive waste in self-shielding repository casks in horizontal drifts) must not be confused with case distinction B1 of the exploratory borehole.

safety-related point of view case C4 is covered by case C2, in which the cavern fully penetrates the CPRZ, case C4 will not be considered any further in this study.

The case in which a cavern reaches into the area of the shafts of a repository need not be assumed as according to the site criteria for the creation of a cavern only homogeneous salt beds may be considered (here the main salt of the Staßfurt series).

For the above reasons, case C2 is considered as also covering cases C1, C3 and C4.

In further dealing with the above-mentioned question of whether any unusual features might be detected in connection with the creation and operation of a cavern, this was discussed with experts from the industry and the authority (see Chapter 3.4).

The results of the meeting with representatives from the cavern construction industry and the mining authority, which were recorded in an agreed memcon, are given in Annex A.3.

The following indicators that can be applied for the identification of unusual features have emerged from the expert discussions:

1. storage losses due to pathways through abandoned mines,
2. pressure drop upon encountering cavities,
3. pressure peaks caused by e. g. the sliding or dropping of a fuel assembly cask into the cavern sump, and
4. structural differences or objects (e. g. repository casks) detected upon the standard recording of the contours of the cavern by sonar measurements.

It furthermore became clear from the technical discussion which possible conditions or unusual features would presumably not be detected by procedural steps in connection with the creation of a cavern or associated studies (see also Annex A.3):

- The composition of the brine conveyed to the surface is only checked for dissolved salts (anions, cations), solids and pH-value, but not for radioactivity. A possible contamination of the brine would thus not be detected during standard quality assurance testing in the laboratory.

- The heat emitted by the waste will not have any noticeable effect on the large volumes of water used in the leaching process, so that the temperature anomaly will presumably remain unnoticed.
- If there were leaky or defective casks in the cavern, radioactive gases would be released immediately and rise to the top of the cavern, mixing with the cavern's sealing medium (mostly nitrogen or oil), the so-called blanket. The radioactivity within the blanket would probably go undetected.
- In connection with the storage of gaseous media in the caverns, e. g. natural gas, samples are taken and analysed which, however, are not expected to lead to the detection of gases that would be released by repository components. There are no examinations for radioactivity provided.

In the following, the central statements of the discussion regarding the detection of unusual features are applied to case C2:

To 1. The water pathways existing in the initial phase following the closure of the repository refer to the excavation-disturbed zone in the salt caused by the driving of drifts and the as yet not sufficiently compacted salt breeze backfill of the underground workings. With progressing time, these pathways will largely reduce as a result of healing processes in the excavation-disturbed zone and due to compaction of the salt breeze backfill brought on by convergence processes. For the above-mentioned reasons and assuming that any intrusion will not take place until after 500 years at the earliest, no noticeable storage losses during cavern operation are expected.

Larger storage losses, if any, may only occur in the infrastructure area of the repository as this is backfilled with crushed rock. This area would, however, not be considered for a cavern site as it is situated outside wider homogeneous rock salt deposits.

To 2. Analogous to 1., no cavities resulting from the repository need to be assumed that would give rise to a noticeable pressure decrease due to the creation or operation of a cavern. The only exception is once more the infrastructure area that is backfilled with crushed rock of little subsidence. However, as stated before, this area is not suited for creating a cavern.

To 3. Repository casks that are uncovered when a cavern is created during the leaching process and which slide or sink down into the cavern sump will probably cause a pressure pulse due to their weight which can be registered.

To 4. In the cavern sump, there are usually the insoluble or not readily soluble constituents of the rock salt, e. g. anhydrite, that arise during the leaching process. If as a result of the leaching process there are one or several repository casks present in the cavern sump (see 3.), these could be perceived as objects foreign to the structure in the prescribed regular measuring of the cavern's geometry.

4.2.3 Derivation of a stylised scenario regarding the basic action "Creation of a cavern"

In summary, a stylised scenario "cavern creation" can be derived regarding the basic action "Creation of a cavern":

Following prior site exploration and the sinking of an initial exploratory borehole that will later be extended by corresponding borehole tubing for the leaching process, a cavern is created in the Gorleben salt dome by leaching for the purpose of storage (mineral oil, natural gas, hydrogen, compresses air) or salt production, fully penetrating the CPRZ and thus also touching emplacement fields. Neither the site exploration nor the sinking of the exploratory borehole leads to the detection of the repository. For the cavern, current common dimensions and operating lifetimes shall be assumed.

The HI scenario defined here assumes that the site exploration to be carried out according to today's standards for the creation of a cavern is executed comprehensively. Any unusual features in this phase would lead to further clarifying examinations. The further discussion of the HI scenario is oriented on case C2.

After the above-ground site exploration procedures, there will be at least one exploratory drilling, which will be extended later on for the leaching of the cavern if the site has been found to be suitable. As regards the borehole that is drilled for the leaching of the cavern, the corresponding HI scenario of Chapter 4.1.3 (Exploratory borehole) is to be applied as a basis and examined. Any possible unusual features during the exploratory drilling (cf. Chapter 4.1.2) would also entail further investigations

for clarification. The further sequence of the basic action "Creation of a cavern" would then no longer have to be assumed.

Hence, for this HI scenario, the phase of the creation of the cavern by the leaching process and the phase of cavern operation have to be discussed separately. The points of discussion have to be oriented along the possible consequences and a possible detection of unusual features, taking into account the usual construction-related, conceptual, operational and accompanying phases of the work involved in the basic action.

The creation of a cavern itself is relatively independent from its kind of use, which means, that the working steps involved in the leaching process are generally always the same. The operation of the cavern, on the other hand, depends strongly on the later form of utilisation. Here, the corresponding differences have to be worked out.

Taking into account possible cavern dimensions mentioned in Chapter 3.4.3 (e. g. diameter from 40 m to 100 m) and the plans for drift emplacement, using the example of POLLUX-10 casks /BOL 11/, the estimate of a reference consideration yields a maximum of 25 casks from 3 emplacement drifts that might be affected by the leaching process. Here, as in the "Exploratory borehole" HI scenario, it was assumed that no unusual feature is detected during the drilling. With the other waste, the maximum possible number of casks affected by the leaching process will be even higher due to the shorter distances of the drifts and between the casks (see Table 4.5 in /BOL 11/).

Finally, the phase following the closure of the cavern also has to be discussed regarding possible consequences and a detection of unusual features.

4.3 Mine

Regarding the current identified human actions, the basic action "Construction of a mine" has to be considered with regard to an inadvertent human intrusion into the CPRZ. As already described Chapter 3.5.1, the further considerations in connection with this basic action will look at the dry, mechanical production of salt, while wet salt production is already covered by the basic action "Creation of a cavern". Moreover, the construction of a mine for the dumping of residual and waste materials or for the disposal of radioactive waste or hazardous chemical waste will not be considered any

further either as it can be assumed that there will be a complete site examination to avoid contamination of the subsoil and that in this connection a repository established in the past would very likely be detected.

Generally, there are two possible ways of intruding into the CPRZ with this basic action. One is prospective drilling carried out prior to the driving of the mine for exploring the deposit. If the repository is not identified as an anomaly by the exploratory drillings, there is still the possibility of an intrusion into the CPRZ by the exploratory work itself. Since the safety-relevant aspects in connection with human intrusion into the repository system have already been comprehensively dealt with in Chapter 4.1.1, the further considerations will be restricted to the aspect of human intrusion into the CPRZ by the underground mining activities, i. e. by the excavating of access drifts and chambers within the Gorleben salt structure.

4.3.1 Detection of a repository during above-ground examinations

Regarding the chances of the repository being detected in the course of surface exploration, what has been stated in Chapter 4.1.1 with respect to exploratory boreholes applies correspondingly. Hence in summary it can be concluded that although the mentioned prospection methods would cover the salt structure including the rim synclines, the repository and especially the casks would not be detected as an anthropogenic anomaly owing to the depth and the associated signal attenuation by the superposed strata.

4.3.2 Detection of a repository during drifting and operation of a mine

In the following, the question of a possible detection of the anomalies during the course of the sinking of shafts and the excavating of access drifts or chambers is discussed. Here, as in the case of the other basic actions, the results of discussions with mining company representatives will be taken into account; the former are contained in the memcon in Annex A.2. In the following, the essential statements on the detection probability of the unusual features linked to the repository are singled out.

Regarding the question of how high the probability of the repository being detected during these actions is or which optimisation possibilities exist to increase the detection probability, a case distinction has to be made as with in the other two basic actions.

Here, different possibilities can be derived regarding the question of whether or in which way the CPRZ will be impaired; these are presented in Fig. 4.3.

The different cases presented can be described as follows:

- S1: Excavating of the mine outside the CPRZ
- S2: Excavating of the mine outside the CPRZ, shaft penetrates the CPRZ
- S3: Excavating of the mine within the CPRZ

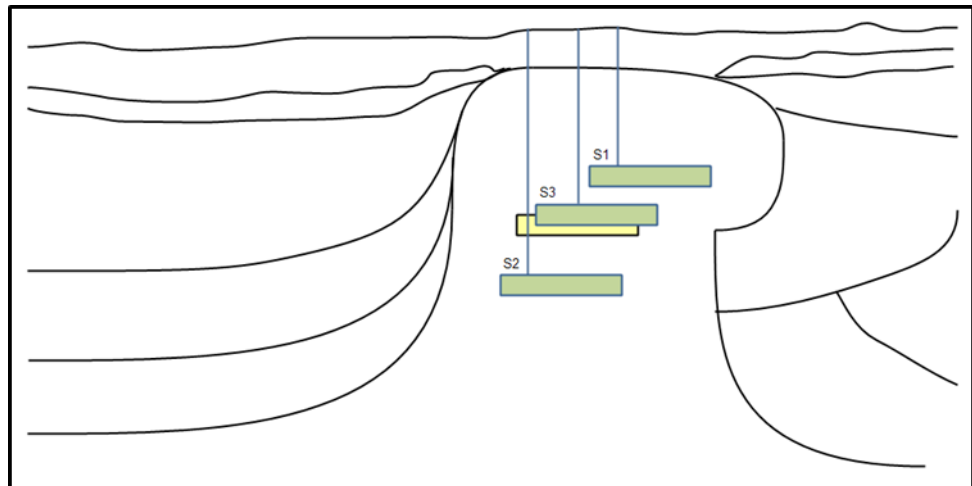


Fig. 4.3 Case distinctions (S1 to S3) for the basic action "Construction of a mine"

In **case S1** there ensue no direct safety-related consequences for the repository system since there is no intervention into the CPRZ. However, in the roof area of the CPRZ, the other host rock, which represents an additional barrier, is affected by the drifting of the cavities. The usually performed flooding of the mine with NaCl solution after its closure leads furthermore to the presence of considerable amounts of solution in the roof of the CPRZ. However, as this case in even more adverse form is covered by case S3, in which the drifted cavities lie directly within the area of the CPRZ, case S1 will not be separately dealt with in the following.

Case S2 corresponds in principle to the case of an exploratory borehole that penetrates the CPRZ without touching any elements (e. g. drifts) of the former mine (cf. Chapter 4.1.2, case B6). For the same reasons, it need not be assumed that the repository mine will be detected as an anomaly. Even though the diameter of the shaft is considerably larger than that of an exploratory borehole, the consequences are

similar to those described in Chapter 4.1.2. Owing to the closure of the shafts with seals towards the roof and the floor, any sustained damage is not very likely. As from a safety-related point of view this case is much more favourable than case S3, case S2 will also remain unconsidered in the following.

Case S3 is the most safety-relevant one among the cases mentioned above. Hence the further deliberations will concentrate on this case. Depending on which parts of the emplacement areas are driven into, which driving techniques are applied and how far the corrosion of the waste containers has advanced, further variants can be derived.

The following indicators have emerged from the technical discussions which can be used to identify unusual features:

1. high degree of wear of the cutting equipment (cutting tools, milling head) and stopping of the drifting advance or stopping of the advance of the drill in connection of the preparation of blasting boreholes
2. exposure of cask surfaces
3. accelerated advance of the drill in connection with the preparation of blasting boreholes due to little boring resistance
4. detection of materials other than salt
5. geophysical anomalies in direction of the excavation, if applicable.

It furthermore became clear from the technical discussion which possible conditions or unusual features would presumably not be detected by procedural steps in connection with the construction of a mine (see also Annex A.3):

- The repository would probably not be detected as an anomaly by the prospecting drilling unless the drill were to enter directly into an emplacement area or directly into a cask. The reason for this is that the geophysical exploration methods such as gravimetric and geo-electrical examination are not used in a borehole in connection with the prospecting for salt.
- Before the shaft is created, an initial drilling is performed in the middle of the prospective shaft. Except for the first metres, this drilling is carried out as a core drilling. In addition, borehole measurements are carried out regarding its course, deviations etc., which do not lead to the detection of any anomalies.

- Samples are taken from the extracted salt and analysed in the laboratory. The quality assurance analysis procedures usually applied to salt are employed. However, even in the case of a release of radionuclides from the waste packages, the standard procedures would not be able to identify any radionuclides.

In the following, the key statements are discussed regarding the above-mentioned indicators for the detection of unusual features, taking the distinctive case S3 into account:

To 1. In salt mining, the usual mining machine used is the so-called continuous miner. It would certainly be noticed if the rotating cutting tools or the milling head were to hit on an intact POLLUX cask. The hitting of other container types, too, involves a resistance in the advance of the drill, which could lead to the perception of an unusual feature. In all cases, this perception depends, however, on the resistance posed by the container and hence on the containers' toughness characteristics at the corresponding time of penetration.

In the case of borehole blasting, preparatory boreholes of approx. 7 m length are drilled into the salt, with explosive charges being inserted into them. As regards the drilling technique, the same applies as in the case of the above-mentioned cutting method. This means that an increased resistance compared with that of the rock salt would be noticed if the drill were to hit on a container.

To 2. With both methods of driving drifts (cutting and blasting technique) there is the possibility that the repository casks will be uncovered. This also means that the surfaces of the casks would become visible and thus detectable.

To 3. In the initial phase following the closure of the repository, the salt breeze backfill of the mine workings has not yet sufficiently compacted. With progressing time, these pathways will largely form back or reduce in size due to healing processes in the excavation-damaged zone and the compaction of the salt breeze backfill caused by convergence processes. For the reasons mentioned above and under the assumption of an earliest possible moment of intrusion after 500 years, it is not expected that there will be any noticeable acceleration of the advance of the drill as a result of less solidified salt breeze backfill material as opposed to the drill's advance in rock salt.

In the area of the shafts and the former infrastructure area of the repository, non-compactible gavel is used as backfill material. Here, a change in the acceleration of the advance of the drill might be perceived. However, the crushed rock – being a foreign material compared to the surrounding environment – presents a much more noticeable unusual feature than a possible change in the acceleration of the drill's advance.

To 4. In the area of the shafts and the former infrastructure area of the repository, non-compactible gavel is used as backfill material, which – being a foreign material compared to the surrounding environment – would be noticed during the creation of caverns.

In certain areas of the repository, there will remain anchor points or internals that will not have been dismantled. Such relics may be detected during salt mining.

Further unusual features due to the casks are not discussed in any further details here as this aspect has already been addressed (see 2.).

To 5. Salt mining is mainly governed by the present homogeneous structures of the salt deposits and by the required safety margins, e. g. to the flanks of the salt dome. Mining is controlled dependent on the results of accompanying geophysical measurements that are performed during operations. This means that the identification of any salt structures that are not homogeneous has a strong influence on the directional orientation of the mining of the salt and that these structure may possibly be bypassed. Here it cannot be assumed that the reason for an inhomogeneous structure will be investigated.

A further unusual feature may be given by the heat-generating waste. this means that a temperature anomaly would be noticed when driving a drift. However, noticeable temperature differences will only prevail for a limited period. This period would be even further narrowed by the boundary condition that a human intrusion into the repository is only assumed to occur after 500 years following the closure of the repository at the earliest. It may furthermore be assumed that any temperature anomaly would have already been identified in the course of the exploratory drillings, as the drilling of a borehole into the central part of the salt dome is quite usual during the exploration of the site with a view to salt mining.

4.3.3 Derivation of a stylised scenario regarding the basic action "Construction of a mine"

Based on the technical discussions (see Annex A.2) and the above considerations, the following stylised scenario "Mine construction" is derived for the basic action "Construction of a mine":

After prior comprehensive site exploration and several exploratory drillings that will later partly be expanded as transport and ventilation shafts, a mine is constructed in the Gorleben salt dome for the purpose of mining salt, reaching the CPRZ and the emplacement fields. Neither site exploration nor exploratory drillings lead to the detection of the repository. For the mine, exploitation from upper to lower levels as well as today's usual operating times are to be assumed.

The defined HI scenario is based on the assumption that the site exploration to be performed according to today's standards for the construction of a mine will be comprehensive. Any unusual features in this phase would lead to further clarifying examinations. The further discussion of the HI scenario is guided by case S3.

Following the above-ground site exploration, there follow a number of exploratory drillings. Some exploratory drillings are executed as deep drillings, with at least two boreholes used for shaft expansion if the site proves to be suitable. As to the exploratory drillings, the corresponding HI scenario described in subsection 4.1.3 is to be applied as a basis and analysed. Any unusual features in this phase would also lead to further clarifying examinations. In this case, the further sequence of the basic action would no longer have to be assumed.

Hence for this HI scenario, the phase of the construction of the mine by the drifting process and the phase of operation of the mine have to be discussed separately. The contents of the discussion have to be focused on possible consequences and a possible detection of unusual features, taking into account the usual construction-related, conceptual, operational and accompanying working steps of the basic action.

Finally, the phase following the decommissioning of the mine also has to be discussed regarding possible consequences and a detection of unusual features.

5 Optimisation measures

The study of the HI scenarios regarding the identification and assessment of possible optimisation measures is carried out in three steps (see Fig. 5.1).

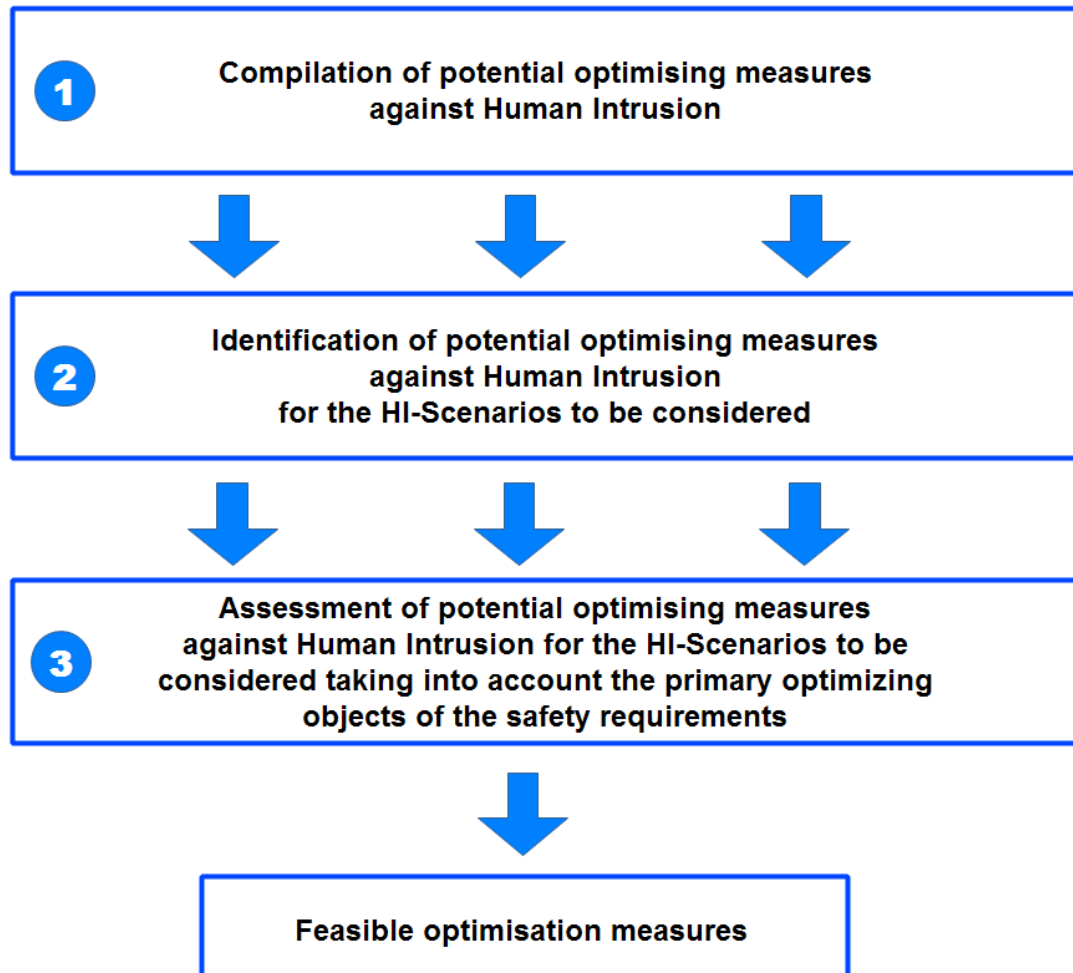


Fig. 5.1 Procedure of deriving and assessing optimisation measures against human intrusion

In the first step, possible optimisation measures are compiled that refer to the general optimisation objectives, a reduction of the probability of human intrusion, and the radiological consequences for the general public (Chapter 5.1). However, it is not possible to determine any probabilities in the mathematical sense for the inadvertent human intrusion into the CPRZ.

In the second step, it is checked for the HI scenarios defined in Chapter 4 which if the optimisation measures identified in Chapter 5.1 come into question in each case (Chapter 5.2).

In the third step, the optimisation measures coming into question for the HI scenarios are examined with regard to whether they are in conflict with the primary optimisation objectives of the Safety Requirements (Chapter 5.3).

If there is the possibility to make a quantitative assessment of the HI scenario before and after the consideration of counter-measures, the corresponding case has to be modelled and analysed. The idea behind this is the assessment of the possible success of the optimisation e. g. by comparing suitable indicators, which have to be quantified for the condition before and after the consideration of the measure.

In this context it has to be noted that the Safety Requirements of the BMU (/BMU 10/, subsection 6.5) do not specify any value for reasonable risks or reasonable radiation exposure levels for developments triggered by an inadvertent human intrusion into the CPRZ.

5.1 Compilation of possible optimisation measures

The technical discussions in the past about possible measures to prevent a human intrusion into the repository or to increase the chance to detect the repository eventually led to the insight that the risk of human intrusion into a repository can only partly be reduced /BEU 08/, /EUR 11/. The concept pursued of concentrating and isolating the radioactive waste in deep geological formations includes inherent measures against human intrusion. On the one hand, it reduces the floor space requirements of a repository and makes access to the waste difficult owing to the depth at which it is stored. On the other hand, by deciding in favour of this concept one inevitably has to accept the possibility that in the event of a human intrusion into the repository, those acting may suffer high radiation exposure. Any further-reaching structural measures depend on the host rock and the pertaining repository concepts as well as on the underlying HI scenarios.

The generally possible optimisation measures have different starting points and can be allocated to the general HI optimisation objectives, as shown in Fig. 5.2.

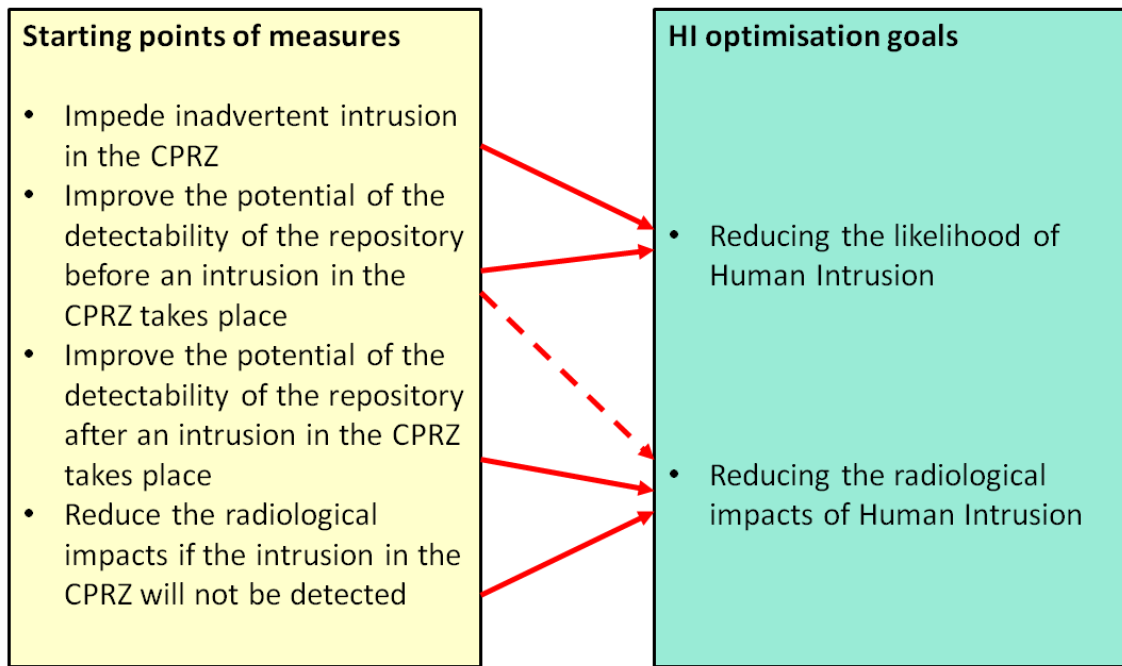


Fig. 5.2 Possible optimisation measures and allocation to the general HI optimisation objectives

Certain optimisation measures are aimed at warning those acting in the future that there is an abnormal situation to be encountered deep underground so that they will take due care in carrying out their next steps.

Measures that improve the chances of detecting the repository before an intrusion into the CPRZ has taken place are to reduce the probability of human intrusion. The assumption is that the future acting individuals will assess the situation and subsequently cease all further activities in the deep underground at the site without touching the CPRZ. In a broader sense, a reduction of radiological consequences is also given by an early detection of an unusual feature and its corresponding interpretation as well as by the respective measures derived.

In contrast, measures facilitating the detection of the repository or the realisation of its danger potential after intrusion into the CPRZ have to be allocated to the limitation of the radiological consequences. Here, the assumption is that the future acting individuals will give up their respective projects and ensure a heavy-duty seal of the access to the CPRZ by suitable technical structures.

Other measures are to serve for the limitation of the potentially resulting radiological consequences of a human intrusion into the CPRZ without detection of the repository by way of conceptual measures. This aspect also includes the delaying of the point in time of the intrusion for as long as possible by suitable measures.

Measures that are already part of current repository plans and concepts and which counteract a future human intrusion are to do with

- the deep location of the emplacement areas and
- the preservation for as long as possible of information about the location, geometry and inventory of the repository. Here it has to be ensured that the information about the repository and its danger potential are preserved and that they will also come to the knowledge of the acting society if activities are planned at the site.

In /BUS 10/ potential measures discussed among experts are compiled. These are aimed primarily at increasing the chance of detecting the repository, like e. g.:

- marking with strong magnets
- use of radiation markers with a selection of radioactive isotopes
- acoustic warning signals (e. g. devices generating strong echoes)
- marking of the waste containers with radiation symbols by conventional pictographic means
- use of spherical objects that could be detected geophysically as anthropogenic anomalies (also as marking on at the surface, e. g. use of a large number of shards or ceramic objects)
- use of materials that will stop or considerably impair the advance of driving or drilling
- use of dyestuffs indicating the presence of an (anthropogenic) anomaly.

Some of these measures, however, will only be effective after a human intrusion into the CPRZ.

A further, albeit temporally restricted preventive measure that is being discussed internationally is institutional control. A prediction of the effectiveness of such

supervision measures over a period of more than 500 years is not possible, though, as this would require a prediction of human society and its behavioural patterns over a period of more than 16 generations.

Furthermore, there are frequent calls for choosing a repository site far away from any location of natural resources /NEA 92/, /NEA 95/. This measure does not apply to the VSG as the site is predetermined. However, it has to be noted with regard to this measure that the perception of the value of goods and raw materials as well as of their demand may be changeable over periods like the demonstration period. This means that raw materials which from today's point of considered view are worth mining or exploring may at some later state be of less or no interest or *vice versa*. It may, however, be assumed that the habits of humans and their demand for today's raw materials will not change fundamentally for a short period after the closure of the repository. This aspect may possibly be taken into account by corresponding provisions ensuring the preservation of information and the knowledge about the repository site. However, a long-term prediction about which substances or materials will be considered as raw materials and natural resources by future generations is not possible /BEU 10/.

The question of whether optimisation measures can be identified in connection with the HI scenarios to be considered that would facilitate the recognition of the repository as an anomaly and possibly as an indication of earlier anthropogenic intervention in the underground (former mining) was analysed systematically. In addition, measures were sought which – should the repository not be discovered- can reduce the radiological consequences of a human intrusion. Imaginable optimisation options under the aspect of human intrusion into a repository have been compiled in a table (Annex A.2). This table, which was drawn up on the basis of a collection of ideas, the expert discussions with industry and authority representatives and several references such as /BUS 10/ contains not only the compilation of possible measures but also a range of attributes like e. g. the kind of measure, effectiveness and use, effort involved, and action (passive, active) required, characterising and helping to assess the measure. From this compilation it is possible to derive five major groups to which the compiled optimisation measures could be allocated (Fig. 5.3).

The two major groups "Information" and "Monitoring" contain measures that require regulatory requirements for their implementation. Hence, of the five major groups, only

"Conception", "Construction" and "Indication" are considered in the following for the derivation of optimisation measures.

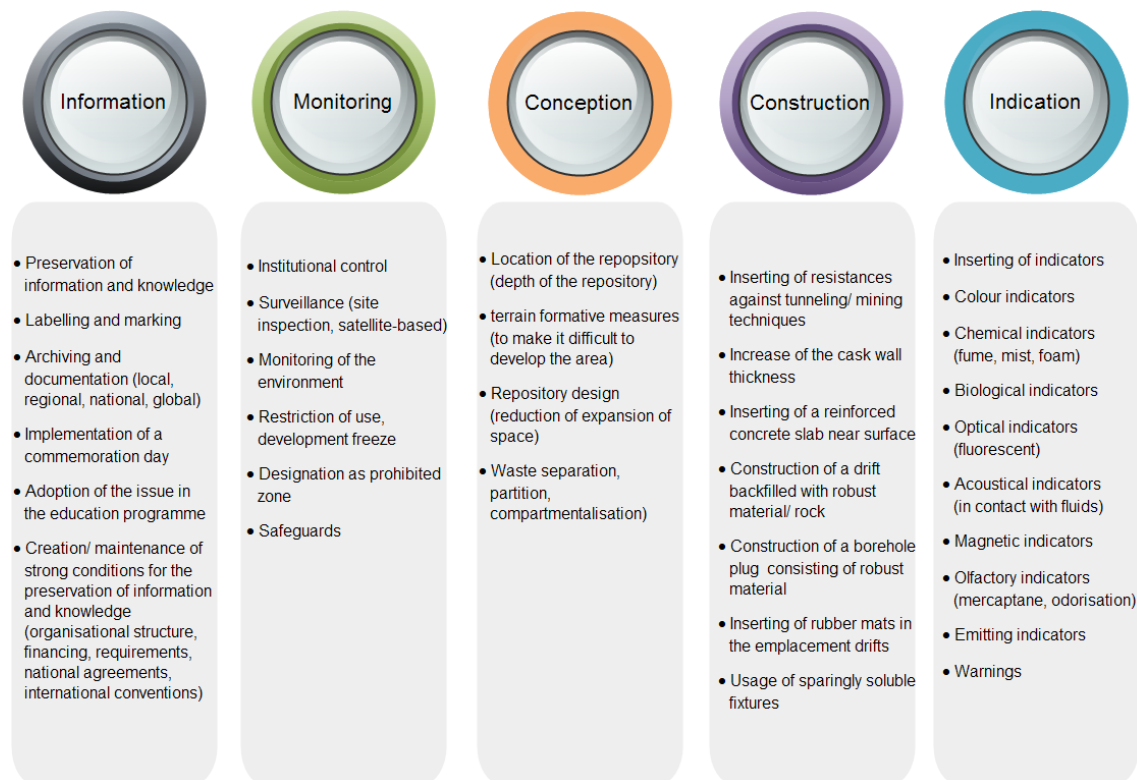


Fig. 5.3 Representation of the possible measures that can counteract human intrusion into a repository, allocated to the major groups

Even though the two above-mentioned major groups "Information" and "Monitoring" are not addressed here any further, the time factor should nevertheless be pointed out that is relevant for the decrease of the radioactivity due to radioactive decay. Fig. 5.4 shows the decrease of the radioactivity over time after emplacement, using different loads of a POLLUX cask as an example. The data base stems from /PEI 11/. Here, it becomes clear that especially over the first approx. 1,000 years, the decrease of the radioactivity is significant, with the activity decreasing disproportionally in the initial phase. For example, the activity in the case of the POLLUX-10 (PWR-UO₂) after 1,000 years is merely 0.27 % of the original activity after loading (see inset in Fig. 5.4 with linear axes). This means that the measures for the preservation of information and knowledge may not only delay the moment of an inadvertent intrusion but also contribute to the reduction of possible radiological consequences. The longer the measures for the preservation of information and knowledge are effective, the lesser will the activity of the radionuclides remaining in the repository be if an inadvertent

human intrusion into the CPRZ occurs following the loss of the knowledge about the repository.

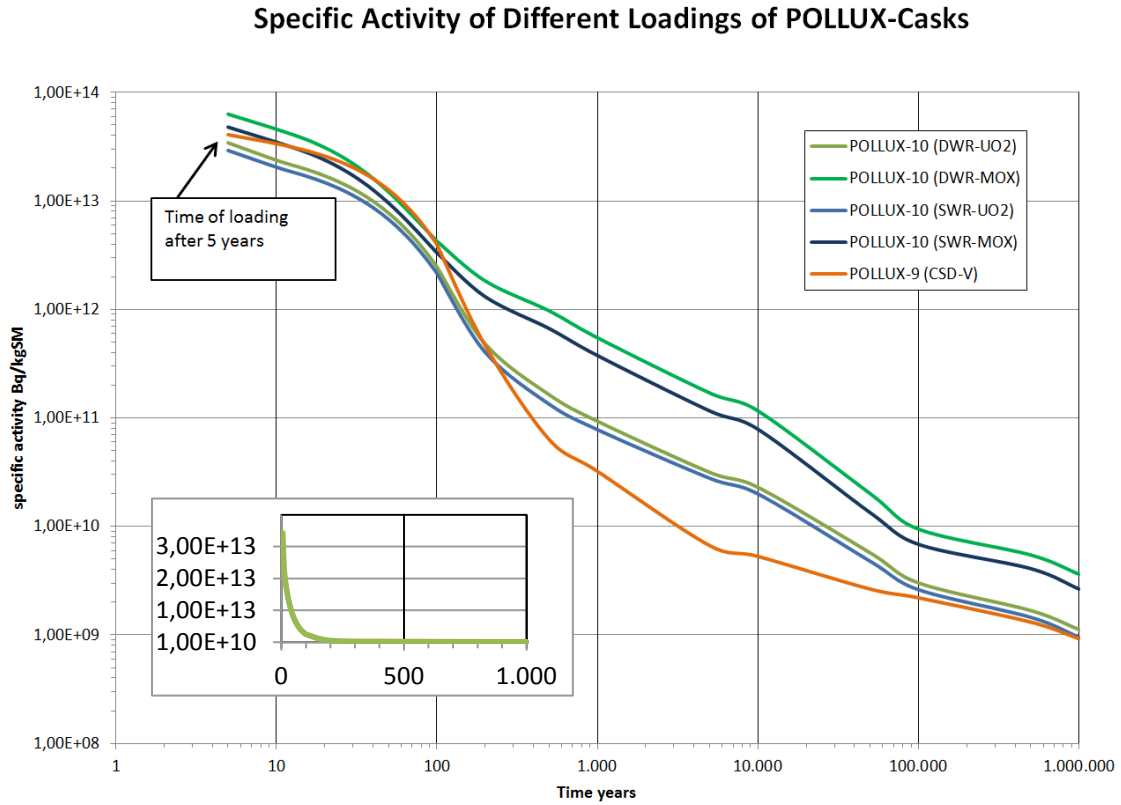


Fig. 5.4 Double-logarithmic chart of the decrease of the specific activity of different loads of a POLLUX cask, with an inset for the POLLUX-10 (PWR-UO2) cask with linear scale of the axes (data base according to /PEI 11/)

Of the possibilities compiled in the tree major groups considered here, the chosen depth of the repository has a large influence on the chance of an inadvertent human intrusion. What is imaginable is that the repository could be constructed at a depth at which an advance by humans would only occur with restrictions and where the motives for such an advance into great depths would be considerably reduced. On the other hand, there are limits to the choice of a repository's depth due to the primary optimisation targets, especially the operational safety of the repository.

5.2 Identification of optimisation measures for the stylised scenarios

In the following, the defined HI scenarios (Chapter 4) will be dealt with individually with regard to optimisation measures against an inadvertent human intrusion. The measures were in part developed in discussions with mining companies (Annexes A.1,

A.2 and A.3). However, in this chapter they are not yet examined in detail regarding their long-term and operational-safety-related consequences, technical feasibility and effectiveness over very long periods.

All HI scenarios have in common that they are preceded by surface exploration activities. These, however, are not capable of discovering a repository. There are no optimisation measures that could be derived which would lead to an increased chance of recognition from above ground.

5.2.1 Exploratory borehole

In the case of the HI scenario "Exploratory borehole", measures can be identified that favour the recognition of a repository. These include above all

- the application of materials presenting a resistance against the advance of the drill such as
 - greater cask wall strengths,
 - reinforcements or mats of iron in the areas of the roofs of the drifts of the former cavities of the repository mine,
 - rubber mats above the waste and/or the use of basalt or granite blocks or other materials in the backfill of the drifts,
- the application of optical indicators, like e. g. the use of a suitable dyestuff in the cavity backfill of the repository which would significantly stain the drilling mud on the application of the rotary-drilling method. The use of powdery xanthene dyes (e. g. "uranine", whose optical detection limit lies at a concentration of about 0.1 mg/l) is imaginable, where a few grams would already suffice to stain many cubic metres of the drilling fluid in a significant yellow hue and
- the application of further indicators in the exploration level, such as magnets, acoustic signal emitters and spherical objects.

A possible measure for reducing the radiological consequences after an intrusion without detection of the repository is aimed at the separation of the waste. Basically, the emplacement variant AB1 contains already a separation of the waste in that it provides a south-western part (Variant A), in which the non-heat-generating waste is

emplaced, and a north-western part (Variant B1), in which the heat-generating waste is emplaced. In order to be able to make a further separation, it is imaginable to separate individual emplacement fields or even emplacement drifts by the implementation of sealing structure (similar to the planned sealing plugs in the cross-cuts /BOL 11/). If an emplacement field or an emplacement drift were to be penetrated by an exploratory drilling, this would as a maximum only affect the respective nuclide inventory contained in there.

5.2.2 Cavern

The initiating working step for the creation of a cavern usually starts with an exploratory drilling. This is why the possible optimisation measures listed in Chapter 5.2.1 also apply to the HI scenario "Creation of a cavern". In the following, possible optimisation measures are shown up which relate to the process of cavern creation by leaching and to the operation of a cavern with consideration of its different kinds of use.

In Chapter 4.2.2, circumstances or effects have already been mentioned that are undesired in cavern creation and that should be avoided if possible, thereby increasing the chance of the repository being detected. This includes the occurrence of cavities, which in the case of storage caverns leads to storage losses, e. g. in the storage of mineral oil. Furthermore, care is taken here that if possible no insoluble strata are encountered that may lead to unpredictable cavity geometries and larger residues in the cavern sump.

- Making use of these conditions one could think of various measures that could be applied during the creation of the repository in connection with the exploration level. For example, the drifts driven into the exploration level could be backfilled with crushed rock of little subsidence in order to create hollow spaces for pressure and storage losses in cavern operation.
- Another possibility is to backfill the drifts driven into the exploration level with formed blocks of granite or basalt, which would sink or slide into the cavern sump as a result of a possible leaching process due to their insoluble or difficultly soluble properties and trigger a noticeable pressure pulse in the course. In addition, there is the possibility that these residues would be noticed as foreign rock types by the regular sonar measurements to record the cavity geometry of the cavern. The

unnaturally even shape of the blocks could increase the perceived contrast even more.

- A further possible measure is also based on insoluble or difficultly soluble and foreign material. The underlying idea of this measure is founded on the discussed repository concept of storage in cased boreholes. Again starting from the exploration level, pipes with a length of several tens of metres could be inserted laterally as well as into upper-lying and/or lower-lying strata. Here, the routing of the pipes has to be such that safety margins e. g. to potentially brine-containing rocks must be kept and that no emplacement areas are penetrated. Such long pipes that reach into a cavern or are fully located inside a cavern are objects that can be registered by sonar measurements. An additional measure one could imagine is the colour indicators or other indicators are added to the pipes.
- As for the use of a storage cavern for natural gas or hydrogen one could imagine providing an indicator that takes an olfactory effect. This means that odourising substances are used that could trigger a corresponding perception. The addition of so-called odourisers to natural gas has already long been practiced by the industry to be able to perceive this way any gas – which is otherwise odourless – that might be escaping from leaks.
- Further indicators aim at acoustic signals and the addition of strong magnets. Furthermore, the colour indicators already described in Chapter 5.2.1 can be used.
- Apart from the indicators mentioned so far, others are also imaginable that will trigger an intense chemical reaction upon contact with the brine or the storage medium (mineral oil, natural gas), e. g. materials that will develop intense smoke or fog formation, have a strong foaming effect, or lead to agglutination or agglomeration.
- As a further group, those material additives have to be mentioned that have a quality-reducing effect on the brine or the storage medium. Here, materials can be imagined that already represent a considerable contamination at low concentrations and which can only be eliminated with considerable effort. For example, the extracted brine is often used in production processes of chemical plants. Contaminated brine that has a quality-reducing effect on the further production process would be noted.

It has to be kept in mind for all measures referring to indicators that a very large amount of water is used for the creation of a cavern. It may well be in this case that the indicators could already be washed away with the brine by the leaching process without being able to become effective. Hence the indicators have to be placed and fixed correspondingly. Moreover, it still has to be practical to use them in the light of the numbers of indicators needed for sufficient perceptibility. Furthermore, their high endurance and longevity need to be considered. Besides the aspects already mentioned, it also has to be pointed out that some indicators will also only be able to take their effect with certain kinds of cavern use or with certain storage media.

5.2.3 Mine

Similar to the case of the HI scenario "Exploratory borehole", measures can be identified that will increase the chance of the repository being recognised as an (anthropogenic) anomaly. Regarding the sinking of shafts or related preliminary drilling, reference is made here to what has been stated in connection with the "Exploratory borehole" scenario as the type of intrusion (intrusion from above) is similar. Beyond that, the following measures are considered to be promising:

- Application of materials presenting a resistance against the advance of the drill. As salt mining is done mostly horizontally, the measures would in contrast to the "Exploratory borehole" scenario not only have to be effective in the area of the roofs but would also need to present a noticeable resistance to a penetration into drifts from the side. Here, selected underground workings (see below) of the repository mine could be backfilled with basalt blocks together with salt breeze in such a way that resistances are presented to both the drillings for the preparation of blasting boreholes and the cutting or milling tools of continuous miners or full-face boring machines when approaching the emplacement areas, hindering or stopping any further advance.
- Application of optical indicators.
With regard to the approach to emplacement areas, the use of a suitable, evenly distributed powdery or fine-grained dye or dyed salt breeze would also be a promising option to allow an early detection of the repository as an anomaly. The dye would have to be a strong contrast to the natural colouring of the salt. What would also be imaginable would be the combination with hydraulic dyes such as

uranine to increase at the same time the chance that the repository would be detected in the case of an "Exploratory borehole" scenario.

- It is assumed that (as is common in mining today) the salt mine will be developed top to bottom in different levels that are connected to the shafts. On the levels themselves, mining is predominantly in horizontal direction. In the case of a repository with a drift emplacement concept it would generally be sufficient to apply the above-mentioned substances to the access drifts and cross-cuts as these surround the individual emplacement fields. This way, an access drift or cross-cut would in any case first have to be penetrated before an emplacement drift would be encountered (see Fig. 5.5).
- The chance of detection could be increased by backfilling the projected exploratory drifts, which lie approx. 30 m above the emplacement area, with advance-hindering and optically conspicuous substances, too. If conventional mining techniques were used, this could allow the recognition of the indicators even before a possible exploration of the emplacement area of the repository and would favour their interpretation as an indication of former mining activities. The intention is here to raise the acting or executing group of persons' awareness for looking out for further unusual features in their subsequent actions.

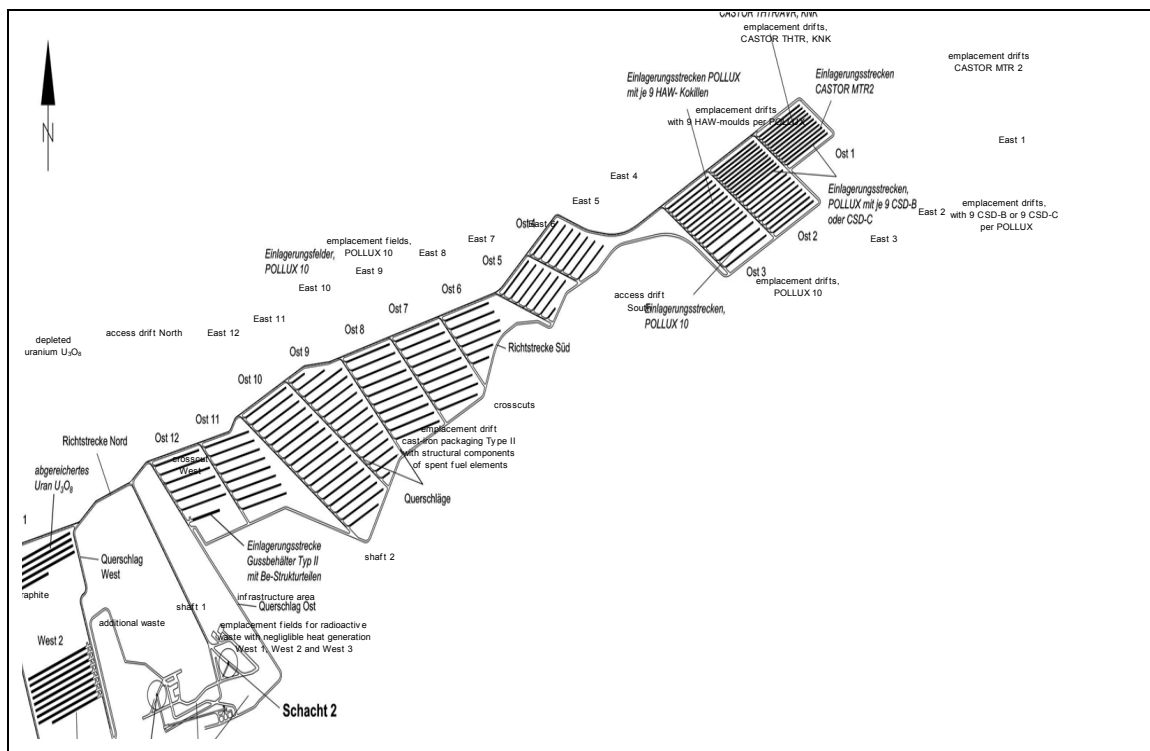


Fig. 5.5 Mine cavities of the repository (according to /BOL 12/)

In Chapter 5.2.1, the measure of separating the waste by sealing structures has been explained. This measure could also have a corresponding effect in the construction of a mine if corresponding emplacement fields or emplacement drifts were to be approached in the course of the salt mining process. The same applies to the measure also mentioned in Chapter 5.2.1 to provide a greater wall-thickness of the waste containers or waste packages, presenting a strong resistance against advance working machines.

The measure described in Chapter 5.2.2 to install pipes starting from the exploration level into lateral as well as upper and lower areas of the salt also represents a possible optimisation against human intrusion in connection with the HI scenario "Construction of a mine".

Beside the mentioned conceptual measures, a range of other measures that have already been described in Chapter 5.2.2 and refer to the consideration of indicators are also relevant in connection with the aspect of the construction of a mine that is considered here. These are especially indicators that are odour-emitting or smoke- and fog-developing, e. g. upon contact with the oxygen in the air or in the incidence of light.

A further measure that has also been described in Chapter 5.2.2 refers to the quality reduction, which in this case, however, is directed at the medium salt. The intention here is the further mining of salt is dispensed with due to the unusual feature encountered and that possibly the reason for the quality reduction may be investigated.

Other measures relate to the marking and characterisation by fluorescent substances and the positioning or attachment of warning signs for optical perception, e. g. in the emplacement areas or on the casks.

5.3 Assessment of the optimisation measures identified

In the following subchapters, the optimisation measures identified in Chapter 5.2 for the stylised HI scenarios "Drilling of a borehole", "Creation of a cavern" and "Construction of a mine" are assessed. This assessment considers the primary optimisation targets of radiation protection for the operating phase, long-term safety, operational safety of the final repository, reliability and quality of long-term waste containment, safety management as well as technical and financial feasibility (Chapter 2.1). If these

measures are in conflict with the primary optimisation targets, they have to be excluded as measures for a possible repository at the Gorleben site. If they are not in conflict with one of the primary optimisation targets, then the chances of success of these measures are assessed.

5.3.1 Exploratory borehole

For the HI scenario "Exploratory borehole", four possible measures have been identified in Chapter 5.3.1:

1. the application of materials, taking greater wall-thicknesses into account, presenting a resistance against the advance of the drill,
2. the application of optical indicators
3. the application of indicators in the exploration level, such as magnets, acoustic signal emitters and spherical objects
4. the separation of individual emplacement fields or even emplacement drifts by the implementation of sealing structures.

To 1. Materials proposed for presenting a resistance to the advance of the drill are iron reinforcements as well as mats made of iron or rubber. The application of these materials is not in direct opposition to the primary optimisation targets radiation protection for the operating phase, operational safety of the final repository, or safety management as well as technical and financial feasibility. However, by taking these measures, substances are introduced into the repository that may lead to gas formation due to corrosion processes as well as microbial decomposition and which therefore have to be taken into account in connection with the long-term safety and the reliability and quality of the long-term containment of the waste. Hence, for the drifts on the emplacement level, such measures have to be discarded.

In the drifts of the exploration level, the influence of such processes on long-term safety is rather slight. Here, corresponding measures could be implemented. However, such measures require great efforts. The benefit of these measures, on the other hand, is rather low as the drifts that have been driven on the exploration level only cover a very small proportion of the horizontal area of the repository that could be affected by an exploratory borehole. Furthermore, the lifetime of the added iron or rubber substances

is short compared to the demonstration period. The probability that drifts that have been reinforced or fitted with mats can be detected is very low.

As regards the wall-thickness of the casks, it can be stated that an even stronger wall-thickness is not necessary in the case of Variant B1. The wall-thicknesses presently provided are sufficient to prevent penetration by the cutter head. The drill would probably be deflected upon hitting on a cask. In Variant C it is the borehole casing that has a sufficient wall-thickness.

It has to be noted in addition that a further increase of the wall-thickness will also provide more substance for possible corrosion and hence may lead to increased gas formation. This has to be taken into account in the assessment of long-term safety and the reliability and quality of the long-term confinement of the waste.

The optimisation measures have to be discarded due to the ratio between the expected high cost and little benefit.

Once a sufficient state of information and knowledge has been achieved and adapted planning data for Variant A are available, this measure should once again be discussed with respect to the increased cask wall-thickness.

To 2. The application of optical indicators, e. g. dye in backfilled drifts, is only then an effective optimisation measure if in an exploratory drilling the colour changes in the hydraulic backfill or, in the case of core drillings, in the drill cores can be identified. If materials are used that neither have a significant effect on the geochemical environment in the backfilled drifts nor on the compaction of the backfill, the primary optimisation targets are not jeopardised by these optimisation measures. This is true of the drifts on the exploration level as well as of those on the emplacement level.

As in the case of the application of reinforcements or mats, the possible area of the backfilled drifts that would have to be is small, so that the chance of recognising the repository as an anomaly when drilling into the CPRZ is also low. Moreover, an indicator needs to be found that has a sufficiently long lifetime compared with the demonstration period. The chance that optically marked drifts will be detected during an exploratory drilling is therefore low, even if all drifts of the exploratory and the emplacement level can be marked.

If a dyestuff can be found that

- does not negatively influence the geochemical environment,
- does not influence the compaction of the salt breeze and
- has sufficient longevity,

the marking of the backfilled drifts with this dyestuff is a method that can be used due to the expected low effort in its technical implementation.

To 3. In principle, the same chain of arguments applies to this optimisation measure as the one already mentioned in connection with 2.). One difference, however, is that a finely distributed dye in the backfill of a drift promises to be more effective than individually placed objects or signal-emitters in a drift on the exploration level. The chance that drifts equipped in this way will be detected by an exploratory drilling has to be assessed as being even much lower as in the case of the above-mentioned dyestuff. Even if a large number of objects and signal-emitters were to be used, no corresponding benefit is to be expected due to the small area of the exploration level.

Furthermore, it would have to be ensured that the objects and signal-emitters have sufficient longevity.

The optimisation measures have to be discarded due to the ratio between the expected high cost (if a large number of objects and signal-emitters are used) and little benefit.

To 4. A separation of the emplacement fields or also of the emplacement drifts would bring no use to Variants B1 and C. In Variant B1, taking the probable development into account, the salt breeze backfill in the emplacement drifts will after 500 years already (earliest time after which human intrusion is assumed) be compacted to an extent that overall a separation not only of individual emplacement fields and emplacement drifts but also of individual repository casks will be given. As for Variant C, separation of the boreholes is already given by the intended borehole casings.

Hence this measure does not represent an optimisation for Variants B1 and C.

Once a sufficient state of information and knowledge has been achieved and adapted planning data for Variant A are available, this measure should once again be discussed.

5.3.2 Creation of a cavern

As prior action preceding the creation of a cavern, (at least) one exploratory borehole is sunk. Corresponding optimisation measures in this respect have been assessed in Chapter 5.3.1. In addition, the following possible measures have been identified in Chapter 5.2.2 in connection with the leaching of a cavern:

1. backfilling of the exploration level with crushed rock of little subsidence
2. backfilling of drifts on the emplacement level with formed blocks of granite and basalt
3. installation of piping (analogous to the casings in Variant C) in the host rock
4. insertion of indicators (dyestuffs, olfactory substances etc.)
5. insertion of quality-reducing substances.

To 1. Crushed rock that settles very little is already intended for the infrastructure areas of the exploration and emplacement levels. Here, it serves above all as storage volume for gas and solutions. The proposed optimisation measure furthermore provides for the backfilling of all remaining drifts on the exploration level with crushed rock of little subsidence very little in order to create hollow spaces for pressure and storage losses in cavern operation. The drifts on the exploration level at a depth of 840 m which in the original concept are to be backfilled with salt breeze would add up to a total volume of approx. 360,000 m³ and, if they were backfilled with material that subsides very little, would provide sufficient hollow space for such a measure.

The current repository concept provides that the emplacement level be established approx. ca. 30 m below the exploration level. All connections (shafts, boreholes) are backfilled and sealed. The levels themselves are backfilled with salt breeze – except for the infrastructure areas – and are sealed at the transitions of the access drifts to the infrastructure areas. The seals of the drifts are designed such that they have a service life of 50,000 years. This means that should the measure to backfill the exploration level with crushed rock of little subsidence be implemented, there will be the possibility that brine may intrude once the end of the indicated service life of the drift seals has expired. This would mean the conscious creation of a potential of a probable development that would violate the requirement for a minimum distance of 50 m of the access drifts to brine-containing areas. Under these boundary conditions, the

optimisation measure considered here is not compatible with the primary optimisation target of long-term safety.

In order to implement the measure nevertheless, the emplacement level would have to be established at a safety margin of > 50 m below the exploration level.

The measure itself only requires little technical and financial effort compared to other possible measures that are being discussed. As both cavern use and final disposal are preferably carried out in homogenous salt rock areas, one may well assume that during the leaching processes of a cavern of a size that is common today the cavities of the drifts backfilled with crushed rock would be encountered and that a noticeable pressure and mud water loss would occur. If, however, the borehole from which leaching is performed were to be drilled from below the repository, waste packages from the repository may already have dropped into the cavern before these optimisation measures could become effective.

A further aspect that has been identified in the discussion about these optimisation measures refers to a possible reduction of the permeability of the crushed rock owing to the ability of the surrounding rock salt to creep into the pore spaces of the backfill. In analogy to this aspect, model calculations were carried out for the materials sand, gravel and crushed rock for a calculation period of 10,000 years. The calculations yielded a permeability reduction for the materials in a range of 2 % – 4 %, with the reduction being smallest for sand. Due to this overall slight reduction that lies within the range of the measuring certainty of permeabilities, it was stated that a noticeable change in the permeability of the backfill as a result of salt with the ability to creep into the pore space cannot be demonstrated by calculations /JOB 99/.

Hence the measure appears to be feasible as an optimisation measure against human intrusion under the condition that there is a sufficient distance between the exploration level and the emplacement level. It may be that the optimisation measure can still be further improved with regard to its long-term effectiveness by the choice of the corresponding backfill material. In addition, it has to be pointed out that the measure will only be effective if a cavern is leached from above or from the side.

To 2. A technically complex measure is the backfilling of drifts on the emplacement level with formed blocks of granite and basalt. These are meant to drop into the cavern during the leaching process and trigger a noticeable pressure pulse. Here, the blocks

have to be formed such that they can be detected as an anomaly when the cause of the pressure pulse is investigated. The measure is not contradictory to the primary optimisation targets.

The pressure pulse of a block dropping down into a cavern can only be measured if the cavern is leached from below. If e. g. the cavern sump is located at the level of the exploration level, no pressure pulse of any dropping blocks will be noticeable. It is therefore not useful to implement this measure on the exploration level as the repository would already have been encountered before the exploration level would be reached. Blocks located on the emplacement level, on the other hand, could drop into the cavern sump and be detected. As the exact leaching process is not predictable, it is also not clear whether it would be a block or a repository cask that would first be encountered during the leaching of a cavern. In the case of borehole emplacement, the borehole casing would first be detected.

Due to the considerable technical effort and the low probability that only blocks and no repository casks will drop into the cavern sump and trigger a pressure pulse, this measure is not expedient and therefore has to be discarded.

To 3. The installation of pipes that are dimensioned such that they can be detected by today's geophysical measuring methods has to be critically assessed from the point of view of the primary optimisation targets of long-term safety and the reliability and quality of the long-term containment of the waste. This applies to horizontally and vertically inserted pipes on the exploration level as well as on the emplacement level.

The pipes have an influence on the stress and temperature distribution in the host rock and contribute to gas formation through corrosion. It cannot be excluded that new pathways will form that lead out of the CPRZ. Hence the integrity of a CPRZ can be put at risk by such measures. Thus these measures can impermissibly influence long-term safety and are therefore not considered as optimisation measures against human intrusion.

To 4. The application of indicators that will trigger such a heavy reaction upon contact with the brine solution that they can be detected has to be excluded as a possible measure when taking the primary optimisation targets into account. These indicators are doubtful above all for operational reasons because such reactions may already be possible during the operational phase.

If, on the other hand, environmentally-friendly substances are used as indicators, it is questionable whether they can be applied at such concentrations that they will still be effective if the creation of the cavern involves water volumes of 200 m³/h. the use of other indicators, such as e. g. acoustic signals or magnets, is also assessed to be low as it will most probably be not be possible to detect these at the surface.

To 5. As for the application of quality-reducing substances there remain a number of open issues, e. g. what substances may be used that on the one hand can be detected but on the other hand will not pose a hazard to future generations (including the intruding person or group of persons). Furthermore, the question arises of whether such materials will remain stable in the long run and whether they can be applied at such concentrations that they will still be effective if the creation of the cavern involves water volumes of 200 m³/h. Depending on their characteristics, all primary optimisation targets, especially operational safety and long-term safety, may be at risk. Hence the measure has to be discarded.

5.3.3 Construction of a mine

As prior action preceding the construction of a mine, (at least) one exploratory borehole is sunk. Corresponding optimisation measures have been assessed in Chapter 5.3.1. For the construction of a mine, the following further possible measures have been identified in Chapter 5.2.3:

1. Application of materials and consideration of stronger cask wall-thicknesses to increase resistance to the advance of the drill
2. Application of optical indicators
3. Application of other indicators (e. g. olfactory substances)
4. Separation of individual emplacement fields or also emplacement drifts by the implementation of sealing structures
5. Installation of casings into the host rock
6. Application of quality-reducing substances.

To 1. As in the case of the HI scenario "Exploratory borehole", the application of materials to increase resistance to the advance of the drill is not in direct opposition to

the primary optimisation targets radiation protection for the operating phase, operational safety of the final repository, or safety management as well as technical and financial feasibility. However, such measures may cause the intrusion of substances into the repository that may lead to gas formation through corrosion processes or microbial decomposition and which therefore have to be taken into account in the long-term safety and the reliability and quality of the long-term containment of the waste.

As for the wall-thickness of the casks it can be stated that an even greater wall-thickness is not necessary in Variant B. The wall-thicknesses currently provided are sufficient to be noticed as resistance to the advance of the drill. The same applies to the intended borehole casings in Variant C.

Analogous to the exploratory borehole (Chapter 5.3.1) it has to be noted that a further increase of the wall-thickness will also offer more substance for possible corrosion and can therefore lead to increased gas formation, which has to be taken into account in the long-term safety and the reliability and quality of the long-term containment of the waste .

Once a sufficient state of information and knowledge has been achieved and adapted planning data for Variant A are available, this measured should once again be discussed with respect to the increased cask wall-thickness.

As already mentioned above, the repository casks or the borehole casings already represent a resistance to the advance of the drill that would be detected when drifting and would point at earlier human activity. With respect to the repository casks emplaced, the measure of applying substances thus presents few advantages. Moreover, there are less complex methods for facilitating the detection of a repository (see below).

To 2. In order to draw attention optically to the repository when a mine is being drifted, it is e. g. possible to apply a colour indicator to the backfill. As the thus marked drifts will be encountered directly, lesser colour changes will suffice as compared to e. g. an exploratory drilling. The longevity of the corresponding substances will also have to be examined and verified.

If materials are used, that neither have a significant effect on the geochemical environment in the backfilled drifts, nor on the compaction of the backfill, the primary optimisation targets are not jeopardised by these optimisation measures. This is true of the drifts on the exploration level as well as of those on the emplacement level.

Hence this measure is a possible optimisation measure against human intrusion.

To 3. The application of other indicators, e. g. odour- or fog-developing substances, is in conflict in particular with operational safety. The influence on the geochemical environment, too, and therefore possibly also on long-term safety has to be clarified. Corresponding measures are excluded due to this conflict with the primary optimisation targets. Also, there is no further advantage compared with the optical indicators.

To 4. Analogous to the exploratory borehole (Chapter 5.3.1), separation of the emplacement fields or also of the emplacement drifts would bring no use to Variants B1 and C. In Variant B1, taking the probable development into account, the salt breeze backfill in the emplacement drifts will after 500 years already (earliest time after which human intrusion is assumed) be compacted to an extent that overall a separation not only of individual emplacement fields and emplacement drifts but also of individual repository casks will be given. As for Variant C, separation of the boreholes is already given by the intended borehole casings.

Hence this measure does not represent an optimisation for Variants B1 and C.

Once a sufficient state of information and knowledge has been achieved and adapted planning data for Variant A are available, this measure should once again be discussed.

To 5. As for the installation of pipes that are dimensioned such that they can be detected by today's geophysical measuring methods, it applies in analogy to what has been stated in connection with the HI scenario "Creation of a cavern" that this measure has to be critically assessed from the point of view of the primary optimisation targets of "long-term safety" and the "reliability and quality of the long-term containment of the waste". The pipes have an influence on the stress and temperature distribution in the host rock and contribute to gas formation through corrosion. It cannot be excluded that new pathways will form that lead out of the CPRZ. Hence the integrity of a CPRZ can be put at risk by such measures.

Thus these measures can impermissibly influence long-term safety and are therefore not considered as optimisation measures against human intrusion. This applies to both horizontally and vertically inserted pipes on the exploration level as well as on the emplacement level.

To 6. As for the application of quality-reducing substances, it also applies in analogy to the HI scenario "Creation of a cavern" that too many open issues remain, e. g. what substances may be used at all. Depending on their characteristics, all primary optimisation targets, especially operational safety and long-term safety, may be at risk. Hence the measure has to be discarded.

5.4 Quantitative analysis of the identified optimisation measures

If one summarises the assessment of the optimisation measures against human intrusion for the identified HI scenarios, it turns out that

1. dyeing of the backfill or adding dyestuffs to the backfill and
2. the emplacement of crushed rock in the exploratory borehole in connection with a corresponding increase in the distance between the exploratory level and the emplacement level

are the two remaining optimisation measures against human intrusion. All other measures are either in conflict with the primary optimisation targets or have such a poor cost-benefit ratio that they have to be discarded as possible measures or are out of the question.

Both remaining measures are aimed at indicating to future acting individuals that there has been former human activity or former mining at the site. What conclusions these individuals will draw from these indications is impossible to predict. However, as a quantitative analysis of the effectiveness of the measures can only be carried out, if clear boundary conditions can be defined, such an analysis is not expedient.

If conceptual measures were to be chosen that aim at a constriction (compartments) of the waste concerned and hence at a reduction of possible consequences, a quantitative assessment would rather more likely be possible. Should such measures

prove to be useful once Variant A becomes a more concrete option at a later stage, then a quantitative assessment is quite conceivable.

6 Summary

Apart from the study of possible future evolutions of the site with consideration of natural as well as repository- and waste-induced phenomena, the scope of examination of the Preliminary Safety case of the Gorleben Site (VSG) also includes phenomena that are caused by human actions. The latter, however, are studied separately from the other possible evolutions due to the insufficient predictability of human actions.

In line with the Safety Requirements for the Disposal of Heat-Generating Radioactive Waste /BMU 10/, the objective in connection with the study of human actions is aimed at the optimisation of the repository. Any optimisations resulting from the study must, however, not jeopardise the primary optimisation targets specified in the Safety requirements.

As a first working step, the basic fundamentals for the study of human activities were compiled in this report in Chapter 2. Beside a list of relevant technical terms and definitions, the basic fundamentals comprise the presentation of the boundary conditions and requirements for the task in hand as well as the description of the methodology for dealing with the task. Furthermore, it was necessary due to the wide spectrum of human actions to narrow down the scope of activities to be addressed in the safety case. One essential aspect of this restriction is the concentration on those human activities that have the potential to reach into corresponding repository depth levels. here, only inadvertent intrusion is to be examined. Moreover, the actions to be considered here are to be based on today's state of the art in science and technology.

Basing on the fundamental basics elaborated in Chapter 2 basic actions were identified in Chapter 3 that comprise the future human activities to be considered. These basic actions include the drilling of a borehole, the creation of a cavern and the construction of a mine. For each basic action, general information was compiled, and the work processes associated with the actions, like e. g. for preliminary exploration, planning and construction, operation and decommissioning, were shown and described according to today's state of the art. To do so, talks were held with specialist companies, on the one hand serving for the determination of the state of the art in science and technology and on the other hand giving information on possible conditions that need to be paid special attention in the planning or execution of the corresponding basic actions.

In Chapter 4, scenarios were identified that refer to human intrusion into the repository. The basic actions were applied for this purpose and their intrusion potential analysed. The analysis of the basic actions contained the consideration of case distinctions that take into account the possible different intrusion locations and kinds of use of the respective activities. It was furthermore discussed to what extent the anomalies or unusual features induced by the repository and by the radioactive waste can be detected by the work processes associated with the basic actions and the corresponding case distinctions. The result of this discussion was included in the identification and specification of scenarios, which focus on the sinking of an exploration borehole, the creation of a cavern and the construction of a mine. The discussion results also point at possible starting points for optimisation measures.

The identified and specified scenarios were analysed in the concluding Chapter 5 with regard to whether there is the possibility to reduce the probability of their occurrence by corresponding measures and/or whether the radiological consequences can be counteracted. The initial basis for this study was a compiled list of conceivable measures that could thematically be allocated to the major groups information, monitoring, conception, construction and indication. As a result, possible optimisation measures were identified, taking the elaborated scenarios into account and aiming predominantly at an early recognition of an anomaly or unusual feature by indicators or by measures with indicating function and at a possible reduction of the consequences associated with the human intrusion by conceptual measures.

The possible optimisation measures that were identified were systematically assessed with respect to whether they might be implemented for the different emplacement variants and whether they have any adverse effects on the primary optimisation targets stipulated in the Safety Requirements. In addition, the possibility of a quantitative assessment of scenarios before and after the consideration of optimisation measures was discussed.

As a result of the discussion and assessment of the possible optimisation measures, only two measures remained that can usefully be implemented under the assumed boundary conditions. These are the use of an indicator for dyeing the backfill materials (salt breeze and crushed rock) and, with a corresponding adaptation of the conceptual planning regarding the distance between the emplacement level and the exploration level, the application of low-subsiding backfill (e. g. sand, gravel and crushed rock) on the exploration level. Both measures are aimed at the presence of unusual features to

be encountered upon an intrusion into the CPRZ that can be interpreted as such by the acting individuals. As these measures are aimed at having an indicating character with regard to human actions or past mining activities at the site, a quantitative assessment is not possible in either case. There are no clear boundary conditions for a quantitative assessment of the effect of the measures. The success of each measure depends on the interpretation of the unusual feature and the resulting decisions by the future acting individuals.

No optimisation measure was identified that can make an inadvertent intrusion into the CPRZ more difficult or that can improve the chance of the repository being detected prior to an intrusion into the CPRZ. As a result, there is no possibility to reduce the probability of an inadvertent human intrusion into the CPRZ.

In all, it can be stated that when it comes to optimising the repository system against human intervention, the possibility of taking effective measures is highly limited. It furthermore remains uncertain whether the triggering or intended effect of planned measures in the event of a future human intrusion will also be correspondingly perceived and interpreted and followed by conclusive reactions.

Finally, it has to be kept in mind that owing to the deep location of the repository that is inherent in its concept, the preservation of information as well as institutional control represent effective measures against an inadvertent human intrusion. A reliable estimate of whether the effectiveness of such measures over periods of several hundreds of years can be assumed is, however, not possible as this would require predictions of the actions of future human societies during these periods. To handle these uncertainties, corresponding specifications regarding these measures are necessary. The creation of corresponding framework conditions is a regulatory task.

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A Memcons

A.1 Memcon of 22/11/2004 at the ITAG company in Celle

Participants:

Dr. Gutsche (ITAG),
Dr. Baltes, Dipl. Geol. Larue, Dipl.-Ing. Beuth (GRS)

Topic:

Inadvertent intrusion into a repository for radioactive waste through the sinking of a deep borehole

Preparatory document:

To prepare the discussion, a brief description of the problem area of "human intrusion" as well as an outline of the issues to be discussed was compiled and distributed.

Memorandum of the result:

The issues discussed during the meeting as well as other aspects addressed during the course of the discussions are outlined in the following:

What is the state of the today in connection with the sinking of boreholes down to depths of 500 m to 1,000 m?

In Germany, deep boreholes are in most cases drilled for the purpose of prospecting mineral oil and natural gas deposits. In recent times, boreholes are also more and more frequently sunk for exploiting geothermal energy. The depth levels of the deposits (1,000 m – 2,500 m in the case of mineral oil deposits and 3,000 m – 5,000 m in the case of natural gas deposits) lie in the majority of cases clearly below those (500 m – 1,000 m) planned for a repository for radioactive waste.

The methods used for deep drilling are predominantly the rotary method, in which the drill bit together with the drill pipe is set in rotary motion via a topdrive and/or a

downhole motor. The formerly used turntable drive has become less important compared to the above-mentioned rotary drives.

To secure the borehole wall during the drilling process and for removing the drill cuttings, a drilling fluid (mostly an aqueous clay solution) is pumped through the drill pipe, rising with the rock to the surface again via the annular gap. To secure the borehole against caving in the long run, steel pipes are inserted and cemented at specified distances.

Is a seismic analysis carried out beforehand? When can a repository be discovered by a seismic analysis?

Prior to an exploratory drilling for a deposit, it is important that potential areas are demarcated in order to avoid high costs and reduce economic risks. For the demarcation of potential areas, geoscientific examinations are performed or referred to. One of the most important geophysical methods is the recording of seismic reflection profiles (3D seismic interpretation) that give clues to the structure of the underground at the corresponding depths and with the corresponding accuracy. In Lower Saxony, seismic reflection profiles are already available for wide areas. Moreover, gravimetric measurements provide information about density differences underground and therefore give clues to certain geological formations.

The question of whether a repository would be noticed in an evaluation of seismic reflection profiles could not conclusively be answered. It is, however, conceivable that repository area that show a low density and a corresponding expansion will be identified as an anomaly if the seismic profile has a resolution that is normal for this depth. A broad-meshed distribution of the geophones, as is usual with the exploration of greater depths, may not result in the necessary resolution of the depth level of the repository. It was recommended that this should be discussed with the specialist services or experts in the field of 3D seismic interpretation.

What are the technical measures that are usual today for preparing a borehole and during the drilling of a borehole?

The technical measures to be taken before, during and after the drilling of a borehole are laid down in the so-called drilling operations plan and in the drilling programme prepared by the operator and by corresponding laws, ordinances and guidelines that

have to be observed. The drilling operations plan contains instructions, framework conditions and information regarding the execution of the drilling such as the boring site, start of drilling, property, drilling fluid, drilling method, monitoring equipment etc. The drilling programme specifies further-reaching instruction on the sequence of the drilling operations.

When and how often during the drilling process are the drilling fluid and the drill cuttings examined by the drilling team and/or the geologist? Would an anomaly as represented by the repository be detected in this process?

From the start of the drilling operations, a geologist is present on site, evaluating the drilling by means of different observations, measurements and examinations in order to obtain information about the penetrated sequence of strata, the types of rock, and the properties of the rock. For example, the drill cuttings conveyed up with the drilling liquid are examined. Any mud loss is registered.

In addition, a range of further geophysical parameters such as temperature, pressure, type of rock, density, borehole inclination, porosity and various others are recorded by borehole probes (gamma log, neutron log, sonic log and various others). Part of the data is already evaluated on site.

It was established in the discussion that with the large number of examinations and the types of measuring methods, any anomalies caused by a repository would most likely be noticed. To underpin this statement it was recommended, however, to seek a further exchange of information with specialised geophysical services or experts (e. g. Schlumberger company, Baker Atlas Group).

Is coring performed often, and when? If so, when is the core examined by the geologist? Would an anomaly as represented by the repository be detected in this process?

The sampling of drill cores is specified in the drilling operations plan. In Addition, the geologist will order that a drill core sample is to taken if there is a change in the geologic sequence. The examination of the drill core sample is carried out by the geologist on site.

In this examination, any foreign material coming from the repository would most likely be noticed. Analogous to the preceding question, it is recommended to seek an additional exchange of information with corresponding specialised geophysical services.

With today's state of the art, would it be noticed if a repository were to be drilled into? If so, when would this be?

If the casks are assumed to be intact, i. e. the casks have not yet been considerably affected by corrosion processes, the drill bit will either be rendered useless or be strongly deflected upon hitting on a cask wall that is made of steel and more than 2 cm strong. Both would be noticed immediately and followed by corresponding examinations.

The drilling into an emplacement drift only in the backfilled area, i. e. between the casks, would presumably not be noticed if backfill material of the same characteristics as those of its environment and of similar density and porosity is used. If a reinforced concrete ceiling above the emplacement area were to be used – which has already been discussed within the expert community in connection with the marking of the repository underground – the same conditions would apply as in the case of the above-mentioned drilling into a steel cask.

Further aspects:

The clastic rock accruing during the drilling is initially stored in a pit at the drilling site and then, whenever necessary and depending on the drilling liquid used, taken to waste dumps as domestic waste or hazardous waste. The examination of the drill cuttings involves the taking of samples and the analysis of their mineralogical composition in the laboratory. Any contaminated material unrecognised so far that is classified as unlikely would be identified in this process.

Analogous to the drill cuttings, all liquids arising are collected at the boring site and subsequently disposed of.

As for drillings that do not make a strike, the borehole is backfilled with cement and sealed with mechanical plugs. Here, care has to be taken that e. g. any aquifers that have been penetrated by the drilling will not suffer a hydraulic short-circuit.

Furthermore, the borehole is secured by a concrete slab located at least 1 m below the surface.

A.2 Memcon of 15/02/2011 at the K+S AG company in Kassel

Participants:

Dipl.-Ing. Deppe, Dipl.-Ing. Jacob (K+S AG),
Dr. Fischer-Appelt, Dipl.-Ing. Beuth (GRS),
Dr. Baltes

Topic:

Future human activities in connection with the construction of a mine

Preparatory document:

To prepare the discussion, selected information and questions relating to the topic mentioned were sent to the participants.

Discussion/memorandum:

The discussion served for the closer examination of the state of the art in science and technology regarding the construction of a mine in a salt dome. The determination of the state of the art in science and technology forms a basis for the preparation of stylised scenarios of human intrusion into a repository for radioactive materials in salt rock. In order to determine the fundamental elements regarding the construction of a mine, it is indispensable beside the study of the available literature to contact and query companies that are experienced and leading in this field. For this purpose, a date for a technical discussion was arranged with K+S AG. In the run-up to this discussion, essential information on this topic was compiled for preparation and sent to K+S AG together with relevant questions. At the meeting, the different questions and aspects were discussed, guided by the different development phases of a mine.

Premises and preliminary considerations:

As an introduction to the discussion, the following boundary conditions and premises for dealing with human intrusion into a repository for radioactive waste were explained:

Human behaviour and hence also future human actions cannot be predicted over the underlying study period of one million years.

For this reason, today's state of the art in science and technology has to be referred to as a basis.

Only unintentional human intrusion into a repository is considered. This means that the information about the repository site and the hazard potential presented by the site is assumed to have been lost. An intentional intrusion into a repository is considered to be the responsibility of the corresponding acting society.

Apart from the above-mentioned premises, further preliminary considerations that are relevant for the discussion were made:

As the essential starting point for the prospection it is assumed that no knowledge about the geology at the site is available. As regards the methods available for a prospection and the mining technology, today's state of the art in science and technology has to be applied as in the case of the possible human actions. This means that e. g. gamma logs are also possible examination methods. This in turn presupposes that the characteristics of the radioactivity are known. There is also general knowledge about the disposal path of storing radioactive waste deep underground. However, it does not necessarily have to be assumed that the fact that the waste has been emplaced in salt rock is common knowledge.

It is furthermore postulated that today's applicable mining safety standards such as e. g. safety margins to flanks of the salt dome have to be observed.

Prospection:

For the exploration of the geological structures, mapping as well as gravimetric and geo-electric measurements are generally carried out as a rule.

The gravimetric measurements provide information about density differences underground and thus to salt deposits. Further examinations regarding the medium salt comprise

- geo-electric measurements to detect the salt table with a depth resolution of approx. 200 m – 300 m,
- vibration-seismic measurements with a depth resolution of approx. 800 m – 900 m and

- seismic blasting with a depth resolution of some 1,000 m.

Following the surface-near measurements, a decision in favour of deep drillings for further exploration is taken if the results are encouraging. The definition of the boring sites depends on the prospection objective:

- In the case of mineral oil and natural gas, the boring sites will be located in the area of the salt dome flanks (dip structure, preferred location of hydrocarbons).
- In the case of salt, the flanks are of lesser interest. Here, the definition of a drilling grid (e. g. 1 borehole/km²) above the salt dome is common. Sinking a borehole into the core of the salt dome is also usual.

The prospection objective also defines the depth range of a drilling:

- In the case of mineral oil and natural gas, the depth range is > 1,000 m.
- In the case of salt, a final depth of 1,500 m is not exceeded as no mine will be driven below this depth due to the high ambient temperatures and convergence as well as the prevailing temperatures limiting the operation of e. g. electronic systems.

The drillings are usually performed as core drillings. The prospection drilling would probably not result in the detection of the repository unless the emplacement areas or a cask were to be drilled into directly. The reason for this is that geophysical examination methods like gravimetric measurements and geo-electric measurements are not used in a borehole in connection with the prospection for salt.

If the drill were to hit on a cask with a corresponding wall-thickness, the resistance represented by the cask would be noticed. If the rotary method were to be applied, the drilling would cause abrasion on the cask surface, and the resulting metal chips would accumulate in the drill cuttings. The reason for the drilling resistance could hence be identified and lead to a raised awareness of the drilling team. This awareness may be raised even further by the possible unexpected encounter of non-geogenic material. This can indicate e. g. earlier anthropogenic activities at the corresponding depth. This might entail the use of other examination methods, such as geomagnetic measurements and gamma logging that are not usually applied in salt exploration.

The following cases have been discussed as possible reactions to the detected unusual feature.

- a) Abandonment of the project due to anomalies and dirtying of the salt. The borehole or boreholes are regularly backfilled with rock salt concrete.
- b) Association with earlier mining activities including waste management techniques
 - b1) backfilling of the borehole or boreholes with rock salt concrete
 - b2) anomaly is investigated even taking into account that there may possibly be ionising radiation
- c) Cask is seen as a temporary obstacle, with possible use of cutting drilling technology.

It was pointed out that generally all materials can be drilled through. This depends on the question of what drilling method is employed, what material is used and whether the decision-maker is willing to continue with the project or not.

Planning and construction phase:

After the site exploration phase and the decision in favour of constructing a mine, the planning phase includes – beside a large number of other preparatory activities – the definition of collars. Usually, at least two shafts are planned. At less deep exploitation depths, it is also possible to decide in favour of constructing a ramp. Regarding a mine intended for salt exploitation, one can assume that the location of the collar for salt extraction will be chosen in a position central to the deposit. If a mine is to be driven for the purpose of storage, the collars will presumably be chosen under different aspects. Here, those planning the mine will be anxious to avoid any unnecessary penetration of the homogenous salt sections that serve as a protective layer. Apart from the above-mentioned practical and safety-related aspects, it is above all the prevailing characteristics of the site that play an essential role. For example, topographic and infrastructure boundary conditions or existing protected areas or objects of protection may have an effect on the choice of collar locations.

Before the shaft is constructed, a preliminary borehole will be drilled at the centre of its planned centre. Apart from the first metres, this drilling operation will be carried out as a core drilling. This preliminary drilling allows not only the geological examination of the drill core but also the determination of the position and course of the drilling by way of

using a multi-shot probe. Nevertheless, there will always be deviation measurements and examinations for humid spots or any influx of water. In the case of rock salt, however, no gamma log measurements will be carried out due to the missing background radiation.

A preliminary borehole sunk for a shaft into the emplacement area of a repository for radioactive waste would presumably make the perception of unusual features probable, not least because of the comprehensive geological and geophysical examinations associated with the preliminary drilling.

Possible optimisation measures were discussed that were related to the application of foreign material into the salt dome, either as an obstacle to the advance of the drill or as a possible indicator of anthropogenic activities at the site. Examples mentioned were granite, basalt and layers of reinforced concrete as well as the application of conspicuous material underground by means of injection drilling.

After the examination results and the preliminary drilling have been assessed as being successful, the shafts are sunk. The final depth depends on a number of factors i. a. on the salt table, on the definition of a protective layer at approx. 200 m – 300 m, and on the salt to be mined (potash or rock salt). It generally applies, however, that for reasons of cost, salt mining is preferably done at the lowest depth possible. For example, 10,000 €/m has been mentioned as a reference figure for shaft building. Apart from that, costs will of course become clearly higher with increasing operating life of the mine, e. g. for the transport of the mined salt at greater depths compared to shallow mining.

For the reasons mentioned above, mining is usually carried out from the upper down to the lower exploitation levels.

Operational phase:

For the mining of salt, cutting and blast heading techniques are usually employed. Safety margins have to be provided for salt mining. For example, a distance of 150 m to the flanks of the salt down has to be kept. A safety margin to the shafts has not explicitly been defined, but here, too, sufficient distances are kept to secure the shaft.

Salt mining is guided predominantly by the existing homogenous structures of the salt deposits and the above-mentioned safety margins. The direction of mining is controlled

in dependence of accompanying geophysical measurements that are carried out during operation.

Regarding the cutting technique, so-called continuous miners are employed. It was commented in the discussion that it would certainly be noticed if the rotating cutting tools or the milling head were to hit on an intact POLLUX cask.

In German salt mining, the blasting technique is most established. Boreholes of approx. 7 m length are drilled into the salt in preparation and fitted with explosive charges. With each blast triggered, more than 400 t of salt are obtained. These are then removed by wheel loaders and/or conveyer belts.

It was pointed out that an intact POLLUX cask would not be destroyed by the blast. With this method it is possible both before and after blasting to detect emplaced casks either through the boreholes that are necessary to accommodate the explosive charges or during the removal of the salt.

In this context, possible optimisation measures were discussed in detail. The use of indicators to enhance the attention or awareness of the miners is seen as an effective measure. The dyeing of sections of rock salt, too, would influence the further mining as much value is placed on a product that is as pure as possible. Hence it is conceivable that the backfill material (salt breeze) in the access drifts of the repository could be dyed and/or added by a material of non-geological origin as an indicator or marking. The exploration level of the repository and the connections of the repository ventilation system with the emplacement areas are particularly suitable for the application of such indicators. In total, these measures considerably increase the chances of the repository being detected should it be encountered in connection with salt mining activities at the site at a later point in time, which cannot be excluded. The application of foreign material like e. g. basalt has the advantage that being very hard, a drilling rotating method usually applied in salt rock could not or only with great difficulty penetrate this rock.

Usually, samples are taken of the mined salt and analysed in the laboratory for quality assurance. However, only the quality assurance analysis procedures that are common with salt are applied. The usual examinations include e. g. the optical examination for impurities and the determination of the content of NaCl and of mineral constituents. The standard procedures would not, however, identify any radionuclides.

Decommissioning:

The decommissioning of salt mines usually provides for the flooding of the mine (mandatory in Lower Saxony) and the backfilling of the shafts with crushed rock. However, exceptions are also possible. The former Salzdettfurth potash mine is referred to as an example, having been decommissioned according to a concept of dry closure. Its chambers were backfilled, while the drifts remained open.

A.3 Memcon of 16/02/2011 at the KBB Underground Technologies GmbH company in Hanover

Participants:

Dipl.-Ing. Hellberg, Dipl. Geol. Horvath, Dipl.-Ing. Crotogino (KBB Underground),
Bergoberrat Weiß (LBEG),
Dr. Fischer-Appelt, Dipl.-Ing. Beuth, Dr. Bracke (GRS)

Topic:

Future human activities in connection with the creation of caverns

Preparatory document:

To prepare the discussion, selected information and questions relating to the topic mentioned were sent to the participants.

Discussion/memorandum:

The discussion served for the closer examination of the state of the art in science and technology regarding the creation of caverns in a salt dome. The determination of the state of the art in science and technology forms a basis for the preparation of stylised scenarios of human intrusion into a repository for radioactive materials in salt rock. In order to determine the fundamental elements regarding the creation of caverns, it is indispensable beside the study of the available literature to contact and query companies that are experienced and leading in this field. For this purpose, a date for a technical discussion was arranged with KBB Underground Technologies. In the run-up to this discussion, essential information on this topic was compiled for preparation and sent to the organisations involved together with relevant questions. At the meeting, the different questions and aspects were discussed, guided by the different development phases of a cavern.

Premises and preliminary considerations:

As an introduction to the discussion, the following boundary conditions and premises for dealing with human intrusion into a repository for radioactive waste were explained:

Human behaviour and hence also future human actions cannot be predicted over the underlying study period of one million years.

For this reason, today's state of the art in science and technology has to be referred to as a basis.

Only unintentional human intrusion into a repository is considered. This means that the information about the repository site and the hazard potential presented by the site is assumed to have been lost. An intentional intrusion into a repository is considered to be the responsibility of the corresponding acting society.

Apart from the above-mentioned premises, further preliminary considerations that are relevant for the discussion were made:

All considerations are under the assumption that that human individuals acting in the future will carry out some exploration in the knowledge of past mining in the salt rock. However, knowledge about details such as the location, kind and scope of the mining activities will have ceased to exist.

Due to the above premise, today's state of the art in science and technology has to be applied. This means that e. g. gamma logs are known methods. This in turn presupposes that the characteristics of the radioactivity are known. However, it does not necessarily have to be assumed that the fact that the waste has been emplaced in salt rock is common knowledge.

Prospection:

In the site exploration and site selection for the creation of caverns in salt, special care is taken to choose salt rock that is as homogenous, unexploited and little permeable as possible since the use of caverns is usually intended for the provision or storage of compressed air, natural gas, hydrogen, methane or liquids (e. g. mineral oil). Possible pathways from past mining activities can lead to considerable storage losses and therefore have to be excluded at all cost.

This is why today checks of whether there have been any past mining activities in the salt are always carried out during exploration. Especially with regard to the residual risk resulting from the loss of knowledge about mining surveys, it can also be assumed for future exploration activities that corresponding studies will be carried out to exclude that any mining has taken place in the past.

The exploration will pay particular attention to the detection of possible cavities underground.

The following methods are available for exploration:

Surface seismics allow a description of the contour of the salt dome. The internal structure of the salt dome, however, cannot be represented by this methodology.

Magnetotellurics can show unusual features within the salt dome that are due e. g. to the emplacement of casks. In the same way, borehole seismics, radargrams and gravimetrics can show up unusual features. The exact interpretation of the unusual features depends strongly on the respective examiner.

Planning and construction phase:

Caverns are preferably created by leaching at a depth of between 550 m and 2,500 m. Most caverns are located below 1,000 m. The usual cavern dimensions are 40 m – 100 m in diameter and up to 300 m in height. The volumes are usually between 500,000 m³ and 1,000,000 m³.

When a cavern is created, safety pillars or safety margins have to be provided to ensure that an adequate distance to certain objects or geological structures is maintained. Among these are the distances to neighbouring caverns, which are 2 to 3 times the diameter of the cavern itself. Other safety margins refer to the distance of 200 m – 300 m to the flanks of the salt dome as well as of 500 m distance to former mine structures (here, one problem is represented by the exploratory boreholes of the former mine) and some 10 m distance to potentially permeable rock types and structures (e. g. anhydrite).

Detection of unusual features:

The composition of the leached brine is only checked for salts (anions, cations), solids, and the value of pH, but not for radioactivity. The unusual feature of the radioactivity originating from waste would hence not be detected in the standard quality assurance of the brine in the laboratory.

Dyed backfill would not necessarily be detected during the leaching process as the backfill will be considerably diluted with the salt rock that is also dissolved. The heat generated by and emanating from the waste will not have a noticeable effect on the amounts of water injected for the leaching process, so that the temperature anomaly will presumably go unnoticed.

A pressure drop upon the encounter of cavities will most likely be detected and examined more closely. Similarly, peak pressures caused by the dropping down of loose rock from the cavern ceiling will be noticed. In such events, the roofs of the cavern and the cavern sump are examined more closely by ultrasonic measuring methods. Owing to its high specific density, a POLLUX cask would lead to a pressure pulse that would surely be noticed if it were to drop or sink down into the cavern. This would entail an ultrasonic examination of the roofs and the brine. The expansion of the cavern is generally examined by means of a sonar device. It is conceivable that the detection of one or more POLLUX casks would – due to their geometric characteristics - be judged as evidence of former anthropogenic intervention in the salt dome and that the creation of the cavern would be stopped due to the risk posed by an old neighbouring mine.

In the case of a leaky or defective cask located inside the cavern, radioactive gases would escape and rise to the top of the cavern, mixing on the way with the sealing medium (mostly nitrogen) of the cavern, the so-called blanket. The radioactivity in the blanket would presumably not be detected.

If any irregularities that have been caused by anomalies induced by the repository were to be identified during the leaching process that would represent an unratable risk for the undertaking of creating a cavern, either further studies would be initiated or, if there were any doubts, the project would be abandoned. In the latter case, the sump would be backfilled (including any repository casks possibly located there) with fly ash, salt or bentonite, and the cavity created would be filled with brine and the borehole cemented.

Operational phase:

From today's point of view, an operational lifetime of the caverns of the order of approx. 100 years is assumed. There is no experience available in this respect as the use of caverns has only developed over the past 50 years.

The pressure fluctuations through gas extraction and re-filling take place below overburden pressure and thus do not lead to the formation of fractures or cracks in the rock.

In connection with the storage of gaseous media, e. g. natural gas, in the caverns, samples are taken and analysed that are, however, not expected to detect any gases released from repository components. There are no tests for radioactivity. Hydrogen is either a constituent of the gases or only of subordinate quantitative relevance.

Decommissioning:

Normally, the cavern will be flooded with freshwater or with brine or unsaturated saline solution. This process is carried out with great care as large temperature differences of brine and rock at the corresponding depth are to be avoided to prevent any resulting stress changes and to not put the integrity of the cavern at risk. After the flooding and following temperature equalisation, the borehole is backfilled with cement. The then still continuing slight convergence corresponds to the impregnation of the surrounding salt rock with the brine.

B Compilation of possible optimisation measures with respect to human intrusion into a repository

Tab. B.1 Categories of possible optimisation measures referring to Tab. B.2

| Entry (No.) | Reference | | Explanation | Example |
|-------------|------------|--|--|--|
| 1.1 | Objectives | Reduction of the possibility of intrusion | Measures with focus on a specific objective | Institutional control |
| 1.2 | | Reduction of the radiological consequences | | Waste separation, compartmentalisation, encapsulation |
| 2.1 | Position | External measures | reference on measures outside the disposal system or be applied | Restriction of use, development freeze |
| 2.2 | | Internal measures | reference on measures inside the disposal system or be activated | Inserting of resistances against tunnelling/mining techniques |
| 3.1 | Action | Passive measures | reference on measures which need no further actions and maintenance if they are once introduced | Labelling and marking |
| 3.2 | | Active measures | reference on measures which need sometimes or continued updates and maintenance | Preservation of information and knowledge |
| 4.1 | Type | Regulative measures | mandatory measures provided by authorities | Surveillance (site inspection, satellite-based) |
| 4.2 | | Constructive measures | measures which require a design layout | Inserting of a reinforced concrete slab near surface |
| 4.3 | Type | Planning measures | measures which require a planning realisation regarding implementation and place of installation | Usage of difficultly soluble fixtures |
| 4.4 | | Conceptual measures | measures which have to be considered in the disposal concept | Placement of the repository (repository depth) |
| 5.1 | Attribute | Delaying | measures which can have a respective effect | Inserting of rubber mats in the emplacement drifts |
| 5.2 | | Detering, preventing, restricting | | Designation as prohibited zone |
| 5.3 | | Indicating, informing, warning | | Optical indicators (fluorescent colours, phosphorescent materials) |
| 5.4 | | Aggravating, hindering, defending | | Increase of the cask wall thickness |
| 5.5 | | Controlling, guarding | | Safeguards |

Tab. B.1 (continued) Categories of possible optimisation measures referring to
Tab. B.2

| Entry (No.) | Reference | | Explanation | Example |
|-------------|---------------------------|---------------------------------------|--|---|
| 6.1 | Dependence | Depending on the spec. human action | measures which are connected to a specific human action | Construction of a borehole top seal, borehole plug made of robust material |
| 6.2 | | Independent of the spec. human action | measures which are not connected to a specific human action | Archiving and documentation (local, regional, national, global) |
| 7.1 | Basic action | Borehole drilling | reference to a specific basic action | Repository dimensions (reduction of spatial expansion) |
| 7.2 | | Creation of a cavern | | Usage of difficultly soluble fixtures |
| 7.3 | | Construction of a mine | | Inserting of resistances against tunnelling/mining techniques |
| 7.4 | | Excavation/ Blasting/ Others | | Inserting of a reinforced concrete slab near surface |
| 7.5 | | General | | Adoption of the issue in the education programme |
| 8.1 | Assessment: cost/ benefit | High | evaluation of the effectiveness of respective measures | Institutional control |
| 8.2 | | Medium | | Labelling and marking |
| 8.3 | | Low | | Alteration of the landscape (difficult to develop) |
| 9.1 | Assessment: effort | Great | evaluation of the expected effort in conjunction with respective measures | Usage of difficultly soluble fixtures |
| 9.2 | | Medium | | Construction of a drift backfilled with robust material/rock |
| 9.3 | | Little | | Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, uranine |
| 10.1 | Assessment: availability | Long-term | evaluation of the temporal availability of respective measures | Placement of the repository (repository depth) |
| 10.2 | | Medium-term | | Inserting of rubber mats in the emplacement drifts |
| 10.3 | | Short-term | | Monitoring of the environment |
| 11.1 | Optimisation conflict | Existing | assessment of the measure regarding optimisation conflicts (e.g. the measure might compromise the safety of the disposal system) | If an optimisation conflict exists depends primarily on the criteria regarding conflicts, respective national regulations, site conditions and disposal concepts. |
| 11.2 | | Explanation | explanation of the reasons in case of an optimisation conflict | |

Tab. B.2 Compilation of possible optimisation measures

| No. | Possible optimisation measures X = applies; (X) = unclear or may not apply, O = no evaluation possible | Categories/ Measures | 1. Objective | | 2. Position | | 3. Action | |
|-----|---|---------------------------------|--|--|--------------------------|--------------------------|-------------------------|------------------------|
| | | | 1.1 Reduction of the possibility of intrusion | 1.2 Reduction of the radio-logical consequences | 2.1 External measures | 2.2 Internal measures | 3.1 Passive measures | 3.2 Active measures |
| A1 | Institutional control | A) Monitoring/ Surveillance | X | | X | | | X |
| A2 | Surveillance (site inspection, satellite-based) | A) Monitoring/ Surveillance | X | | X | | | X |
| A3 | Monitoring of the environment | A) Monitoring/ Surveillance | X | | X | | | X |
| A4 | Restriction of land use, development freeze | A) Monitoring/ Surveillance | X | | X | | | X |
| A5 | Designation as prohibited zone | A) Monitoring/ Surveillance | X | | X | | | X |
| A6 | Safeguards | A) Monitoring/ Surveillance | X | | X | | | X |
| B1 | Placement of the repository (repository depth) | B) Design, engineering barriers | X | | | X | X | |
| B2 | Repository dimensions (reduction of spatial expansion) | B) Design, engineering barriers | | X | | X | X | |
| B3 | Waste separation, compartmentalisation, encapsulation | B) Design, engineering barriers | | X | | X | X | |
| B4 | Inserting of resistances against tunnelling/mining techniques | B) Design, engineering barriers | X | (X) | | X | X | |
| B5 | Increase of the cask wall thickness | B) Design, engineering barriers | X | | | X | X | |
| B6 | Inserting of a reinforced concrete slab near surface | B) Design, engineering barriers | X | | | X | X | |
| B7 | Construction of a drift backfilled with robust material/rock | B) Design, engineering barriers | X | | | X | X | |
| B8 | Inserting of indicators for attracting attention, pointing at existing anomalies | B) Design, engineering barriers | | X | | X | X | |
| B9 | Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, uranine | B) Design, engineering barriers | | X | | X | X | |
| B10 | Chemical indicators (colouring through oxidisation with oxygen in the air, e.g. indigo) | B) Design, engineering barriers | | X | | X | X | |
| B11 | Biological indicators | B) Design, engineering barriers | | X | | X | X | |
| B12 | Optical indicators (fluorescent colours, phosphorescent materials) | B) Design, engineering barriers | | X | | X | X | |
| B13 | Acoustic indicators (set off upon contact with fluids, light, touch, | B) Design, engineering barriers | | X | | X | X | |
| B14 | Mangetic indicators | B) Design, engineering barriers | | X | | X | X | |
| B15 | Olfactory indicators (sulphuric-organic compounds , mercaptane, e.g. odourisation of natural gas) | B) Design, engineering barriers | | X | | X | X | |
| B16 | Emitting indicators | B) Design, engineering barriers | | X | | X | X | |
| B17 | Construction of a borehole top seal, borehole plug made of robust material | B) Design, engineering barriers | X | | | X | X | |
| B18 | Inserting of rubber mats in the emplacement drifts | B) Design, engineering barriers | X | | | X | X | |
| B19 | Warnings, labelling in the emplacement area | B) Design, engineering barriers | | X | | X | X | |
| B20 | Usage of difficultly soluble fixtures | B) Design, engineering barriers | X | (X) | | X | X | |
| B21 | Specific shaped casings which might deflect borehole drillings | B) Design, engineering barriers | X | X | | X | X | |
| C1 | Preservation of information and knowledge | C) Knowledge management | X | | X | | | X |
| C2 | Labelling and marking | C) Knowledge management | X | | X | | | |
| C3 | Archiving and documentation (local, regional, national, global) | C) Knowledge management | X | | X | | | X |
| C4 | Implementation of a commemoration day | C) Knowledge management | X | | X | | | X |
| C5 | Adoption of the issue in the education programme | C) Knowledge management | X | | X | | | X |
| C6 | Creation/maintenance of strong conditions for the preservation of information and knowledge (organisational structure, financing, requirements, national agreements, int. agreements) | C) Knowledge management | X | | X | | | X |
| D1 | Alteration of the landscape (difficult to develop) | D) Siting | X | | X | | X | |
| D2 | Avoiding of resources | D) Siting | X | | X | | X | |
| D3 | Choose regions with low population density | D) Siting | X | | X | | X | |
| D4 | Choose underdeveloped regions | D) Siting | X | | X | | X | |

Tab. B.2 (continued) Compilation of possible optimisation measures

| No. | Possible optimisation measures X = applies; (X) = unclear or may not apply, O = no evaluation possible | 4. Type | | | | 5. Attribute | | | | |
|-----|---|-------------------------------|---------------------------------|-----------------------------|-------------------------------|-----------------|---|--|--|--------------------|
| | | 4.1 Regulative measures | 4.2 Constructive measures | 4.3 Planning measures | 4.4 Conceptual measures | 5.1 Delaying | 5.2 Detering, preven- ting, restricting | 5.3 Indicating, infor- ming, warning | 5.4 Aggravating, hin- dering, defending guarding | 5.5 Controlling |
| A1 | Institutional control | X | | | | X | X | | | X |
| A2 | Surveillance (site inspection, satellite-based) | X | | | | X | | | | X |
| A3 | Monitoring of the environment | X | | | | | | X | | X |
| A4 | Restriction of land use, development freeze | X | | | | X | X | | | X |
| A5 | Designation as prohibited zone | X | | | | X | X | | | X |
| A6 | Safeguards | X | | | | X | | | | X |
| B1 | Placement of the repository (repository depth) | | | | X | | X | | X | |
| B2 | Repository dimensions (reduction of spatial expansion) | | | X | X | | X | | | |
| B3 | Waste separation, compartmentalisation, encapsulation | | | | X | | | | | |
| B4 | Inserting of resistances against tunnelling/mining techniques | | X | | | X | X | | X | |
| B5 | Increase of the cask wall thickness | | X | | | X | X | | X | |
| B6 | Inserting of a reinforced concrete slab near surface | | X | | | X | X | | X | |
| B7 | Construction of a drift backfilled with robust material/rock | | X | | | X | X | | X | |
| B8 | Inserting of indicators for attracting attention, pointing at existing anomalies | | X | X | | | X | X | | |
| B9 | Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, uranine | | X | X | | | X | X | | |
| B10 | Chemical indicators (colouring through oxidysation with oxygen in the air, e.g. indigo) | | X | X | | | X | X | | |
| B11 | Biological indicators | | X | X | | | X | X | | |
| B12 | Optical indicators (fluorescent colours, phosphorescent) | | X | X | | | X | X | | |
| B13 | Acoustic indicators (set off upon contact with fluids, light, touch, | | X | X | | | X | X | | |
| B14 | Magnetic indicators | | X | X | | | X | X | | |
| B15 | Olfactory indicators (sulphuric-organic compounds , mercaptane, e.g. odourisation of natural gas) | | X | X | | | X | X | | |
| B16 | Emitting indicators | | X | X | | | X | X | | |
| B17 | Construction of a borehole top seal, borehole plug made of robust material | | X | | (X) | X | X | | X | |
| B18 | Inserting of rubber mats in the emplacement drifts | | X | | | X | X | | X | |
| B19 | Warnings, labelling in the emplacement area | | | X | | | X | X | | |
| B20 | Usage of difficulty soluble fixtures | | X | X | X | X | X | | X | |
| B21 | Specific shaped casings which might deflect borehole drillings | | X | X | | | | | X | |
| C1 | Preservation of information and knowledge | X | | | | X | | X | | |
| C2 | Labelling and marking | X | X | | | X | X | X | | |
| C3 | Archiving and documentation (local, regional, national, global) | X | | | | | | X | | |
| C4 | Implementation of a commemoration day | X | | | | X | X | X | | |
| C5 | Adoption of the issue in the education programme | X | | | | X | X | X | | |
| C6 | Creation/maintenance of strong conditions for the preservation of information and knowledge (organisational structure, financing, requirements, national agreements, int. agreements) | X | | | | X | X | (X) | | |
| D1 | Alteration of the landscape (difficult to develop) | | | X | | | X | | X | |
| D2 | Avoiding of resources | | | X | | | X | | | |
| D3 | Choose regions with low population density | | | X | | | X | | | |
| D4 | Choose underdeveloped regions | | | X | | | X | | | |

Tab. B.2 (continued) Compilation of possible optimisation measures

| No. | Possible optimisation measures X = applies; (X) = unclear or may not apply, O = no evaluation possible | 6. Dependence | | 7. Basic action | | | | |
|-----|---|---|---|-----------------------------|--------------------------------|----------------------------------|--|--|
| | | 6.1 Depending on the spec. human action | 6.2 Independent of the spec. human action | 7.1 Borehole drilling | 7.2 Creation of a cavern | 7.3 Construction of a mine | 7.4 Excavation/ Blasting/ Others | 7.5 General (no ref. to a specific basic action) |
| A1 | Institutional control | | X | | | | | X |
| A2 | Surveillance (site inspection, satellite-based) | | X | | | | | X |
| A3 | Monitoring of the environment | | X | | | | | X |
| A4 | Restriction of land use, development freeze | X | | | | | | X |
| A5 | Designation as prohibited zone | | X | | | | | X |
| A6 | Safeguards | | X | | | | | X |
| B1 | Placement of the repository (repository depth) | X | | | | | | X |
| B2 | Repository dimensions (reduction of spatial expansion) | X | | X | | | | |
| B3 | Waste separation, compartmentalisation, encapsulation | | X | | | | | X |
| B4 | Inserting of resistances against tunnelling/mining techniques | X | | X | | X | X | |
| B5 | Increase of the cask wall thickness | X | | X | | X | X | |
| B6 | Inserting of a reinforced concrete slab near surface | | X | | | | X | X |
| B7 | Construction of a drift backfilled with robust material/rock | | X | | | | | X |
| B8 | Inserting of indicators for attracting attention, pointing at existing anomalies | | X | | | | | X |
| B9 | Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, uranine | X | | X | X | | | |
| B10 | Chemical indicators (colouring through oxydysation with oxygen in the air, e.g. indigo) | | X | | | | | X |
| B11 | Biological indicators | | X | | | | | X |
| B12 | Optical indicators (fluorescent colours, phosphorescent materials) | | X | | | | | X |
| B13 | Acoustic indicators (set off upon contact with fluids, light, touch, | | X | | | | | X |
| B14 | Magnetic indicators | | X | | | | | X |
| B15 | Olfactory indicators (sulphuric-organic compounds , mercaptane, e.g. odourisation of natural gas) | | X | | | | | X |
| B16 | Emitting indicators | | X | | | | | X |
| B17 | Construction of a borehole top seal, borehole plug made of robust material | X | | X | | | | |
| B18 | Inserting of rubber mats in the emplacement drifts | X | | X | | (X) | | |
| B19 | Warnings, labelling in the emplacement area | X | | | | X | X | |
| B20 | Usage of difficulty soluble fixtures | X | | | X | | | |
| B21 | Specific shaped casings which might deflect borehole drillings | X | | X | | | | |
| C1 | Preservation of information and knowledge | | X | | | | | X |
| C2 | Labelling and marking | | X | | | | | X |
| C3 | Archiving and documentation (local, regional, national, global) | | X | | | | | X |
| C4 | Implementation of a commemoration day | | X | | | | | X |
| C5 | Adoption of the issue in the education programme | | X | | | | | X |
| C6 | Creation/maintenance of strong conditions for the preservation of information and knowledge (organisational structure, financing, requirements, national agreements, int. agreements) | | X | | | | | X |
| D1 | Alteration of the landscape (difficult to develop) | | X | | | | | X |
| D2 | Avoiding of resources | | X | | | | | X |
| D3 | Choose regions with low population density | | X | | | | | X |
| D4 | Choose underdeveloped regions | | X | | | | | X |

Tab. B.2 (continued) Compilation of possible optimisation measures

| No. | Possible optimisation measures X = applies; (X) = unclear or may not apply, O = no evaluation possible | 8. Assessment: cost/ benefit | | | 9. Assessment: effort | | | 10. Assessment: availability | | | 11. Optimisation conflict | |
|-----|---|------------------------------|---------------|------------|-----------------------|---------------|---------------|------------------------------|---------------------|--------------------|---------------------------|---------------------|
| | | 8.1 High | 8.2 Medium | 8.3 Low | 9.1 Great | 9.2 Medium | 9.3 Little | 10.1 Long-term | 10.2 Medium-term | 10.3 Short-term | 11.1 Existing | 11.2 Explanation |
| A1 | Institutional control | X | | | X | | | | | X | | |
| A2 | Surveillance (site inspection, satellite-based) | X | | | | X | | | | X | | |
| A3 | Monitoring of the environment | | X | | X | | | | | X | | |
| A4 | Restriction of land use, development freeze | X | | | | | X | | | X | | |
| A5 | Designation as prohibited zone | X | | | | | X | | | X | | |
| A6 | Safeguards | X | | | | X | | | | X | | |
| B1 | Placement of the repository (repository depth) | X | | | X | | | X | | | | |
| B2 | Repository dimensions (reduction of spatial expansion) | | X | X | X | X | | X | | | | |
| B3 | Waste separation, compartmentalisation, encapsulation | | X | | | X | X | X | | | | |
| B4 | Inserting of resistances against tunnelling/mining techniques | | X | | X | | | X | | | | |
| B5 | Increase of the cask wall thickness | X | X | | X | | | X | X | | | |
| B6 | Inserting of a reinforced concrete slab near surface | | X | | X | | | | X | | | |
| B7 | Construction of a drift backfilled with robust material/rock | | X | X | | X | | | X | | | |
| B8 | Inserting of indicators for attracting attention, pointing at existing anomalies | | X | X | | | X | X | X | | | |
| B9 | Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, uranine | | X | X | | | X | X | X | | | |
| B10 | Chemical indicators (colouring through oxidisation with oxygen in the air, e.g. indigo) | | X | X | | | X | X | X | | | |
| B11 | Biological indicators | | X | X | | | X | X | X | | | |
| B12 | Optical indicators (fluorescent colours, phosphorescent materials) | | X | X | | | X | X | X | | | |
| B13 | Acoustic indicators (set off upon contact with fluids, light, touch, | | X | X | | | X | X | X | | | |
| B14 | Magnetic indicators | | X | X | | | X | X | X | | | |
| B15 | Olfactory indicators (sulphuric-organic compounds, mercaptane, e.g. odourisation of natural gas) | | X | X | | | X | X | X | | | |
| B16 | Emitting indicators | | X | X | | | X | X | X | | | |
| B17 | Construction of a borehole top seal, borehole plug made of robust material | | X | | X | | | X | | | | |
| B18 | Inserting of rubber mats in the emplacement drifts | | | X | | X | | | X | | | |
| B19 | Warnings, labelling in the emplacement area | | X | X | | | X | X | X | | | |
| B20 | Usage of difficultly soluble fixtures | | X | X | X | | | X | | | | |
| B21 | Specific shaped casings which might deflect borehole drillings | | X | X | X | | | X | X | | | |
| C1 | Preservation of information and knowledge | X | | | X | | | | | X | | |
| C2 | Labelling and marking | | X | | | X | | | X | X | | |
| C3 | Archiving and documentation (local, regional, national, global) | X | | | X | | | | | X | | |
| C4 | Implementation of a commemoration day | X | X | | | | X | | | X | | |
| C5 | Adoption of the issue in the education programme | X | X | | X | X | | | | X | | |
| C6 | Creation/maintenance of strong conditions for the preservation of information and knowledge (organisational structure, financing, requirements, national agreements, int. agreements) | X | | | X | X | | | | X | | |
| D1 | Alteration of the landscape (difficult to develop) | | | X | X | | | O | O | O | | |
| D2 | Avoiding of resources | | X | X | | | X | O | O | O | | |
| D3 | Choose regions with low population density | | X | X | | | X | O | O | O | | |
| D4 | Choose underdeveloped regions | | X | X | | | X | O | O | O | | |

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