Optimization of the Direct Disposal Concept by Emplacing SF Canisters in Boreholes

Final Report

DBE TECHNOLOGY GmbH

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Abstract

In Germany, the reliable and safe transportation and emplacement of remote-handled waste and spent fuel canisters has to be demonstrated before a final repository can be implemented. The amounts and types of waste and spent fuel packages to be disposed of are the key factors that determine the design of both, the transport as well as the emplacement systems. In this context, this project considered the emplacement of small diameter canisters for heat-generating spent fuel and containers for vitrified waste into deep vertical boreholes.

Within the project, a transfer and emplacement system that can be used to dispose of both categories of heat-generating disposal packages (vitrified waste from reprocessing and spent fuel) in up to 300-m-deep boreholes in a repository in salt was designed and developed and its safety and reliability was demonstrated. For consolidated spent fuel, a new fuel rod canister with a length of 4.97 m, an outer diameter of 0.43 m, and a weight of 5.2 metric tons was designed and provided by the German nuclear industry. This so-called BSK 3 canister (in accordance with the acronym for the German word for fuel rod canister, i.e. Brennstabkokille) can be filled with the fuel rods of 3 PWR or 9 BWR fuel assemblies.

After the new BSK 3 disposal concept had been developed in a series of paper studies, it was decided to carry out a comprehensive demonstration programme to confirm the expected advantages. The main expectations were:

- Improved repository layout due to higher packing density when combining the emplacement of heat-generating packages (SF and vitrified HLW) and waste with negligible heat generation also designated for borehole disposal according to the reference concept
- Reduced areal extension of the repository by three-dimensional utilization of the host rock, at the same time reducing the exploration effort
- Reduction of potential gas problems due to significantly reduced amount of metal when using unshielded containers
- Complete isolation of the waste in the impermeable host rock by the converging salt is an important safety feature of a salt repository. As the void around the BSK 3 canisters in the borehole is small, isolation can be attained within less than a year whereas enclosure of the POLLUX® casks may take several decades.
- Reduction of the variety of container and cask systems required due to the fact that the SF canister has the same external diameter as the vitrified HLW canister. The BSK 3 concept will lead to an emplacement technology that is harmonized and standardized to a large extent and will use essentially the same equipment for hoisting and transport for all packages designated for disposal in a repository for HLW and SF.

All full-scale demonstration tests of the emplacement system were carried out in a surface facility using inert canister dummies with the same dimensions and masses as real BSK 3 canisters. The test facility was a former turbine hall of a power station in Landesbergen, a village near Hanover, Lower Saxony. In spring 2008, the platform for the test stand and a 10-m-long vertical steel metal casing simulating the emplacement borehole below the platform were erected 10 m above the ground floor of the turbine hall, followed by the delivery and assembly of the components of the emplacement system in the summer of the same

year. After a successful Site Acceptance Test, the test and demonstration campaigns comprising demonstration tests, simulation tests, and tests to identify potential operating failures and to develop preventive and corrective measures were carried out between September 2008 and July 2009. Furthermore, backfilling tests were carried out. As the aim was to develop an emplacement technology for all types of radioactive waste, additional transport and emplacement tests with HLW canister dummies were carried out as well.

Results of demonstration tests

The demonstration tests comprised all the process steps, starting with the acceptance of the BSK 3 canister and concluding with the emplacement of the canister into the vertical borehole. In total, 1,004 complete emplacement operations had been carried out by the end of the test programme. The entire system and each component proved to be safe, reliable, and robust. The masses involved in the BSK 3 concept are slightly lower than those in the POLLUX® concept. It can thus be assumed that all shaft transport and hoisting devices developed for the POLLUX® concept are applicable for the BSK 3 concept as well.

Simulation tests and tests of operational disturbances

Several technical and safety-related features were tested additionally. To simulate more realistic conditions within the borehole, the BSK 3 dummy was lowered onto a salt layer covering the head of a previously "emplaced" canister at the bottom of the simulated emplacement borehole. The challenge was to safely open the grab after the canister had been emplaced, even if the canister was not in a strictly upright position but touching the wall of the borehole. It was demonstrated that the grab of the emplacement device could safely be unhooked from the canister in all cases.

After one borehole has been filled, the emplacement device will be transported to the next borehole by means of the transport cart. This process was also simulated at the full-scale test facility. The safe transport of the emplacement device from borehole to borehole could be demonstrated as well.

In case of derailing, the transport cart loaded with the transfer cask needs to be set back onto the rails by means of conventional equipment. Corresponding demonstration tests were carried out successfully.

Additional emplacement tests with HLW canister dummies

The full-scale demonstration programme was extended by additional tests with HLW dummies. The idea was to demonstrate the technical feasibility of handling HLW canisters with the same equipment as was used for BSK 3 canisters. For this purpose, a so-called triple pack was designed and fabricated; a steel envelop containing three HLW dummies with almost the same outer diameter and the same height as the BSK 3. A further series of emplacement processes (110) was successfully performed with this triple pack, confirming the reliability of the emplacement system for this type of canisters as well.

Demonstration test regarding the technology for backfilling emplacement boreholes

From the point of view of radiation protection and with regard to thermal aspects, the gap between BSK 3 and the borehole wall needs to be backfilled, even in the area close to the borehole cellar. In a repository in salt, crushed salt will be used as backfill material. The objective of this additional demonstration test was to develop the corresponding technology and to investigate whether the space around the BSK 3 could be completely filled or not; just to confirm existing assumptions. A prototype backfill canister was fabricated and the crushed salt inserted into the borehole. The grain size of the crushed salt was between 4 and 8 mm. The test showed that the space between BSK 3 canister and borehole wall can be filled completely.

Conclusions and Outlook

Several years after the demonstration test of all the elements of the German reference concept for spent fuel disposal (POLLUX concept) had been concluded, a new, alternative system was developed and tested comprehensively. The reliability of the handling technologies for the BSK 3 concept has been confirmed in aboveground “cold” full-scale demonstration tests as well. From a technical point of view, both concepts are now ready for testing underground to simulate typical “mining conditions” with higher temperatures and a dustier environment.

While the operational handling technology for the disposal of the POLLUX® and the BSK 3 concept have been tested at full scale aboveground, the testing of the related conditioning technologies is still pending. It is recommended to continue the demonstration tests with full-scale underground handling test programmes and with a pilot program for the conditioning of fuel assemblies as soon as the system of safety requirements for final disposal is sufficiently developed.

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1 Introduction

The integrated project ESDRED (Engineering Studies and Demonstration of Repository Designs) was a joint research project within the 6th Framework Programme of EURATOM. The overall aim within a 5-year programme was to demonstrate at an industrial scale the technical feasibility of a number of specific technologies related to the construction, operation and closure of a deep geological repository for spent fuel and long-lived radioactive waste.

The ESDRED programme consisted inter alia of the technical Module # 2 "Waste canister transfer and emplacement technology".

DBE TECHNOLOGY GmbH was responsible for the management of Module # 2: Waste canister transfer and emplacement technology. The contracting partners in Module # 2 were ANDRA (France), DBE TECHNOLOGY GmbH (Germany) and NRG (Netherlands).

The detailed objectives of this Module were:

- Identification of a clear set of shielding cask requirements based on European nuclear regulations and on the safety objectives of the implementers

- Demonstration at an industrial scale of the technical feasibility of the transportation and emplacement of remote-handled vitrified waste canisters in horizontal cells (French case) and spent fuel canisters in deep vertical boreholes (German case)

According to some of the national waste management programmes, the feasibility of a reliable and safe transportation/emplacement technology for remote handled waste canisters has to be developed and demonstrated prior to repository implementation.

In Germany, an alternative to the existing reference concept which proposes the emplacement of self-shielded 65-t carbon steel POLLUX® casks containing spent fuel assemblies in horizontal drifts of a repository in salt has been developed. This report outlines a new disposal technology for spent fuel canisters and HLW canisters in deep vertical boreholes starting from the 870-m level of a repository in salt. This is an approach to minimize and optimize the efforts for transport, handling, and disposal of spent fuel rods compared to the reference concept of drift disposal of heavy self-shielding POLLUX® casks. The corresponding spent fuel canister (BSK 3) and the necessary equipment for the disposal operations, i.e. transfer cask, transport cart, mining locomotive, borehole lock, and emplacement device as well as the operational sequences are described. A test programme for tests with inactive canister dummies in a surface facility was carried out as well. These tests were necessary to demonstrate the reliability and safety of the emplacement system by means of a large number of tests. As a result conclusions are drawn and recommendations are given for the industrial application of this technology in a repository. The demonstration tests were followed by tests to eliminate operational disturbances, by simulations and backfilling tests. The results were to provide all information required for a new back-end technology, satisfying the legal requirements for a German final repository. The report starts with a brief description of the German repository concepts for spent fuel and high level waste.

2 Description of the German Reference Concept for the Disposal of Spent Fuel Casks and Vitrified Waste Canisters

The German reference concept proposes to dispose of heat-generating HLW and spent fuel in a salt formation. For this purpose, it is intended to excavate a new mine in a virgin salt formation far from existing mining cavities. The salt formations in the north of Germany are considered to be suitable for the emplacement of HLW and spent fuel as they possess several favourable properties, thus fulfilling stipulated siting criteria /1/:

- absence of water within a geological time period shown by the existence of salt
- tightness of undisturbed salt host rock against salt solutions (permeability to gas $< 10^{-21}$ m^2 disconnected pore space)
- closing of cavities and voids induced by mining activities due to creep behaviour and elimination of fractures over time due to healing capacity
- high thermal conductivity
- simple mining conditions and large experience in salt mining
- abundance of salt in northern Germany
- stable geologic conditions in northern Germany with negligible seismic activities

Since 1979, the salt dome near the village of Gorleben in Lower Saxony is being evaluated as to its suitability to host a repository for all kinds of radioactive waste. The site exploration is aimed at furnishing the body of data and information needed to prove the site suitability on the one hand and to support a subsequent licensing procedure on the other hand.

The geologic setting, the gross structure of the dome, how it is embedded in the adjacent geology as well as the hydrogeological situation of the overburden were carefully evaluated during an extensive geological and hydrogeological surface exploration programme. The information obtained confirmed that the Gorleben dome spans from 260 m below the surface down to a depth of 3,500 m, is about 15 km long and 2 to 4 km wide at a depth of 800 to 1,000 m (Figure 2-1).

The results of the surface survey supported the assumption that the dome is suitable to host a repository. Therefore, underground survey was started in 1983 to obtain additional data and information about the dome's geological structure and to confirm the existence of sufficiently large homogenous rock salt volumes to host waste disposal areas. First, two shafts were sunk in the central part of the dome and in 1996 these were connected by a drift at the exploration level of 870 m below the surface. The drifts and chambers for the infrastructure of the exploration level are almost completely excavated.

In 1998, excavation of the survey areas to the northeast of the shafts was started. Concurrently, an extensive geo-scientific survey programme was carried out, making wide use of core drillings and non-destructive survey methods. The work included mapping of the geological strata of the exploration mine, analysis of the drill cores, seismic profiling, and several methods to determine the rock permeability, the states of stresses, and the rock temperature. In autumn 2000, a moratorium on the exploration campaign at the Gorleben site was ordered by the Federal Government for a period of three to ten years.

The reference concept for the disposal of heat-generating radioactive waste comprises the emplacement of canisters containing vitrified waste in deep vertical boreholes, whereas spent fuel will be disposed of in self-shielding POLLUX® casks in horizontal drifts inside a salt mine /2/. The disposal zones for both, spent fuel and vitrified waste, are to be constructed at a depth of 870 m. In the disposal concept, which allows a temperature of 200 °C max. at the contact between waste canister and host rock, unshielded canisters with vitrified high-level radioactive waste (HLW) are to be emplaced in up to 300-m-deep boreholes with a diameter of 60 cm. In order to facilitate the fast encapsulation of the waste by the host rock (rock salt), the boreholes are not to be furnished with lining. The POLLUX® casks, which are 65-tonne carbon steel casks, will be placed on the floor of a horizontal drift. The space between the casks and the drift walls will be backfilled with crushed salt.

Obtaining a license to construct a repository in Germany requires prior demonstration to the competent authority that the level of protection (dose or risk) can be met with a high level of confidence. In the case of waste canister transport and handling systems, the fulfilment of the regulatory requirements can be provided by means of full-scale demonstration and reliability tests. In the 1990s, the transport, handling and emplacement technologies for the POLLUX® cask were subject to successful demonstration and in-situ tests performed. As a result, the Atomic Energy Act was amended in 1994. Before the ESDRED project was carried out, this demonstration was still pending for waste canisters with high level waste from reprocessing.

2.1 Disposal of POLLUX® Casks in Horizontal Drifts

The reference fuel is a UO_2 PWR fuel assembly with a uranium enrichment of 4 % and 50 000 MWd /t_{HM} average burn-up. The waste package is a POLLUX®-8 cask, filled with the rods of 8 disassembled fuel elements. Originally, it was planned to fill the cask's central bin with compacted structural parts of fuel assemblies. The gross weight of a loaded POLLUX® Cask is 65 t max. In a concept update, it was later decided to load the central bin with the fuel rods of two additional fuel elements (POLLUX®-10 cask) (Figure 2-2), and to dispose of the compacted fuel element structural parts in so-called CSD-C containers ("colis standard de déchets compactés" i.e. "standard package for compacted waste").

In the case of drift disposal of POLLUX® casks, surface operations in a repository consist of the following steps. Waste packages arrive by railway or truck. After passing inspection, the waste packages are loaded on rail-bound transport carts by a bridge crane. Thereafter, the transport cart is positioned for hoisting in front of the hoisting cage safety gate. When the hoisting cage is in place, the safety gate opens and the transport cart is loaded into the cage by means of an underfloor caging device. The cage is then lowered down to the emplacement level.

Figure 2-1: **Gorleben Salt Dome (prospective geology as in the working model)**

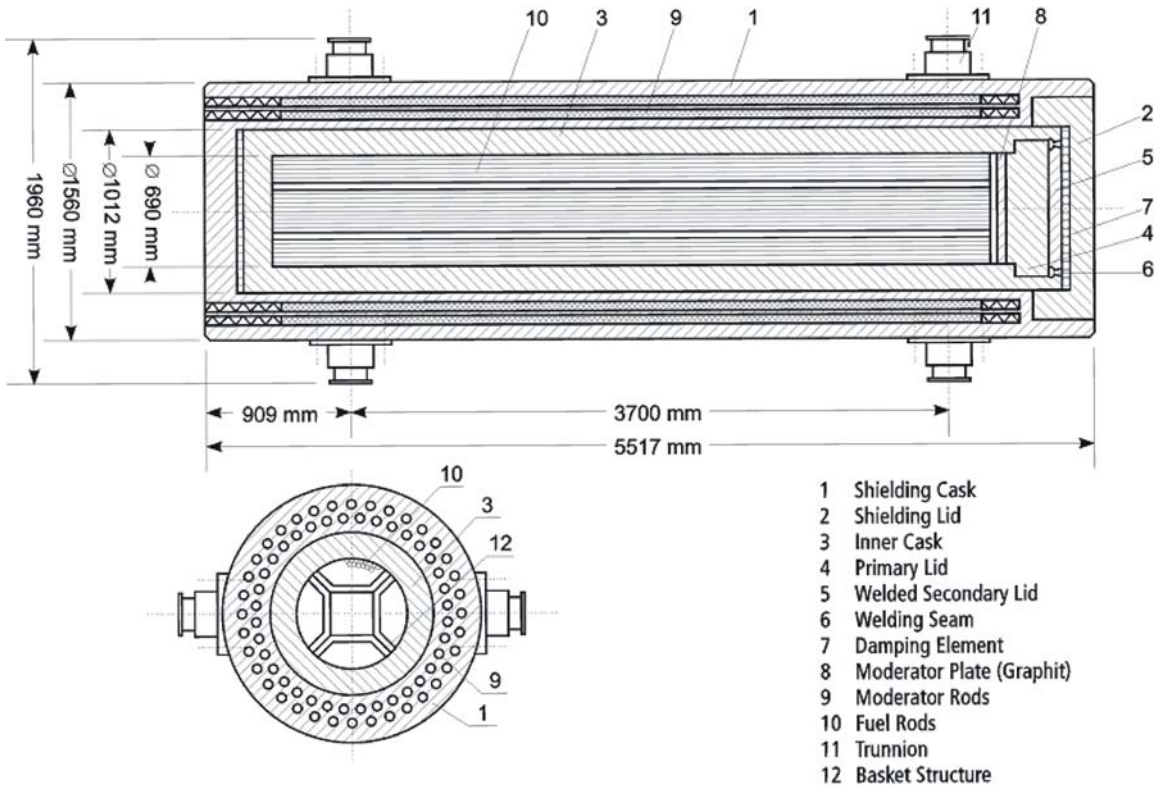


Figure 2-2: POLLUX® cask for 10 PWR spent fuel elements max.

A battery-driven mining locomotive pulls the loaded transport cart from the underground shaft landing station through the access drift into the disposal zone until it reaches the designated position in the disposal drift. The waste container is lifted from the transport cart by the emplacement device; the cart is then towed away to clear the cask for emplacement, and the empty cart is transported back to the surface on the same way but in reverse direction.

Thereafter, the waste package is lowered onto the drift floor and the emplacement device is towed away into the neighbouring drift. With the emplacement drift now free of heavy equipment, it is possible to backfill the void volume around the emplaced waste container. The steel rails on which the heavy equipment is hauled into and out of the emplacement drift remain in place after the disposal cycle has been completed. Figure 2-3 shows the reference disposal concept, and Figure 2-4 the equipment prototypes.

The mining locomotive, the transport cart, the emplacement device, and a POLLUX® cask dummy were manufactured in compliance with the full set of specifications of the real disposal equipment and successfully tested under simulated repository conditions. The competent certification bodies certified all components as ready for licensing. The same was done with the shaft transport equipment.

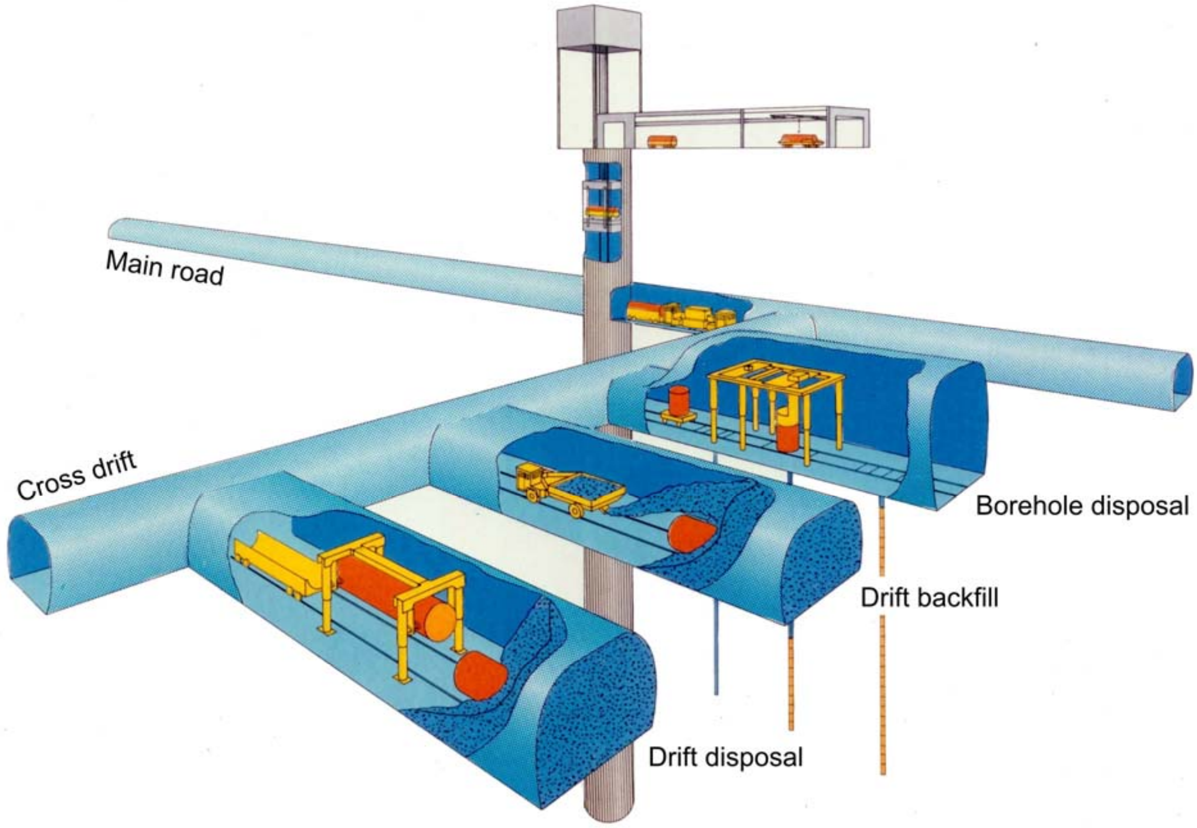
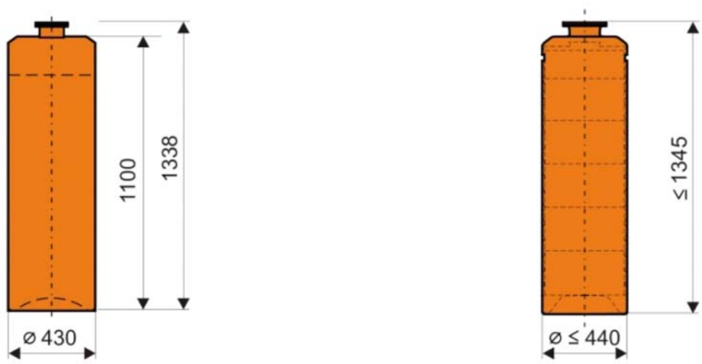


Figure 2-3: **Reference concept for HLW and spent fuel disposal in salt**

Figure 2-4: **Emplacement equipment**

2.2 Disposal of HLW and CSD-C Canisters in Vertical Boreholes

For the final disposal of heat-generating, unshielded HLW canisters, the emplacement in vertical boreholes is conceptually feasible. The depth of the vertical boreholes is approximately 300 m. Allowing 10 m for the seal, the useable length of deep boreholes is approximately 290 m. The actual usable borehole length in the final disposal concept is not yet determined as it depends on a number of factors like heat quantity, waste quantity, emplacement technique, and drilling technique. It is furthermore possible to emplace CSD-C canisters by means of this technique as long as their outer geometry is adapted to the HLW canisters (Figure 2-5). The diameter of the borehole depends on the convergence rate of the surrounding salt and the time elapsed before filling the borehole with waste canisters. Heat-generating vitrified HLW is contained in standard COGEMA canisters while highly active technical waste with low heat generation, mainly caps and claddings, is contained in CSD-C canisters. The main waste canister characteristics, including the amount to be disposed of, are given in Table 2-1.



	HLW Canister	CSD-C Canister
Weight:	0.50 t	0.85 t

Figure 2-5: HLW- and CSD-C-canisters

Table 2-1: Characteristics of the waste canisters for the disposal of heat generating waste

		HLW Canister	CSD-C Canister
Number of canisters		4,778	8,764
Number of boreholes needed		30	55
Length	mm	1,338	≤ 1,345
Diameter	mm	430	≤ 440
Total mass	kg	approx. 492	≤ 850
Heat generation • at loading • after 10 years • after 30 years	kW	 1.120*) 0.67**)	 0.02

*) after 9 years **) after 29 years

For borehole disposal, the boreholes are drilled in designated emplacement drifts at regular intervals. The drilling begins closest to the cross-cut of the emplacement drift and ends at the opposite end of the drift. After the borehole has been drilled, the borehole mouth accommodates the borehole lock, which takes care of the shielding of the borehole during the emplacement phase. Ventilation of the boreholes during the backfilling operations is effected via an annular gap and a socket onto which a suction pipe is attached which cleans out dust generated during backfilling operations.

The HLW and CSD-C canisters are delivered to the shaft station handling facility in transfer casks, reloaded onto transport carts, and transported to the final disposal location underground. Each transport cart can carry one transfer cask.

The boreholes are filled up to within 10 m of the borehole mouth, backfilled and subsequently sealed at the level of the drift floor. The height of the transportation drift is determined by the height required by the drilling equipment or the emplacement device.

When one borehole is filled, the emplacement device is moved to the next borehole by means of a transport cart and set up again for operation. After attachment of the power supply and data transmission cables as well as a test run, the emplacement of further canisters takes place in the same way as described above. After the filling and sealing of all boreholes in a disposal drift, the drift is backfilled as well.

3 Optimization of the Direct Disposal of Spent Fuel

In order to harmonize and optimize the emplacement technology for both categories of waste (vitrified waste and spent fuel), alternative technical approaches were sought during the past couple of years. In this context, the borehole emplacement technique for consolidated spent fuel as already considered for high-level waste from reprocessing was reconsidered. A starting point was the decision of the German nuclear industry to develop a new fuel rod canister (called BSK 3 canister), which can be filled with the fuel rods of 3 PWR or 9 BWR fuel assemblies.

3.1 Potentials of the BSK 3 Concept to Optimize SF Emplacement

Compared to the reference concept, the BSK 3 concept offers the following optimization potentials:

The new BSK 3 canister is tightly closed by welding and designed to withstand the lithostatic pressure at the emplacement level. It has almost the same diameter as the standardized HLW canisters for HLW and compacted technological waste from reprocessing abroad. Thus, it is possible to use the same transfer and handling technology for both categories of packages (vitrified HLW and spent fuel).

The residual heat generation of a canister loaded with fuel rods burned up to 50 GWd/t_{HM} (4 % initial enrichment) will allow its emplacement in a salt repository after only about 3 to 7 years after reactor unloading of the fuel assemblies. This has been verified by thermal calculations.

Due to the close contact between canister and host rock, the heat transfer from the waste canister will be improved. Compared to the emplacement of POLLUX® casks, the creep process of the host rock (rock salt) will be accelerated which leads to a faster (earlier) encapsulation of the waste canister. This might reduce the requirements for geotechnical barriers. Furthermore, as there will be less metallic material mass, the potential for gas generation (e.g., by corrosion) will be reduced.

As the host rock will be used in three dimensions, the footprint of the repository can be kept to a minimum.

The following design requirements need to be met by the BSK 3:

- Guarantee of sub-criticality of the fuel rod configuration
- Post-decay heat dissipation from the fuel rod configuration
- Protection of the fuel rod configuration against mechanical impact during emplacement in a borehole as well as during transportation from a conditioning plant to the emplacement location in a final repository
- Tight enclosure of the radioactive materials of the fuel rod configuration.

3.2 Description of the BSK 3 canister

The BSK 3 canister was designed to contain a total activity of up to 0.8E+17 Bq, and to be capable of transferring a maximum heat load of 6 kW. For interim storage purposes, the minimum decay time of the spent fuel assemblies must be determined so that the maximum allowable gamma and neutron dose rates at the surface of the interim storage cask as well as the permissible structural and fuel-rod cladding temperatures will not be exceeded. The calculations were carried out based on an assumed loading of the BSK 3 canister with 3 PWR uranium fuel assemblies. The active length of the fuel rods is 3.9 m. The design value of 6 kilowatts is reached after a decay time (time after extraction from the reactor) of 3 years and 11 months. The main design criteria are:

- Capacity for heavy metals up to 1.63 t_{HM}
- Max. heat output capacity of the canister contents 6 kW
- Max. cladding strain for the storage time by limitation of the cladding temperature < 1 %
- Max. tangential tension < 100 MPa
- Neutron multiplication factor during transport and inspection conditions $k_{eff} + 2\sigma < 0.95$
- Permissible He-Standard-Leakage rate (sealing of the primary lid) $1 \cdot 10^{-3}$ hPa *l/s
- Permissible He-Standard-Leakage rate after welding of the secondary lid
  << 1·10-7 hPa *l/s
- Strength (maximum isostatic rock pressure in the repository) 30 MPa

The main BSK 3 canister characteristics, including the numbers that need to be disposed of, are given in Table 3-1.

The new Federal Government inaugurated after the 1998 elections has declared its intention to phase out nuclear power use in Germany after a transition period. They stipulated that each power plant be closed down after reaching a total electricity generation output equivalent to a service life of approx. 32 years without unplanned outages. Such generation permits can be transferred from one power plant to others, notably from older to newer ones. The total allowed future electricity generation amounts to slightly more than 6;000 TWh.

Table 3-1: Characteristics of the BSK 3 canister for the disposal of heat-generating waste

		BSK 3 Canister
Number of canisters		approx. 5,525
Number of boreholes needed		approx. 95
Length	mm	4,980
Diameter	mm	≤ 440
Total mass	kg	5,226
Mass HM	t_{HM}	1.6
Heat generation • at loading • after 10 years • after 30 years	kW	 21.220 3.030 1.930

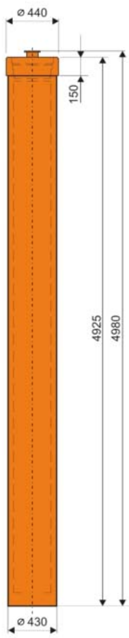


Figure 3-1: **BSK 3 canister**

The BSK 3 canister is designed for the final disposal of irradiated fuel rods from fuel assemblies. This report addresses the loading of the transfer cask with a BSK 3 canister which can contain the spent fuel rods of 3 PWR fuel assemblies. For handling reasons, the fuel rods are inserted into semi-cylindrical inner casings which are placed into a BSK 3. The BSK 3 canister is designed in such a way that it meets the requirements for internal on-site use as well as for final disposal in boreholes.

A BSK 3 canister is a cylindrical container with a welded base plate of fine grained construction steel. The top end of the BSK 3 canister is closed by a system of covers, comprising a threaded primary cover and a welded secondary cover. A grab attachment integrated in the secondary cover is used for handling. On the underside of the primary cover, an enclosed moderator plate is installed.

The outer diameter of a BSK 3 is the same as the outer diameter of an HLW glass canister for vitrified highly radioactive waste from reprocessing. Thus, the same handling equipment and technology can be used for both canister types.

The post decay output is not homogeneously distributed over the active length of the fuel rods, as there is a distinctive power distribution with a maximum in the fuel rod middle. The maximum additional power (peaking factor) is a factor of 1.1 for the considered PWR fuel assemblies.

The BSK 3 concept therefore may provide a common solution for the emplacement of all types of heat generating radioactive waste in Germany and a considerable reduction of the necessary efforts in terms of time.

In chapters 4 and 5 the conceptual design, the basic design, the detailed design and the manufacturing of the transport and emplacement components for the vertical borehole disposal system are described.

4 Conceptual and Basic Design

In this chapter, the input data and functional requirements are compiled followed by the technology required to drill the emplacement boreholes under the expected boundary conditions of the Gorleben salt dome. Furthermore, the emplacement sequence is described.

4.1 Input Data and Functional Requirements

To compile the safety requirements the following documents were taken into account:

- Konrad repository licensing documents
  - Shaft landing station straddle carrier

- Gorleben repository conceptual design documents
  - Description of the shaft hoisting equipment
  - Waste emplacement device

- The HLW project: Test disposal of highly radioactive radiation sources in the Asse salt mine
  - Waste emplacement device
  - Borehole slider (lock)
  - Transfer cask

4.1.1 Preliminary Safety Requirements

Based on this, the following list of safety requirements were taken into account:

- Designation of radiation protection areas (controlled area, limited access areas)
- Adequate measures to reduce the radiation exposure of operating personnel including prevention of radiation leakage at the contact zones between transfer cask, borehole lock and shielding cover. The personnel has to be able to inspect, repair, and maintain the emplacement device during the operational phase
- Fire prevention for supporting devices and components as well as electric systems and components
- Preventing that waste packages crash into the borehole during emplacement operations
- Preventing that battery locomotive and cart crash into the emplacement device
- Preventing that other heavy loads crash onto the waste packages
- Preventing hoisting winch from overwinding
- Ensuring that load lowering or other movements are carried out at adequate speed
- Transfer of the system into a safe condition in case of operational malfunction or power failure
- Locking or stopping of the emplacement device winch in case operational limits for the selected operating mode are exceeded

- Availability of approved design and operational-engineering documentations
- Preventing emplacement device from moving during BSK 3 emplacement

4.1.2 Preliminary Operational Requirements

On this basis, the following operational design requirements were taken into account:

- Possibility to safely reach the disposal position
- Possibility to reach the storage level depth
- Emplacement device with capacity to hoist cylindrical BSK 3 with a gross weight of up to 5.3 t and with the following dimensions:
  - Height 4;980 mm
  - Diameter 440 mm
- Compliance with the necessary throughput capacity
- Reliable transfer of signals and power to the BSK 3 grab control and the backfill canister
- Safe power supply for the hoisting components
- Reliable control cabin power supply
- Easy maintenance and servicing, including decontamination of systems coming into contact with waste packages, corrosion protection, systems designed for mining conditions and operations
- Equipment made of materials compatible with the anticipated loads and climatic conditions
- Components, parts, and devices to be certified for operation under mining conditions
- Preventive maintenance and repair of all equipment at regular intervals

4.1.3 Climatic Conditions on Site and Site Characteristics

The following boundary conditions had to be taken into account in the equipment design:

- Climatic conditions on site
  - Temperature max. 52 °C
  - Humidity max. 70 %
- Dust
- Lighting
- Convergence of the salt
- Power supply

4.1.4 Technical External Requirements

The technical external requirements comprise:

- Technical conditions of the BSK 3 filling station
- Technical conditions of the shaft hoisting system

4.1.5 Range of Application of the Emplacement System

The emplacement system is:

- to transport the transfer cask from the loading station to the shaft
- to transport and position the emplacement device
- to transport the BSK 3 through the shaft to the shaft landing station
- to transport and position the borehole lock
- to emplace the BSK 3 into the borehole
- to transport backfill to the borehole
- to backfill the borehole

4.1.6 Interfaces between External and Internal Equipment

The main interfaces are:

- for the transfer cask, the trunnions and the trunnion mounting of the transport cart
- for the transfer cask, the locks of the reloading station above ground, the shielding cover of the emplacement device, the cask lock, and of the borehole lock
- for the transport cart, the loading and unloading devices at the shaft and the equipment necessary for the shaft transport
- for the transport cart, the underground rail system
- for the transfer cask, the trunnions and the trunnion mountings of the emplacement device
- for the emplacement device winch, the grab to handle the BSK 3
- for the BSK 3 head, the grab of the emplacement device
- for the transport of the backfill, the borehole lock
- for the battery locomotive, the coupling to the transport cart
- for the battery locomotive, the intended wireless control of the emplacement device

4.2 Preparation of the Emplacement Boreholes

4.2.1 Drilling Technology for the Emplacement Boreholes

For the emplacement of BSK 3 canisters in deep geological formations, deep boreholes are to be drilled underground at the emplacement level. The boreholes must have a diameter of 600 mm and are to be drilled vertically with a borehole-to-borehole distance of approx. 50 m. The final depth of each borehole is to be at a maximum of 300 m below drift level.

For the planning of this drilling task, conditions corresponding to the situation in the Gorleben exploration salt mine are assumed. Thus, from the point of view of rock mechanics, the bore-holes will be drilled in a soft but stable formation.

A precondition for the emplacement of BSK 3 canisters is a "dry" borehole. This means that during the drilling process the borehole has to be kept dry. Furthermore, a so-called blowout preventer (BOP) must be used to impede uncontrolled leakage of gas and/or brine from the borehole.

Undue vertical deflection of the borehole is to be avoided to prevent the hoisting cable from touching the borehole wall during the emplacement process which can lead to abrasion and premature wear and tear of the hoisting cable.

4.2.2 Preparation of the Emplacement Borehole

Securing a borehole with a diameter of 600 mm against uncontrolled escape of gases and/or brines mentioned above is currently technically not feasible as pressures of up to 20 MPa must be expected. There are not yet any preventers for underground use which can absorb these high pressures and lateral forces of up to 6 MN at the mouth of the borehole.

For this reason, it is planned to drill an emplacement borehole in two steps. First, a preliminary or exploratory borehole with a small diameter is drilled using a corresponding preventer. An extension borehole with the final diameter is produced without the use of a preventer, unless uncontrolled gas and/or brine escapes.

4.2.2.1 Preparation of the Drilling Site

Due to the space required by the drilling equipment, the current emplacement concept specifies the lowering of the borehole mouth into a borehole cellar with a depth of 2.85 m. This borehole cellar is used for the installation of securing and guiding elements on the borehole mouth. The clearance is then sufficient to feed the standardised 3-m-long drilling rod sections to the borehole in the drilling process.

4.2.2.2 Preliminary or Exploratory Borehole

Usually, a simple preliminary borehole is drilled using a preventer as mentioned above. If the mining authority so demands, an exploratory borehole is drilled using a core drilling system. The cores drilled are used to assess the surrounding rock and to prove the quality of the borehole.

A prerequisite for core drilling is the production of a secured borehole. For this, a 3-m-long borehole is drilled first; it can be drilled without securing. An upright pipe with packer is inserted into this borehole to seal the borehole towards the rock with lateral securing elements and to house the preventer, i.e. the sealing element to the drill pipe. The upright pipe packer and the drill pipe are chosen as small as possible in order to avoid the use of a large preventer. In the next working step, drilling is done down to 25 m. If an undisturbed rock formation is found, there is drilling for the setting of the anchor pipe. After cementation of the anchor pipe, the core drilling process can be carried out down to a depth of 300 m.

4.2.2.3 Extension Borehole

The drilling work for the extension borehole is carried out with a larger drilling system which has much higher performance features for the drilling work and scavenging than the equipment for the preliminary/exploratory boreholes. By means of a core drill, the inner diameter of which is larger than the cement annulus around the conductor pipe, the latter is over-drilled and salvaged. Then, the borehole is extended down to a depth of about 6 m in order to insert the upright pipe. The upright pipe supports the drill head and is also fitted with sealing elements towards the borehole wall. This method ensures that the scavenging air pressure in the borehole is maintained. After the upright pipe has been set, the emplacement borehole is drilled with a diameter of approx. 600 mm.

4.2.3 Summary of the Conceptual and Basic Design Results of Vertical Borehole Drilling

In the following, the equipment for the preliminary or exploratory borehole, the drilling methods, and the equipment for the extension borehole are listed.

4.2.3.1 Scope of Equipment for the Preliminary or Exploratory Borehole

The equipment for the preliminary or exploratory borehole comprises:

- Drilling system
  - Drilling system equipped with components for the rotary drilling process, i.e. one drilling mast with driven bogie trucks and added force scavenging head
  - Equipment for the cable core procedure, if needed
  - Conveying of drilled material with direct air scavenging process, standard components for generation of compressed air and feeding to the drill string and dust-free removal of the drill cuttings

- Drilling equipment for the preliminary borehole
  - Equipment for the preparatory measures, setting of upright pipe packer
  - Core drill
  - Upright pipe packer, 3 m long
  - Core drill for the 25-m-deep exploratory borehole, axial conduit run
  - Chisel bit (with centring tip) to extend the exploratory borehole axial conduit run for cementing in the axial conduit run
  - Axial conduit run, 25 m long

- Drilling equipment for the exploratory borehole
  - Core drill as special construction with target drill device, double core pipe and constructional prerequisites for the cable core process
  - Drill string as special construction with integrated lines for energy supply of the target drill device and the transmission of control and measurement signals
  - Annular preventer for connection to the borehole (axial conduit run)

- Drilling equipment for final work on the exploratory borehole
  - Core drill to over-drill the cement jacket of the cemented axial conduit run
  - Inner pipe cutter for section separation of the axial conduit run with the cement jacket
  - Collecting pipes to recover the pipe sections

4.2.3.2 Drilling Methods and Equipment for the Extension Borehole

The drilling methods and equipment for the extension borehole comprise:

- Drilling system
  - Drilling system equipped with components for the rotary drilling process, i.e. drilling mast with driven bogie trucks and added force scavenging head
  - Conveying of drill cuttings with the indirect air scavenging process, standard components for generation of compressed air and feeding to the drill string and dust-free removal of the drill cuttings

- Drilling equipment for preparatory measures
  - Upright pipe, 660 mm outer diameter, 25 mm wall thickness, 4 m long, as special construction with a connection construction for sealing the borehole annulus against the borehole wall
  - Drill bucket with centring mandrel, 800 mm bore diameter, to extent the borehole to support the upright pipe down to a depth of 4 m

- Drilling equipment for the extension borehole
  - Drill pipe, drill with centring tip designed for indirect circulation; the use of a drill with roller bit or stationary cutters is determined according to the knowledge from the first trial boreholes
  - Drill pipe in 3-m sections, cable core processes of the boring pipe connection as a finish, the pipe dimensions are stipulated after first trial boreholes
  - Rotary preventers for sealing the ring space of the borehole against the drill pipe
  - Drill collar as a special construction to generate the drill propulsive thrust

- Drilling equipment for completion of the emplacement borehole
  - Support pipe, 660x20 mm, to support the lock, provided with centralisers for centring and fixing in the borehole as a special construction
  - Face cutters with centring mandrel as a special construction

4.3 Description of Emplacement Sequence

The transport, emplacement of BSK 3 fuel rod canisters and the subsequent backfilling of the borehole are summarized below.

Type B /3/ approved CASTOR® transport casks containing 10 BSK 3 canisters arrive at the repository's surface waste reception station either by rail or by road. For unloading, the CASTOR® transport cask, which arrives in a horizontal position, is raised into a vertical position and docked to a hot cell. After the transport cask has been opened, the canisters are pulled out of the transport cask and transferred into the hot cell one by one. Subsequently, each of the BSK 3 canisters is placed individually into a transfer cask which is docked to the hot cell as well. During operations, the drifts will be ventilated in such a way that temperatures will remain below 52 °C and humidity below 70 %.

After the transfer cask has been closed and disengaged from the hot cell, it is placed onto a transport cart to be transported underground. The loaded transport cart is placed in the hoisting cage and subsequently transported through the shaft down to the repository level where it is parked in the underground shaft station. Finally, a battery driven mining locomotive brings the transport cart to one of the active disposal drifts where the emplacement device (Figure 4-1) takes over.

If the conditioning plant and the repository are located next to each other, the transfer cask is loaded with a BSK 3 canister in the hot cell of the conditioning plant and closed. Subsequently, the transfer cask is transported on a road- or rail-bound transport vehicle in a horizontal position from the conditioning plant to the final repository. There, it is transported - still in a horizontal position - on a rail bound transport cart via the hoisting shaft to the underground facility.

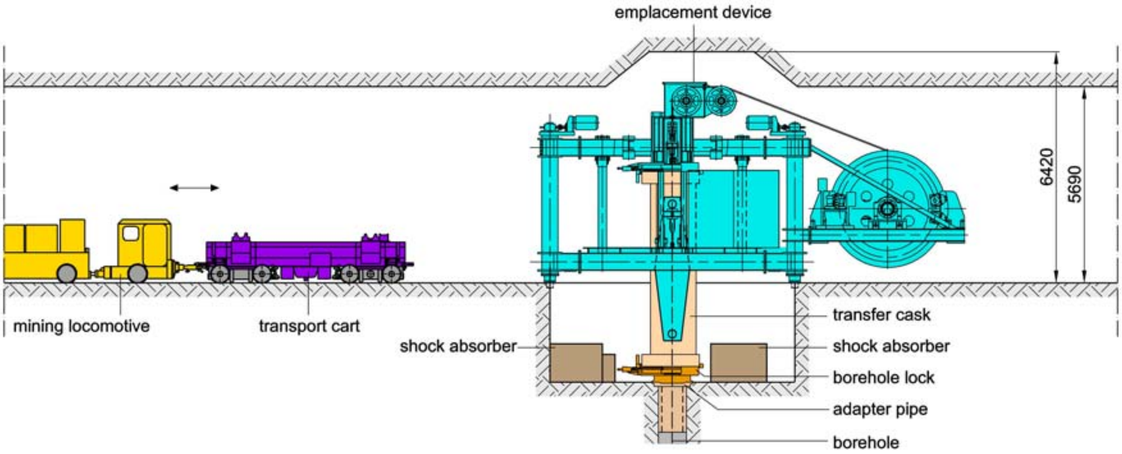


Figure 4-1: Borehole emplacement procedure

Once it reaches the active part of the disposal drift, the transport cart is driven into the emplacement device which is positioned over an active disposal borehole. The flap frames of the emplacement device pick up the transfer cask and raise it off the transport cart, still in a horizontal position. Subsequently, the transport cart is hauled away. The emplacement device then tilts the transfer cask into a vertical position and subsequently lowers and docks it onto the borehole lock.

The borehole lock includes a body and a flat horizontal sliding door (hereafter called the “slider”), both made of stainless steel, as well as the equipment needed to guide and drive this slider. The upper part of the body is collar-shaped, supporting the transfer cask once it is in docked position. The upper part of this supporting collar is funnel shaped to guide the transfer cask during its insertion. The lock slider is a solid rectangular cuboid steel body providing protection against radiation from the borehole. Once a transfer cask has been docked onto the borehole lock, its slider is mechanically locked to that of the transfer cask so that both sliding doors are operated simultaneously by the drive of the borehole lock.

The lower part of the body of the borehole lock extends into a flange providing sufficient isolation of the open borehole. The upper part of this extension flange contains a number of ducts arranged in segments that conduct exhaust air from the borehole. The exhaust air is collected in a ring channel which is connected to the venting system. To reduce possible radiation leakage, there are no ducts in the lower part of the extension flange.

After the transfer cask has been tilted into a vertical position, the shielding cover (which is part of the hoisting installation in the load portal above the raised transfer cask) is lowered and locked onto the upper end of the transfer cask. This shielding cover contains pulleys and ducts to guide the hoisting cables. Then, the transfer cask is docked onto the borehole lock. After the lock slider at the top of the transfer cask has been opened, the canister grab, which is retracted inside the shielding cover, is lowered into the transfer cask where it takes hold of the BSK 3 canister and lifts it off the transfer cask bottom so that the lower lock slider, which is mechanically connected to the borehole lock slider, can be opened.

After both lock sliders have been opened, the hoisting installation lowers the BSK 3 canister into the borehole to a position just above the last emplaced canister, followed by an inching operation for the last few centimetres. Limit or proximity switches signal the release of the grab jaws, after which the grab unlocks and is retracted into the shielding cover of the emplacement device.

Undocking and return to the surface of the empty transfer cask is done in reverse order:

- Closing of the borehole lock slider as well as the coupled lower lock slider of the transfer cask
- Closing of the top of the transfer cask
- Disconnecting the empty transfer cask from the borehole lock and subsequent lifting of the shielding cover
- Lifting of the empty transfer cask and its subsequent rotation into horizontal position inside the emplacement device
- Placing the empty transfer cask on the transport cart
- Placing the empty transfer cask onto the transport cart
- Retraction of the emplacement device load portal and disconnection of the transport cart

- Return of the transport cart to the underground shaft station by means of the mining locomotive
- Return of the transport cart through the shaft to the surface waste reception facility

After the load portal has been retracted into the emplacement device, it is lifted into its highest position to provide access for a backfill transport vehicle which is rail-bound. This vehicle, which carries a cask in horizontal position filled with crushed salt backfill, positions itself over the borehole within the emplacement device: The backfill volume is sufficient to fill the gap between the BSK 3 canister and the borehole wall as well as to cover the canister.

Waste canisters are to be stacked in a borehole up to about 10 m below the floor of the disposal drift. Immediately after the last canister has been emplaced, the borehole is backfilled with crushed salt up to a predefined level. Finally, the emplacement device is moved to the next borehole by means of a transport cart where, after set-up, re-attachment of the supply and control cables (if not wireless) and a test run, emplacement of the waste canisters continues in the same way as described above. Boreholes filled up to their capacity and backfilled with crushed salt are closed with a permanent seal. After emplacement the canisters will be fully encapsulated in crushed salt which, due to the increased convergence rate of the surrounding rock salt caused by the generated heat, will quickly become impermeable.

In order to avoid the escape of dust particles during the emplacement of the waste packages, a borehole venting station is to be provided for the borehole. The borehole venting station (Figure 4-2) comprises a filter system, a radial ventilator with electric motor, and an automatic control device and is to keep the borehole under a lower pressure than the environment during the working processes.

As a result of the low pressure in the borehole, air flows into the borehole, e. g. through the cable guidance system fixed on the lid of the shielding cask and through other small gaps. The suction necessary to generate and to maintain the low pressure is done by a closed circular pipeline integrated into the housing of the borehole slider to which the filter fan system is connected (via a flexible hose before the start of the emplacement or before the movement process) and put into operation.

The filter system is designed on the basis of specific requirements, e.g. the de-dusting of the air or the retention of aerosols. The crucial parameters for the design of the borehole venting station are the air through flow and the required degree of separation.

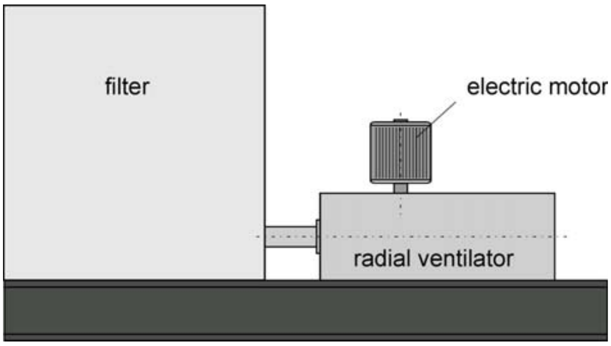


Figure 4-2: Borehole venting station

5 Design and Manufacturing of the Transport and Emplacement Components for the Vertical Borehole Disposal System

There are two components within the vertical emplacement concept that were not designed or fabricated within the scope of this R&D project, namely the dummy of the fuel rod canister BSK 3 and the battery locomotive.

5.1 BSK 3 Canister Dummy

For the demonstration tests, a BSK 3 canister dummy (Figure 5-1) was provided by the German Nuclear Industry. This dummy has the same dimensions and weight as the original canister, however, without the radioactive content as there was no need for real radiation during the tests. The radiation shielding necessary for the transfer cask and the emplacement device was calculated based on a real BSK 3 canister. The calculations were reviewed by TÜV-SÜD Industrie Service GmbH. To reach the weight of an original BSK 3 filled with heavy metal, the canister dummy was fabricated as a massive steel body. The main characteristics of the BSK 3 canister dummy are listed in Table 5-1.

Figure 5-1: Fabricated BSK 3 canister dummy

Table 5-1: Main dimensions and mass of a BSK 3 canister dummy

BSK 3 canister dummy	Dimensions
Outer diameter	430 mm
Outer diameter at the collar	440 mm
Height (including grab attachment)	4,980 mm
Height of the grab attachment	55 mm
Mass	5,266 kg

5.2 Battery Locomotive

The battery locomotive (Figure 5-2) was provided by DBE TECHNOLOGY GmbH. It had already been used during a demonstration test campaign for the direct disposal of spent fuel in drifts carried out in the early 1990s (see chapter 3.1 and Figure 2-4).

Figure 5-2: Battery locomotive for the test site in Landesbergen

For the performance of the old demonstration tests and the new tests for the borehole disposal of BSK 3, the standard gauge battery locomotive was equipped with a control cabin and a power unit. Its main characteristics are described in Table 5-2 below.

Table 5-2: Main dimensions and mass of the battery locomotive

Battery Locomotive	Dimensions
Length:	6,725 mm
Width:	1.80 m
Height:	1.79 m
Gauge (standard spacing of rails):	1,435 mm
	Weight
Power unit:	14,000 kg
Control cabin:	4000 kg
Total:	18,000 kg

Since the gauge of the new transport cart is wider than that of the locomotive (see chapter 5.3), another rail gauge was selected and fabricated specifically for the battery locomotive and also installed at the test site facility. A detailed description of the battery locomotive is given in /4/.

5.3 Transport Cart

The transport cart is designed for the transport of the transfer cask as well as for the transport of the emplacement device. The design of the transport cart is to a large extent determined by the weight of the emplacement device (67 t) and the boundary conditions (size of the openings in the repository). A low overall height of this component is of major importance as it determines the height of the excavated emplacement drift.

As the transport cart is to be used both above and below ground, the components are subjected to extreme corrosion conditions. Thus, corrosion-resistant materials are used for most moving parts and all bearings are tightly encapsulated. On corrosion-prone surfaces, suitable protective coating is applied. To facilitate decontamination, all components should have flat and closed surfaces.

Table 5-3: Main characteristics of the transport cart

Transport Cart	Dimensions
Length	6.15 m
Width	2.20 m
Height	1.40 m
Gauge	1,990 mm
Mass	10,000 kg

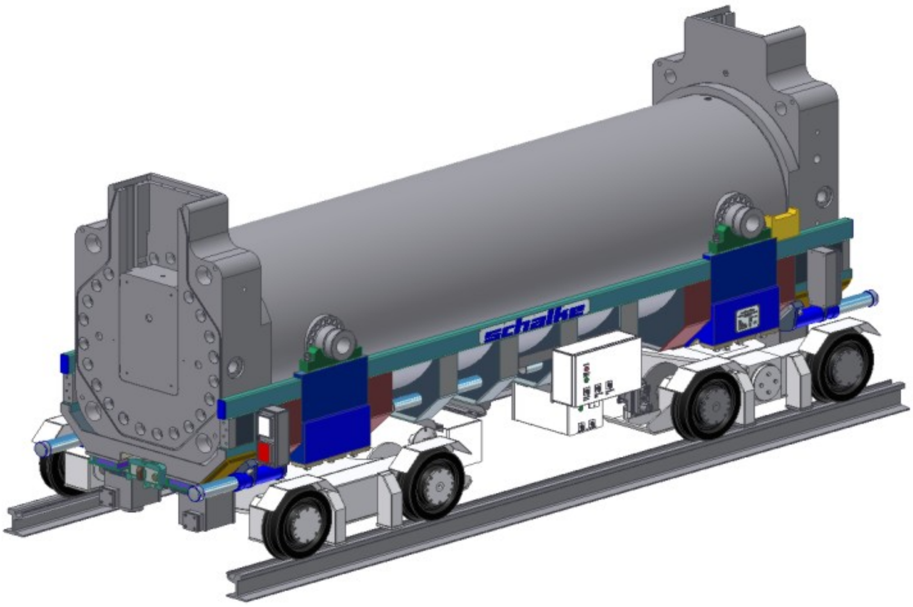


Figure 5-3: Transport cart with transfer cask

The transport cart is built for a service life of 20,000 operational hours and is operational when loaded even in the following cases:

- Vertical acceleration forces during the shaft transportation when braking with 1 g (over-running of hoisting cage and cage emergency braking)
- Crash into a buffer at 10 km/h
- Crash into the safety control devices of the shaft guard (retardation force 70 kN/hook)
- Reset on railway tracks after derailment with re-railing equipment

The running wheel diameter is 500 mm and, when running on suitable rails, is designed for a max. wheel load of 10 Mg and a velocity of 10 km/h. The running wheels are made of solid metal and are covered by decontaminable corrosion protection except on the running surfaces. Four of the running wheels are additionally connected to the brake disks of the locking brakes by means of central shafts.

Disc brakes are used as locking brakes. The braking force is produced by a spring accumulator that can be electro-magnetically or manually ventilated with a crank. The braking force is sufficient to hold a loaded transport cart in a drift with a slope of 1 %. During the coupling of the locomotive the locking brakes are applied manually by means of a selector switch and when coupling to stationary hauling equipment, e.g. during cage loading, they are applied automatically by means of proximity switches. In the event of failure, manual operation is possible.

The fuses as well as the control and display elements for the locking brakes and lights are in the upper carriage control box. Both types of lights are positioned at each end of the carriage, allowing for pushing (headlights) or pulling (taillights). The lights are controlled manually.

Figure 5-4 shows the transport cart during the acceptance tests at the fabrication site.

Figure 5-4: Transport cart during the acceptance test

Figure 5-5: Transport cart with transfer cask

Figure 5-5 shows the transport cart already loaded with the transfer cask at the test site in Landesbergen.

5.4 Transfer Cask for Fuel Rod Canisters BSK 3

The transfer cask is used for the transport of BSK 3 canisters from the conditioning plant (above ground) to the final repository (underground). At the repository level, the transport cask is also used to transport the BSK 3 canisters through different drifts to the disposal location in the disposal drift. For the industrial demonstration within the R&D project, the transfer cask was manufactured and assembled at the premises of a German sub-contractor.

The transfer cask consists of a cask body made of ductile cast iron with spheroidal graphite and two cask locks made of stainless steel (Figure 5-7).

The wall thickness and the wall design of the cask body comply with the requirements with regard to the mechanical strength as well as the neutron and gamma radiation shielding. In the cask wall, there are two rows of boreholes on different circles which are filled with polyethylene rods for neutron moderation. The neutron shielding in the region of the cask locks is provided in each case by neutron moderator plates. Four trunnions are provided on the cask body for handling the transfer cask.

Lock sliders in the cask locks operate according to the drawer principle and are guided in a spring-groove system. The lock sliders are secured by two locking studs each to prevent accidental opening.

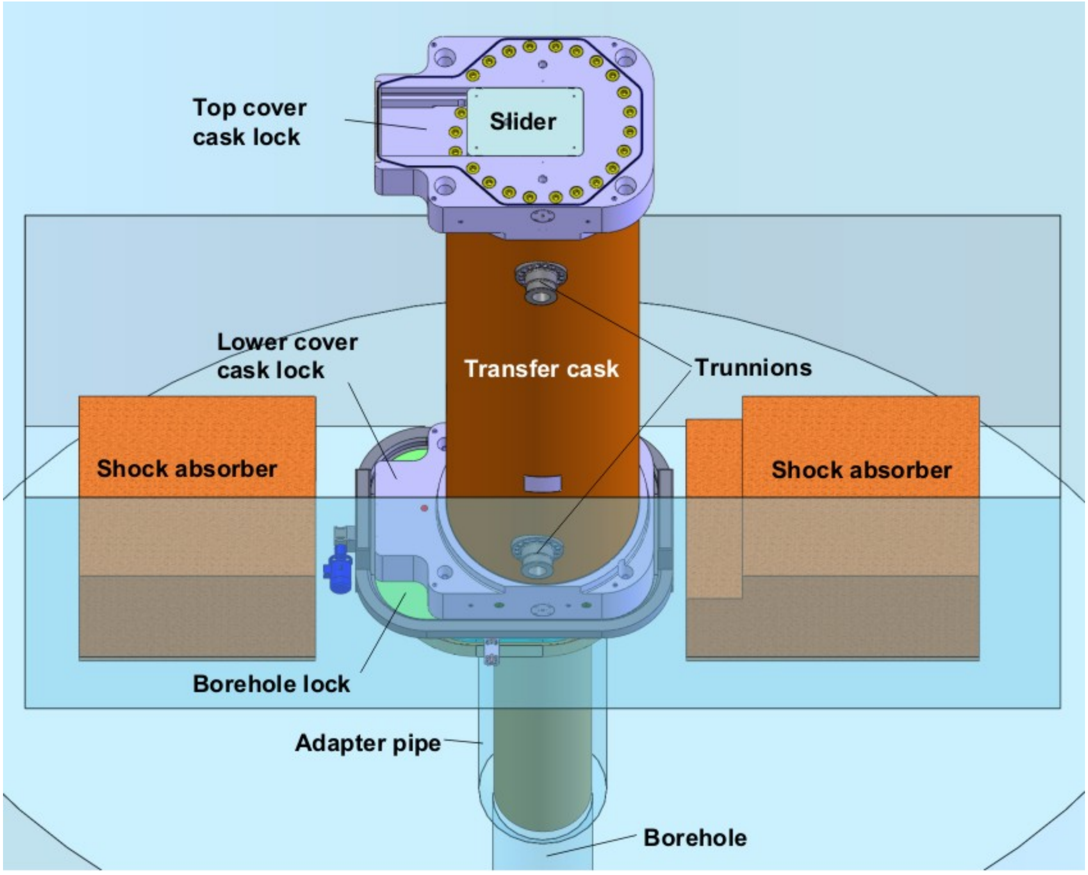


Figure 5-6: **Transfer cask docked on borehole lock**

The transfer cask has no control device of its own for activating the lock sliders. Opening and closing of the lock slider at the bottom end is effected by means of the control unit of the borehole lock. The lock slider at the top of the transfer cask is opened and closed by means of the control unit of the shielding cover.

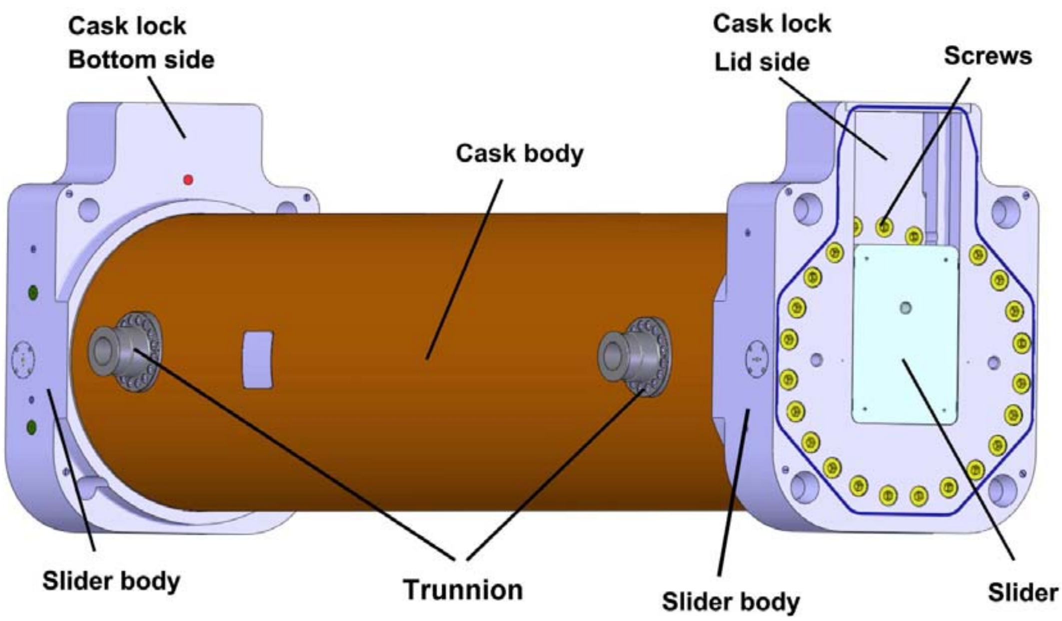


Figure 5-7: **Design of the transfer cask**

The completely assembled transfer cask including one lock with slider at each end is shown in Figure 5-8, while the main characteristics of the transfer cask are listed in Table 5-4.

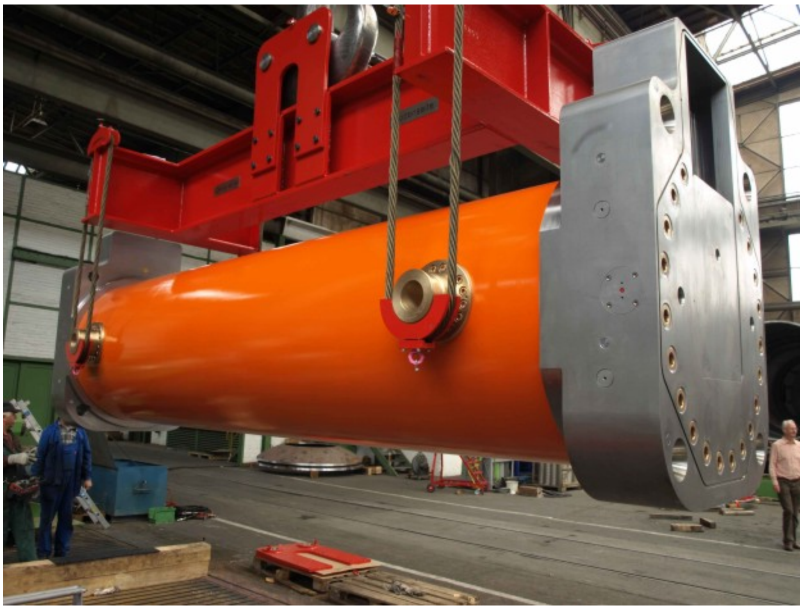


Figure 5-8: Transfer cask with cask locks

Table 5-4: Main characteristics of the transfer cask

Transfer Cask	Dimensions
Cask body diameter	1,305 mm
Cask locks height	1,885 mm
Overall length	5.57 m
Mass without BSK 3 canister Dummy	45,700 kg

5.4.1 Shielding Requirements for the Transfer Cask

In the present report, the loading of the transfer cask with a BSK 3 canister containing the spent fuel rods of 3 PWR fuel assemblies is considered. The BSK 3 canister is described in chapter 3.

It had to be demonstrated that the transfer cask loaded with a BSK 3 canister does not exceed the dose rate limits during internal transportation from a conditioning plant to the final repository mine up to the emplacement of the BSK 3 in a final repository neither during normal operations nor in case of an accident.

Two different cases were considered. Model A describes the transport of the transfer cask on the surface, whilst model B describes the underground transport in a drift in salt. The maximum permissible values are summarized in Table 5-5.

Table 5-5: Maximum permissible dose rate transfer cask

Location	Dose rate			
	Model A		Model B	
	Normal operation	Malfunction	Normal operation	Malfunction
Surface of the transfer cask	≤ 2 mSv/h		≤ 2 mSv/h	
2 m from the cask surface	≤ 0.1 mSv/h		≤ 0.1 mSv/h	
1 m from the cask surface		≤ 10.0 mSv/h		≤ 10.0 mSv/h

5.4.2 Results of the Shielding Calculations

The results of the calculations are afflicted with statistical uncertainties due to the methods used. For the calculations presented, the dose rate standard deviation is less than 8 %, and in places with a high dose rate less than 1 %. These margins have to be taken into consideration in the following calculation results.

Model A:
The maximum dose rate at the surface of the transfer cask during normal operation above ground is 298 µSv/h and occurs in the middle of the housing. Approx. 77 % of the dose rate is due to neutron radiation. Due to the good shielding of the BSK 3 canister top, the dose rate is very low at the top of the transfer cask (6 µSv/h). The maximum dose rate at the bottom end of the transfer cask is 271 µSv/h. At a distance of 2 m from the transfer cask, a maximum dose rate of 43 µSv/h is reached. In case of an accident, a maximum dose rate of 790 µSv/h is to be expected at a distance of 1 m.

Model B:
The maximum dose rate at the surface of the transfer cask during normal operation mode underground is 258 µSv/h at the cask bottom and 257 µSv/h in the middle of the housing. Approx. 60 % and 80 % respectively are due to neutron radiation. At a distance of 2 m from the transfer cask a maximum dose rate of 68 µSv/h is reached. In case of an accident, the maximum dose rate at a distance of 1 m is approx. 1.7 mSv/h. Due to the reflections from the salt, the dose rate values at a distance of 2 m from the surface are higher than in model A.

In the current transfer cask design the dose rates remain well below the maximum permissible dose rates. As the summary of the results in Table 5-6 shows, the dose rates take up only approx. 43% of the permissible dose rate in model A and 68% of the permissible dose rate in model B.

Table 5-6: Summary of the transfer cask results in comparison with the permissible dose rates

Operating conditions		Permissible dose rate [mSv/h]	Model A Transport on the surface		Model B Transport underground	
			Max. dose rate [mSv/h]	Utilization limit value [%]	Max. dose rate [mSv/h]	Utilization limit value [%]
Normal operation	Surface	≤ 2	0.298	15	0.258	13
	2 m	≤ 0.1	0.043	43	0.068	68
Incident	1 m	10	0.790	8	1.700	17

5.4.3 Mechanical Design Requirements

According to the relevant regulations, it must be demonstrated that the transfer cask provides sufficient safety margins in normal operation. The loads acting on the transfer cask under normal operating conditions result from accelerations that occur during handling and transportation. A maximum of 2 g is assumed for these accelerations.

Assessments of load bearing capacity were performed for the following components which carry the main load under operating conditions:

1. the trunnions and trunnion bolts as load attachment points for the transfer cask
2. the rollers on the lock slider
3. the threaded connection of the covering plate on the slide bar housing
4. the threaded connection of the cask locks with the cask body

In accordance with /7/, the trunnions including the trunnion bolts are to be designed for special requirements. The certification of the threaded blind holes in the cask body which receive the trunnion bolts is in accordance with /8/.

The sealing plugs are fastened to the lower cask lock by means of an interference fit. They must be secured so that they cannot be squeezed out during normal operations. The design temperature to be used in the mechanical-safety verification is 80 °C.

As for the shielding certification in case of an incident, the transfer cask is assumed to be mechanically intact. It is necessary to prove in the mechanical safety verification that the integrity of the transfer cask is maintained in case of an incident. The incidents to be considered cover the following drop scenarios:

1. 5.0-m drop in the conditioning plant in a vertical position (bottom flat drop) onto a stationary shock absorber (Figure 5-9).
2. 3.0-m drop in the transfer station in a horizontal position (surface line drop and slap-down drop) onto a stationary shock absorber (Figure 5-10).

3. 3.0-m drop in the vicinity of the underground borehole lock during the handling in the emplacement device in horizontal position (surface line drop, including slap-down drop) onto a two-part stationary shock absorber (Figure 5-11).
4. 0.5-m bottom edge drop (transfer cask centre of gravity vertically above the impact point) onto the borehole lock during the handling in the emplacement device (Figure 5-12).
5. 0.6-m bottom flat drop onto the borehole lock during the handling in the emplacement device (Figure 5-12).

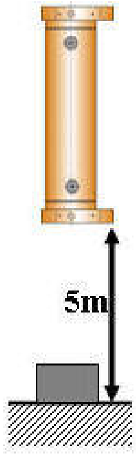


Figure 5-9: 5-m drop of the transfer cask in the conditioning plant onto a shock absorber

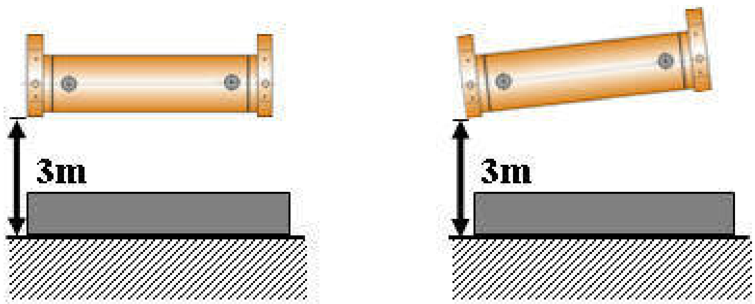


Figure 5-10: 3-m surface line drop and 3-m slap-down drop in the transfer station onto a shock absorber

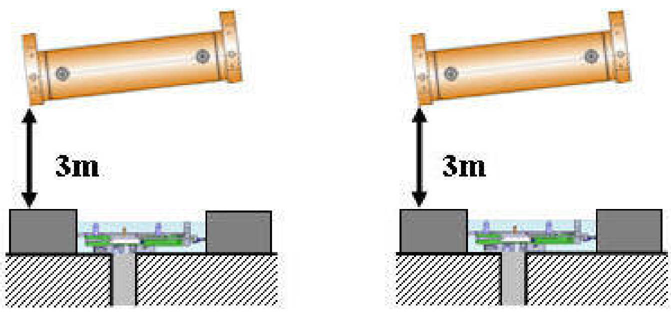


Figure 5-11: 3-m surface line drop and 3-m slap-down drop in the vicinity of the borehole lock onto shock absorbers

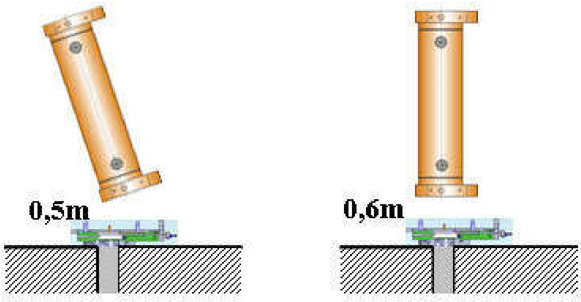


Figure 5-12: **0.5-m bottom edge drop and 0.6-m bottom flat drop onto the borehole lock**

5.4.4 Results of the Mechanical Calculations

For the safety-relevant sub-assemblies of the transfer cask, the mechanical performance was analysed and evaluated within the framework of a hypothetical incident analysis, both under normal operating conditions and under defined drop scenario conditions.

All threaded connections were in compliance with the permissible yield point capacity of 70 %. Sufficient length of engagement was proven under assembly conditions.

The calculated load for the main load bearing components in normal operations are summarized in Table 5-7.

Table 5-7: **Calculation results of the mechanical load of the transfer cask**

Component	Permissible load	Maximum load	Utilization limit
1. Trunnions	405 MPa	237 MPa	59 %
2. Trunnion bolts	658 MPa	497 MPa	76 %
3. Rollers on the lock slide bar	88 kN	60.4 kN	69 %
4. Threaded connection of the covering plate on the slider housing	399 MPa	265 MPa	66 %
5. Threaded connection of the cask lock with the cask body	890 MPa	436 MPa	49 %
6. Sealing plugs of the moderator holes in the bottom cask lock	11.9 MPa	0.43 MPa	4 %

Design-relevant drop scenarios with regard to the contact forces were developed in preliminary analytical and numerical analyses by means of a draft design, which to a large extent corresponds to the final design except for the construction of the lock slider system and the dimensions of the threaded connection of the cask locks and cask body. This way, the number of detailed drop cases to be calculated in detail could be reduced as follows:

- drop scenario 5 covers drop scenarios 1 and 4

- slap-down drops 2 and 3 are covered by the corresponding surface line drops

The drop scenarios 2 and 3 of the transfer cask were analysed by means of the FEM-programme ANSYS.

The 0.6-m bottom flat drop of the transfer cask onto the borehole lock was calculated with the explicit FEM-programme LS-DYNA. The results show that the form-fitting tongue and groove connection of the lock slider system has sufficient shearing strength. Local, very limited plastic strains occurring at the surface of the contact points between the tongue and groove have no safety relevance.

The locking bolts which are stressed upon impact due to bending by shock waves, experience strains which lie below the yield point.

All screws at the connection of the cask locks and the cask body show sufficient safety levels with regard to the yield point. The screws that fix the covering plate to the slider housing are adequately designed.

The calculations carried out for the transfer cask using acknowledged methods and FEM programmes show that this cask has sufficient mechanical integrity both during normal operations and in case of an accident. The transfer cask meets the requirements of the regulations for normal operations as well as the mechanical preconditions for the compliance with the protection objective of providing sufficient shielding of the BSK 3 canister under the drop scenario conditions considered as hypothetical malfunctions.

5.4.5 Thermal Design Requirements

During normal operation, the maximum post-decay heat production of the BSK 3 canister inventory of 6 kilowatts must be dissipated in compliance with the maximum permissible transfer cask surface temperature. The normal operating mode includes transport from the conditioning plant via the transfer station and the shaft down to the mine and to the boreholes. At the borehole lock, the transfer cask is swivelled into a vertical position to unload the BSK 3 canister. At a constant air temperature of 30 °C (not considering direct sunlight and with unobstructed heat dissipation) the temperature of the open surface of the transfer cask may not exceed 85 °C.

For the case of fire (30 minutes at 800 °C), it is to be shown that the dose rate limits are not exceeded due to a loss of parts of the shielding. The thermal calculations for a hypothetical fire and the calculation of the heat induced stress in the transfer cask are only for general orientation and are supposed to give an indication for a further verification process which will be carried out when the fire load is adapted to the specific conditions in the underground repository.

5.4.6 Results of the Thermal Calculations

During transport in normal operating mode (horizontal alignment of the transfer cask), the highest temperatures are reached at the shaft wall and on the moderator plate of the bottom cask lock. The maximum surface temperature of 70 °C is clearly below the permissible limit value of 85 °C. For the design temperature to be considered in the mechanical verification, a transfer cask temperature of 80 °C is applied for the transportation processes as higher mechanical loads are to be expected in the cask locks and in the transition region to the cask body.

Supplementary calculations with an ambient temperature of 38 °C and considering direct sunlight above ground resulted in a maximum surface temperature of 83 °C that is also still below the permissible limit value of 85 °C.

The temperatures calculated at the external surfaces of cask body and cask locks are relevant for the design of the transfer cask placed in the borehole lock (vertically orientated). These are 74 °C for the cask body and 76 °C for the cask lock and are clearly below the permissible limit value of 85 °C.

The maximum permissible temperature for the moderator components made of polyethylene is 120 °C. The temperatures of 82 °C max. in the moderator rods in the cask walls, 61 °C max. for the moderator plate in the upper cask lock, and 105 °C max. for the moderator plate in the bottom cask lock all remain below the permissible temperature.

A study of the thermal expansion of the transfer cask moderator components was carried out using the following temperatures:

- Moderator rod inside: 90 °C
- Moderator rod outside: 90 °C
- Upper cask lock, moderator plate: 90 °C
- Lower cask lock, moderator plate: 110 °C

The calculations showed that up to a material temperature of 130 °C sufficient expansion space is available and that the load on the moderator material through thermal expansion is still acceptable.

5.5 Emplacement Device for Fuel Rod Canisters (BSK 3)

The emplacement device is the core component of the entire BSK 3 emplacement system. Design and manufacturing was carried out in accordance with KTA 3902 /9/ and KTA 3903 /10/.

The emplacement device fulfils the following functions:

- lifting of the loaded transfer cask from the transport cart
- swivelling the transfer cask into a vertical position
- covering the transfer cask top with the shielding cover
- placing the transfer cask onto the borehole lock
- emplacing a BSK 3 into the borehole
- loading the transport cart with the discharged transfer cask

The emplacement device consists of the following main assembly groups:

- Lifting gantry
- Lifting platform and canister lifting gear
- Swivelling device
- Shielding cover
- Canister grab with hoisting cable
- Electronics and control system

Table 5-8 shows the main characteristics of the emplacement device.

Table 5-8: Main characteristics of the emplacement device

Emplacement Device	Dimensions
Total length	12.10 m
Total width	4.70 m
Total height (lift position swivel)	6.19 m
Total height (transportation position)	5.19 m
Cable length	330 m
Total weight	67 t

The lifting gantry (Figure 5-13) is the main component of the emplacement device. To transport the gantry down a mine, it can be dismantled into several single components and then reassembled once on site. The steel construction elements are bolted together via connecting surfaces which are constructed as head plates and which are mechanically machined in order to achieve the required geometrical precision.

Figure 5-13: Lifting gantry

The lifting gear platform (Figure 5-14), which carries the canister lifting gear, is a welded sectional steel construction.

Figure 5-14: Lifting gear platform and canister lifting gear

Viewed from the rear corner supports, the two outer girders taper off by 5° from the outer profile of the emplacement device. This way, a better cornering performance is ensured when transferring between emplacement drifts with the transport cart. These two girders are fitted with further transverse and longitudinal girders that form the base for mounting the canister lifting gear.

The swivel device (Figure 5-15) consists of two flap frames and two swivel girders and their drive mechanisms.

Figure 5-15: Swivel device

When docked onto the transfer cask, the shielding cover (Figure 5-16) allows the canister grab access to the BSK 3 in the transfer cask. Usually, the shielding cover is kept in its lowest position. For the docking process, the shielding cover must be lifted to its highest position. This can only be achieved when the emplacement device is lowered to the position where it is possible to swivel the transfer cask. This way, the total height of the emplacement device (and thus the roof height of the emplacement drift) can be kept as small as possible during the emplacement cycle.

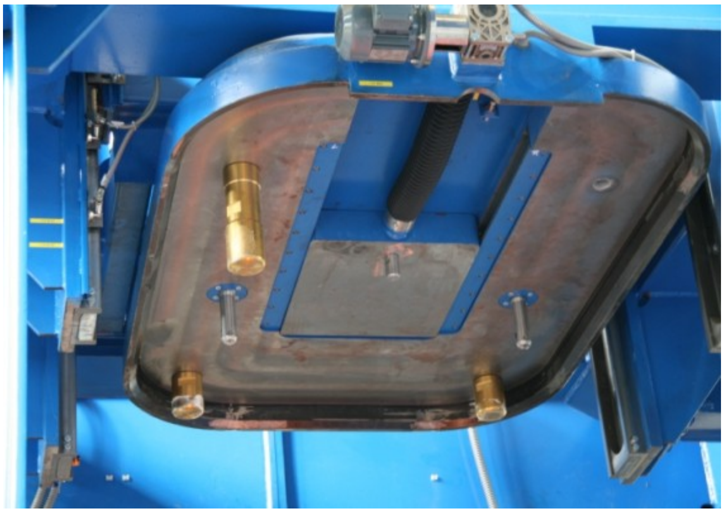


Figure 5-16: Shielding cover

The lowest shielding cover position is also held during the transportation of the emplacement device with the transport cart.

To lift the BSK 3 load using the grab attachment, the canister grab (Figure 5-17) is equipped with three grab jaws. The grab jaws are opened and closed by a connecting rod powered by an electric linear motor.

Figure 5-17: Canister grab with hoisting cable

The jaws and the fixed fulcrum of the toggle joint are mounted in three double web plates which are arranged on a circular surface at an angle of 120° and welded to a base and cover plate. The linear motor is mounted on components of the emergency system in the centre of the grab head. The piston rod of the linear drive motor ends in three gallows-shaped booms. The booms are joined with the toggle joints via toggle levers.

The emergency system is integrated in the grab head. In case of a malfunction of the grab drive, the emergency system can be activated to remove the grab from the transfer cask. The main components of the emergency system are two metal discs arranged one on top of the other which are connected to a linear motor on the one side and to a cast socket on the other side. The discs are designed with internal and external cogs respectively and can be turned against each other during emergency operation. In this case, the disc with the linear motor can interlock itself with the other disc via an axial movement. The movement necessary for the interlocking of the cogs is provided by the canister lifting gear. This relative movement of the linear motor to the grab body causes the grab jaws to open and to release the transfer cask. The reciprocal turning of the discs is activated by manually operated levers through side openings of the shielding cover.

As the load is held by only one cable, the hoisting cable is designed with an ordinary lay and thus has low torsion. The cable nominal diameter was designed according to the higher requirements of the nuclear industry regulations. For the electric energy transmission needed to drive and control the canister grab the cable core consists of a 10-wire cable. The cable is pressure encased in order to prevent that mechanical loads which occur during winding and guiding of the cable, are transferred to the cable.

The hoisting cable is joined with the grab by a cast socket. For casting, the end of the cable is spliced down to its single wires like an open brush and cast with synthetic resin in a conically formed cast body. As a proof that the cable end connection withstands all forces up to the breakage strength of the cable, a stipulated tensile test was carried out successfully under collaboration of an external expert.

For the emplacement device there are three modes of operation:

- maintenance operation activated by key as unlocked manual operation
- manual operation locked including all safety features like the automatic operation
- automatic operation

The operations of the emplacement process (in particular the different movements of the emplacement device) are controlled and monitored via two (2) remote-controlled cameras and a display system. The operator can monitor and control the emplacement process from the control cabin (Figure 5-18).

Figure 5-18: Control system in the control cabin

5.5.1 Shielding Requirements for the Shielding Cover

The dimensions of the shielding cover must be adequately designed to fulfil the required shielding function. The dose rate must remain below the maximum permissible limits during normal BSK 3 emplacement operations and in case of malfunction.

The design calculations carried out examine the part of emplacement phase when a transfer cask is docked onto the borehole lock and the BSK 3 canister is lifted by the canister grab to allow the opening of the borehole lock / lower cask lock which starts the emplacement process.

When defining the maximum permissible dose rate limits, the following two models are considered for both normal operations and malfunction. Model A describes the position of the canister grab holding the BSK 3 called emergency stop (es) if the canister grab does not stop at the hold point in case of a malfunction. Model B examines the position of the canister grab holding the BSK 3 called hold point (hp) (Table 5-9).

Table 5-9: Maximum permissible dose rate shielding cover

	Dose rate
Outer contours	≤ 2.0 mSv/h
2 m distance	≤ 0.1 mSv/h

5.5.2 Results of the Shielding Calculations

The results of the calculations are afflicted with statistical uncertainties due to the methods used. For the calculations presented, the standard deviation of the dose rate is less than 10 % and in places with a high dose rate less than 2 %. These error margins have to be taken into consideration for the following calculation results (Table 5-10).

Table 5-10: Compilation of the results compared with the permissible dose rates

	Permissible Dose rates mSv/h	Model A	Model B
Outer contours	≤ 2	0.65	0.62
2 m distance	≤ 0.1	0.019	0.039

In model A, the disturbed situation differs from the normal emplacement process only with respect to the position in which the BSK 3 canister remains in the transfer cask. Therefore, when adhering to the maximum permissible dose rate during a normal operation, it is not possible that the dose rate limits are exceeded during this incident.

The dimensions of the shielding cover used in both models are according to the current design. As the values are clearly below the maximum permissible dose rate of 2.0 mSv/h at the outer contours of the shielding cover and the maximum permissible dose rate of 0.1 mSv/h at a distance of 2 m from the shielding cover, no excess of these limits is expected even when considering shielding cover component tolerances during normal operations.

5.6 Borehole Lock

During the emplacement process, the borehole lock acts as a permanent seal of the borehole on the one hand and as the connecting link between the final disposal borehole and the transfer cask on the other hand. It is positioned in a borehole cellar (below the drift floor level) on a flange-shaped adapter pipe (Figure 5-19). In addition to this, the borehole lock closes the emplacement borehole during the filling phase and shields the emplacement drift from radiation from the fuel rod canisters (BSK 3) already emplaced inside the borehole. The main dimensions of the borehole lock are given in Table 5-11.

The borehole cellar is 7,000 mm long, 2,200 mm wide and 2,850 mm deep. In the test facility (see chapter 6), it is represented by a steel structure.

To reduce the level of forces acting on the transfer cask and borehole lock in case of a mechanical failure, two shock absorbers are positioned around the borehole lock in the borehole cellar.

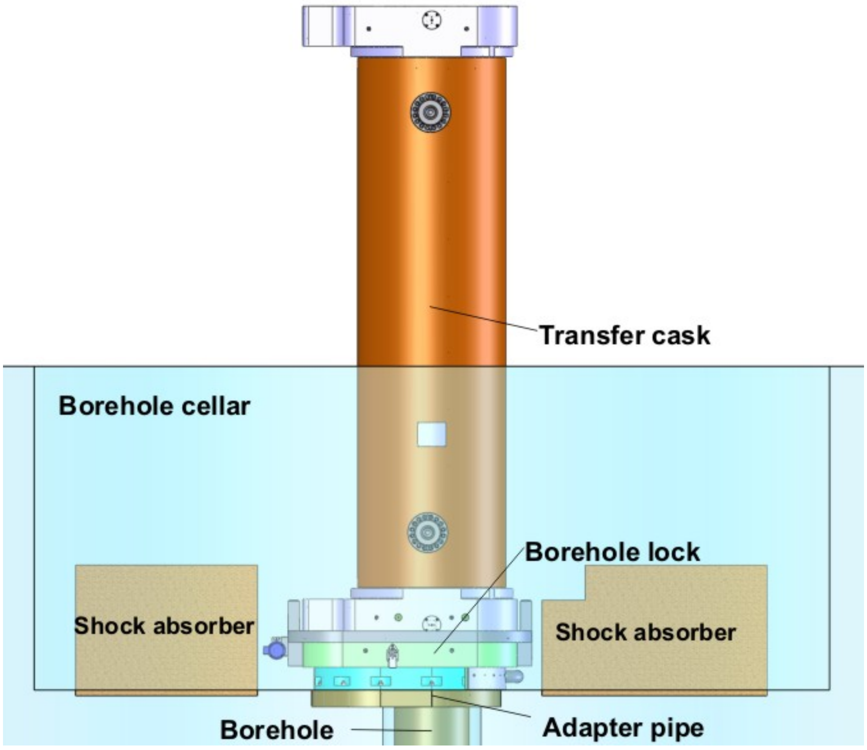


Figure 5-19: Borehole lock with docked transfer cask

The borehole lock consists of two sections. The upper section of the borehole lock with the connection face for the transfer cask is constructed as a lock system, whereas the lower section of the borehole lock consists of an exhaust air flange. On the upper side of the main body of the borehole lock, four stud holes are provided for handling the borehole lock. For the connection of the borehole lock to the hoisting apparatus, connecting elements (eye bolts) which can be rotated and swivelled are screwed into the main body.

The lock system of the borehole lock consists of a slider housing with integrated slider, which is pot-shaped on the upper side to accommodate the transfer cask, the slider drive, and the positioning studs for the positioning of the transfer cask (Figure 5-20).

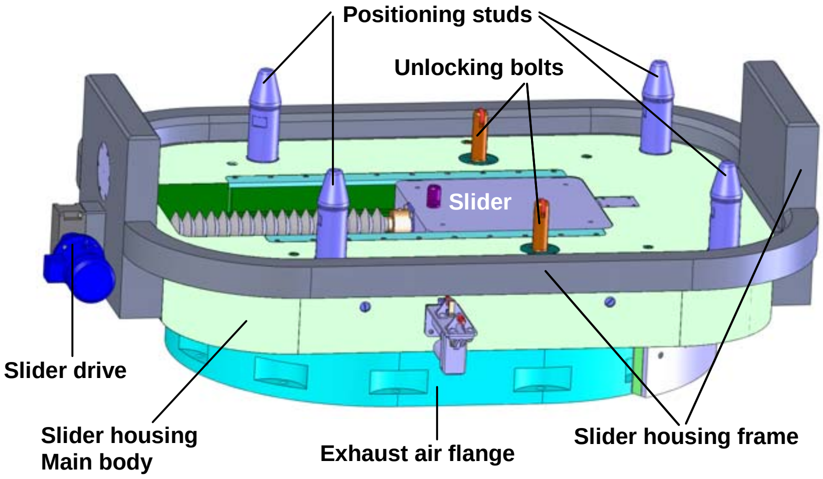


Figure 5-20: **Borehole lock construction**

Table 5-11: **Main characteristics of the borehole lock**

Borehole Lock	Dimensions
Length	2,362 mm
Width (slider housing frame)	1,590 mm
Height	821 mm
Mass	7,140 kg

Figure 5-21 shows the fabricated borehole lock at the fabrication site and Figure 5-22 the acceptance test carried out to check the interface compatibility of the borehole lock with the lower transfer cask lock.

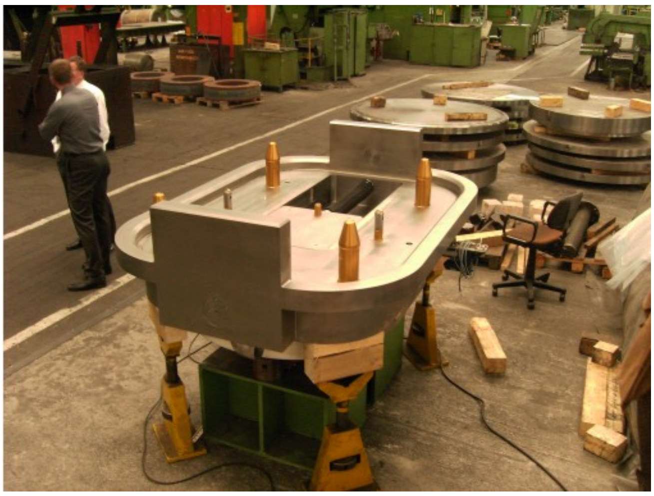


Figure 5-21: **Borehole lock**

Figure 5-22: **Acceptance test for borehole lock and cask lock**

5.6.1 Opening and Closing Mechanism of the Borehole lock

During the emplacement process the transfer cask is picked up at the trunnions by the emplacement device lifting gear, raised, and swivelled into a vertical position after the departure of the transport cart.

In the following step, the shielding cover of the canister lifting gear of the emplacement device is lowered onto the head of the transfer cask. Upon connection, the slide bar latch at the top of the cask lock and the actuator of the shielding cover are coupled automatically.

The subsequent lowering of the lifting gantry places the transfer cask on the borehole lock. There are four positioning studs on the base plate of the slider housing of the borehole lock for guiding the transfer cask during the docking process to the borehole lock. The cylindrical bolts are conical at the top so that the transfer cask is precisely positioned before the opening bolts are engaged. During the docking process, the lock slider of the lower transfer cask lock and the borehole lock are coupled automatically in order to facilitate opening and closing procedures with the borehole lock slider via the connected actuator.

The transfer cask is opened on the upper side by the lock slider of the emplacement device and the BSK 3 canister is lifted with the grab of the emplacement device canister hoisting gear. Subsequently, the borehole lock slider and the lower cask lock are opened simultaneously, and the BSK 3 canister is lowered through the borehole lock into the borehole.

After the canister grab has been retracted, the lock sliders of the borehole lock and the cask lock are closed. Subsequently, the operational steps described above take place in reverse order and end with the lifting of the empty transfer cask from the borehole lock by means of the emplacement device.

5.6.2 Shielding Requirements for the Borehole Lock

The dimensions of the borehole lock must be adequately designed to fulfil the required shielding function. The dose rate must remain below the maximum permissible limits during normal BSK 3 emplacement operations and in case of an accident or malfunction.

The design calculations carried out examine the part of the emplacement phase when a transfer cask is docked onto the borehole lock and the BSK 3 canister passes the open borehole lock and lower transfer cask lock. In addition to this, the scattered radiation out of a borehole filled with canisters is examined when the borehole lock is closed and the transfer cask is removed.

When determining the existing dose rates, the following two models are considered for both, normal operations and malfunctions. Model A describes the emplacement process and the transfer of a BSK 3 canister from the transfer cask through the open borehole lock into the borehole, focusing on the direct radiation from a BSK 3 canister. As a worst-case scenario, it is assumed that the hoisting process is interrupted at a depth of 2,000 mm when the borehole lock is open.

Model B examines radiation scattering from a borehole containing BSK 3 canisters which are not yet covered with rock salt while the borehole lock slider is closed and the transfer cask is raised. In this case, the topmost BSK 3 canister in the borehole is considered as a maximum for the calculations. As a worst case scenario, it is assumed that due to a mechanical or thermal incident resulting in damage to the borehole lock, the borehole lock slider is completely open. The maximum permissible limits are summarized in Table 5-12.

Table 5-12: Maximum permissible dose rate borehole lock

Place	Dose rate			
	Model A		Model B	
	Normal Operation	Incident	Normal Operation	Incident
2 m distance from the transfer cask at rail level	≤ 0.1 mSv/h			
1 m distance from the open surfaces of borehole lock and transfer cask		≤ 10.0 mSv/h		≤ 10.0 mSv/h
Surface of the borehole lock			≤ 2.0 mSv/h	
2 m distance from the surface of the borehole lock			≤ 0.1 mSv/h	

5.6.3 Results of the Shielding Calculations

The results of the calculation are afflicted with statistical uncertainties due to the methods used. For the calculations presented the standard deviation of the dose rate is less than 10 % and in places with a high dose rate less than 2 %. These margins have to be taken into consideration for the following calculation results (Table 5-13).

Table 5-13: Compilation of results and comparision with permissible dose rates

Operating conditions		Permissible dose rate [mSv/h]	Model A BSK 3-Transfer in boreholes		Model B Borehole disposal of BSK 3 canister	
			Max. dose rate [mSv/h]	Utilization limit value [%]	Max. dose rate [mSv/h]	Utilization limit value [%]
Normal operation	Surface	2	0.156	8	0.001	< 1
	2 m*	0.1	0.079	79	< 0.001	< 1
Operational disturbance	1 m	10	0.112	1	1.370	14

* In model A: top edge of the borehole cellar at rail level and 2 m from the part of the transfer cask protruding over the borehole cellar.

In model A, the disturbed situation differs from the normal emplacement process only with respect to the time the BSK 3 canister remains in the borehole lock. Therefore, when adhering to the maximum permissible dose rate during a normal operation, it is not possible that the dose rate limits are exceeded during this incident.

The dimensions of the borehole lock used in model B are according to the current design. As the values are clearly below the maximum permissible dose rate of 2.0 mSv/h at the surface of the borehole lock and the maximum permissible dose rate of 0.1 mSv/h at a distance of 2 m from the borehole lock, it is not expected that these limits will be exceeded even when taking into account borehole lock component tolerances during normal operations.

To investigate the maximum mechanical and thermal malfunctions with resulting damage to the borehole lock slider, where the borehole lock slider is not capable of shutting the borehole, the borehole lock was modelled with a completely open slider. The results of the calculations remained clearly below the maximum permissible dose rate of 10 mSv/h. If the transfer cask is dropped by the emplacement device during underground emplacement operations or in case of an underground fire, it is thus impossible that the loss of parts of the shielding, which is a part of the borehole lock, would lead to a dose rate exceeding the limit during a malfunction. Thus, during a malfunction, a guarantee of the borehole lock protective function is not necessary with regard to the shielding function of the borehole lock.

Safety-relevant damage to the components due to gamma and neutron radiation exposure can be excluded due to the short period of time a BSK 3 canister remains in the borehole lock.

5.6.4 Mechanical Design Requirements

In normal operating mode, safe handling must be ensured. The loads acting on the borehole lock result from the accelerations occurring during mechanical handling. For these, a maximum value of 2 g is determined.

During underground emplacement operation, the borehole lock is exposed to salty air with a low humidity. Furthermore, it is not possible to prevent salt dust settling on all open surfaces of the borehole lock. However, due to the uninterrupted underground use of the borehole lock, the possibility of electrolytically active substances attacking material contact areas can practically be ruled out. Corrosion of the normally corrosion-resistant materials through surface, pitting, crevice, or stress corrosion is not to be expected.

At a live load factor of 1.35, the load attachment points must comply with the requirements of the accident prevention regulations and show sufficient endurance for the planned number of handling processes.

All threaded connections must be designed in such a way that the screw loading is less than 70 % of $R_{p0,2}$ (T) of the screw material under assembly conditions.

The borehole lock must maintain its mechanical integrity both during normal operations as well as in case of an accident or malfunction. The following loads are considered as hypothetical accidents:

- 0.5-m bottom edge drop of the transfer cask onto the borehole lock
- 0.6-m bottom flat drop of the transfer cask onto the borehole lock

In both cases the borehole lock must provide sufficient shielding, corresponding to the dose rate limits for malfunctions. Except for the already mentioned shielding criterion, no specific mechanical requirements were made for the borehole lock for the hypothetical cask dropping scenarios. It is thus permissible that during the mentioned drop situations the borehole lock completely fails mechanically and can be considered to be no longer present because the limit value of the total dose rate defined for malfunctions will not be exceeded.

5.6.5 Results of the Mechanical Calculations

All pre-tensioned threaded connections were in compliance with the permissible yield point capacity of 70 %. Sufficient length of engagement of the screw threads in the nut threads and plug threads was also proven. Thus, it is guaranteed that regardless of the actual load the load is carried by the bearing capacity of the screw shank and not by the screw thread in the nut or the thread in the plug.

In accordance with DIN EN 1677-1, the connecting elements have a fatigue limit against breakage of 20,000 working load changes. Based on at least 5 crane operations per borehole lock transfer process (working cycles) and 10 load changes per crane operation (in accordance with KTA 3905), the connecting elements have to be replaced after 400 transfer cycles.

For the main load-bearing components the results of the calculations are summarized in Table 5-14.

Table 5-14: Calculation results of the mechanical load on the borehole lock

Component	Safe load	Maximum load	Utilization of limit value
1. Unlocking bolts in the slider housing	659 MPa	14 MPa	2 %
2. Threaded connection between slider housing and exhaust air flange	399 MPa	262 MPa	66 %
3. Threaded connection M20 of the guide rail	399 MPa	251 MPa	63 %
4. Threaded connection M12 of the additional shielding on the exhaust air flange	399 MPa	325 MPa	81 %
5. Slide bolt ∅ 40 on the slider	247 MPa	48 MPa	19 %
6. Rollers KR 90 on the slider	88 kN	4.4 kN	5 %
7. Welded connections between connecting frames and slider housings	305 MPa	2 MPa	< 1 %
8. Connection element	12 Mg	7.14 Mg	15 % *

*) Four-fold safety limits

The calculations carried out for the borehole lock show that the borehole lock has sufficient mechanical integrity under normal operating conditions as well as during operational disturbances. For all components and welded connections considered, sufficient load-bearing capacity was proven. In addition, the slider shows sufficient durability. The selected stop rails meet the requirements of the accident prevention regulations.

The borehole lock thus meets the standard regulations concerning mechanical behaviour during normal operations as well as the mechanical requirements in compliance with the safety objective of „shielding" under the conditions of the drop scenarios considered as hypothetical incidents.

5.6.6 Thermal Design Requirements

Under normal operating conditions no verification process is necessary for the borehole lock design. The maximum temperatures of the borehole lock components during normal operations are not calculated as an input parameter for the mechanical design but are derived from the calculated temperature distribution of the transfer cask placed into the borehole lock.

It has to be demonstrated that the borehole lock maintains its mechanical integrity during a hypothetical fire (30 minutes at 800 °C), so that it fulfils its protective shielding function. It is guaranteed that the permissible dose rate limit is not exceeded during a disturbance or malfunction even when parts of the shielding are lost.

5.6.7 Thermal Calculation Results

It is possible to derive the maximum temperatures of borehole lock components during normal operations from the calculated temperature distribution of the transfer cask placed into the borehole lock. In this calculation, the surfaces of the cask locks are considered to be adiabatic. The borehole lock itself does not contain any heat sources. In reality, the temperatures in the bottom lock of the transfer cask decrease due to heat dissipation into the surrounding structures of the borehole lock. The temperatures estimated for the surfaces of the bottom lock of the transfer cask thus represent conservative maximum values for the borehole lock. This results in a maximum temperature of 71 °C for the slider housing and of 76 °C for the slider. The temperatures of the remaining components of the borehole lock are lower than these temperatures.

For the design temperature to be assessed in the mechanical certifications, a worst-case temperature of 80 °C for all components of the borehole lock is applied.

For the calculations of the incident condition "fire", the temperature developments over time were analysed for all essential components of the borehole lock during the fire and cooling phase. To this end, the temperature for each component was considered at the spot where the highest temperature occurs over the entire period to be considered.

The local maximum temperatures of the borehole lock components occurring during a fire are between 658 °C at the exhaust air flange and 790 °C at the attachment frame.

The design changes made to the borehole lock have a negligible influence on the calculated maximum temperatures in case of fire. The above mentioned temperatures can thus be seen as covering these changes.

5.6.8 Exhaust Air Flange

The lower part of the borehole lock consists of an exhaust air flange made of forged steel (Figure 5-23). The exhaust air flange has rounded corners and has an external length of 1,620 mm and a width of 1,170 mm. The height of the exhaust air flange is 270 mm. The exhaust air flange has a clearance hole with a diameter of 456 mm through which the BSK 3 canister can be lowered into the borehole during the emplacement process.

The shape of the underside of the exhaust air flange facilitates the connection to the adapter pipe in the borehole. The flange is connected to the adapter pipe by means of 16 M24 threaded pins, where the threaded pins are screwed into the adapter pipe flange. Recesses are cut into the skin surface of the adapter pipe in the area of the locking holes so that assembly on the adapter pipe is possible.

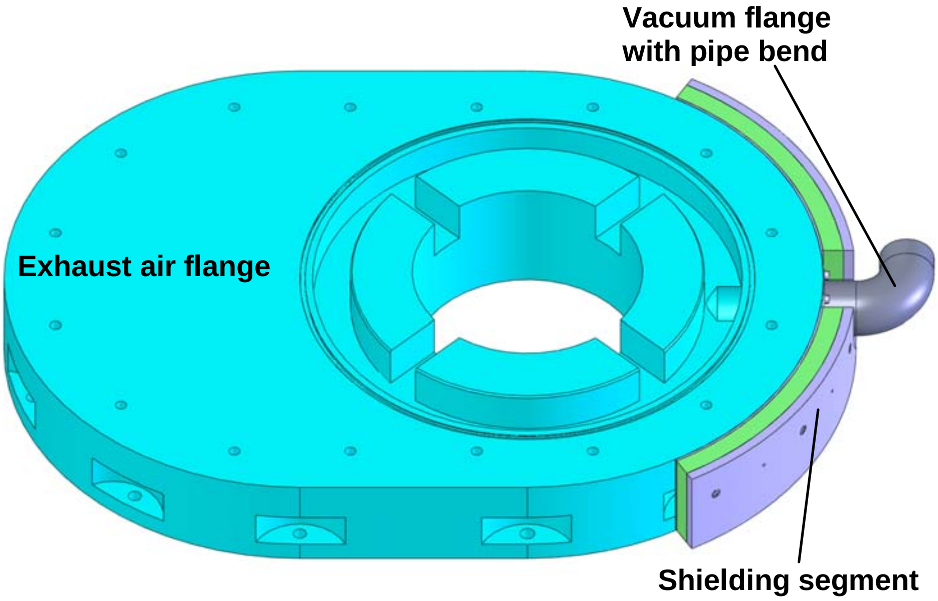


Figure 5-23: Design of the exhaust air flange

In the upper part of the exhaust air flange, 4 segments are arranged in a circle thus forming 4 notches with a cross-section of 70 mm x 70 mm each through which exhaust air from the borehole is conducted. The exhaust air is passed through a ring duct with the same cross-sectional area to the vacuum flange of the venting system. The vacuum flange is situated on the opposite side of the borehole lock drive unit. To avoid radiation paths, there is no notch in the vicinity of the vacuum flange in the respective circle segment.

The piping coming from the vacuum flange ends in a right-angled pipe bend, onto which further piping can be welded.

A shielding segment covering the entire vertical height is attached to the exhaust air flange on the vacuum flange side. This shielding segment consists of a 120°-ring segment, made of two 5-mm and two 20-mm-thick stainless steel metal plates with a 40-mm-thick polyethylene plate between them.

Under normal operating conditions, it is intended to maintain negative pressure in the borehole during the emplacement process (i.e. when the transfer cask is docked onto the borehole lock). For this purpose, circular grooves run in both, the exhaust air flange faces towards the adapter pipe and in the slider housing, into which elastomeric seals are set. Similarly, elastomeric seals are set into the plugs of the slider emergency override and of the shielding-block, in the cylinder consoles, and in the vacuum flange.

6 Demonstration Programme and Results

The full-scale demonstration programme was carried out successfully in a surface facility, a former turbine hall of a power station in the village of Landesbergen close to the city of Hanover, Federal State of Lower-Saxony. In spring 2008, the platform for the demonstration tests was erected 10 m above the ground floor, followed by the delivery and assembly of the components of the emplacement system in the summer of the same year. After a successful SAT (Site Acceptance Test), the test and demonstration campaigns were carried out from September 2008 until the end of the DENKMAL project in July 2009.

6.1 Description of Test Facility

The test facility was a former turbine hall of the "Robert Frank" power plant in the village of Landesbergen.

The test stand consists of a steel construction (approx. 100 metric tons) which supports the emplacement device and constructional replicas (mock-ups) of the emplacement borehole and the borehole cellar. To simulate the transfer cask transportation to and from the emplacement device, rail tracks with substructures were provided. Furthermore, it was necessary to provide access to all components as well as observation points and a control unit in a control cabin. Figure 6-1 shows a sketch of the test facility with the layout of the various components of the emplacement system.

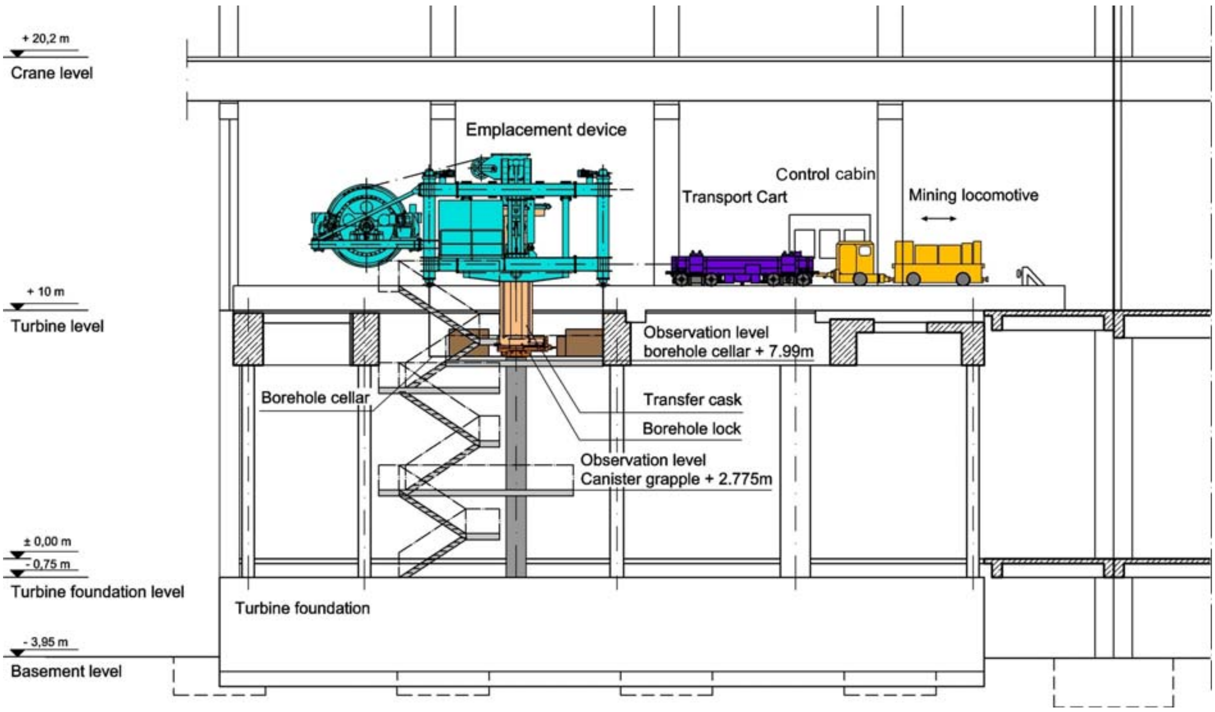


Figure 6-1: Sketch of test site with emplacement components

The test platform is a steel construction approx. 10 m wide and 30 m long which serves as a basis for the support and operation of the emplacement device and as a work area for the operating staff. The platform was erected approx. 1.0 m above the original turbine level.

Figure 6-2 shows a photograph of the completely assembled steel construction with the emplacement device, the transport cart with transfer cask, and the mining locomotive. In the background, the control cabin can also be seen.

The delivery rail tracks consist of two railway tracks with different gauges so that the new transport cart can be moved with the existing mining locomotive. In the final repository, a uniform gauge of 1,990 mm would be chosen from the beginning.

- Gauge 1,435 mm for the battery locomotive. The railway tracks end at the front borehole cellar edge with brake chocks as track terminators.
- Gauge 1,990 mm for the transport cart. The railway tracks skirt the borehole cellar and end at the rear borehole cellar edge with fixable brake chocks. The tolerance of the gauge in the area of the borehole cellar is ±2.5 mm.

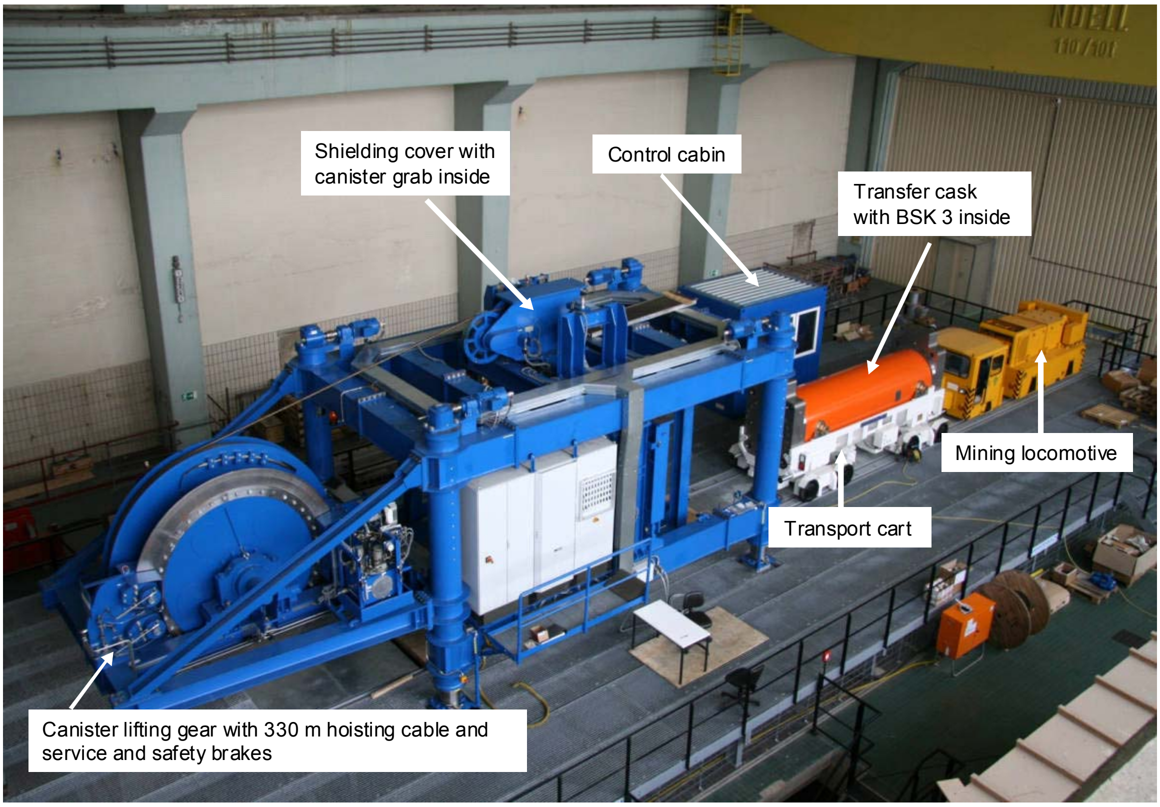


Figure 6-2: **Test stand with components**
(Photo of the Test Site in Landesbergen, Germany)

Figure 6-3 shows a photograph of the borehole cellar mock-up.

The borehole cellar is necessary for positioning drilling machinery when preparing a borehole in salt. The borehole cellar is also necessary during the emplacement process when the transfer cask is swivelled into an upright position. This means that the overall height of the emplacement device and thus, the gallery height can be kept to a minimum.

The borehole cellar is 2,200 mm wide and 7,000 mm long. The borehole cellar depth is determined by the configuration of the adapter pipe. The distance from the upper edge of the borehole lock mounting flange to the top of the transport cart rail is 2,850 mm. The borehole cellar in the test bed was supplied as a complete unit in order to test if the design offers adequate space for the assembly of the borehole lock.

Figure 6-3: View into the borehole cellar

During normal operations, the emplacement device is operated from the control cabin. The operating sequence can be monitored by means of the displays of the camera system.

The overall dimensions of the control cabin, which is constructed as a standard container, are 3,250 mm x 2,200 mm with a height of 2,700 mm (Figure 6-4). The cabin is equipped with five windows, four of which allow the monitoring of the emplacement process. The control cabin front which faces the emplacement device has a window over its entire length.

In addition to this, the emplacement process can be monitored from the control cabin by means of 3 cameras. Each remote-controlled camera can be horizontally swivelled through 360° and has a tilt range of 90 °, thus having the range of coverage of a semi sphere.

Figure 6-4: Control cabin

The pictures supplied by the cameras are shown on two monitors. Preset positions can be reached by simply pressing a button. Every other possible viewing position can be reached by means of a joystick.

The cameras are positioned at the following places:

- under the front cross beam of the emplacement device for the monitoring of the transport cart entrance area
- at the left side of the lifting gantry for the monitoring of the docking process of the shielding cover onto the transfer cask
- in the borehole cellar for the monitoring of the docking process of the transfer cask onto the borehole lock

During the tests, the control unit, which is necessary for the operation of the emplacement device, is also installed in the control cabin. From here, the automatic handling processes of the emplacement device are initiated and shown on displays. Manual operation from the control box is enabled by a key-operated switch on the control console.

Figure 6-5 is a photograph taken from the entrance of the hall showing the simulated (steel) borehole and the observation platforms.

Figure 6-5: Emplacement borehole and observation points

6.2 Results

During the demonstration tests, all relevant components operated like they are supposed to in a real final repository. Between September 2008 and February 2009, 502 double operating sequences were performed. A double operating sequence consists of an emplacement sequence and a retrieval sequence of the BSK 3 to start the emplacement sequence again. A retrieval sequence is an emplacement sequence in reverse and thus places a second realistic load on the emplacement device. Hence, these 502 double operating cycles correspond to 1004 emplacement sequences in the final repository.

6.2.1 Reliability Test

The reliability test programme includes the documentation and evaluation of all disturbances that occurred during the demonstration tests. When a disturbance occurred, counteractive measures were taken. This way, the disposal system was continuously improved.

For the evaluation of the reliability of the prototypes at the test stand the period between the "Teething Troubles" and the first signs of wear is decisive. The failure rate was increased at the beginning of the tests. It was essential to determine whether the faults were due to random failures which can also occur during real emplacement operations of whether they could be eliminated by means of design changes or preventive action. The failures were classified as shown in Table 6-1.

Table 6-1: Classification of the Failures / Disturbances that occurred

Class	Failure / Type of Disturbance
1	Random failure
2	Design failure which will be corrected
3	Preventable operating or maintenance failure
4	Fabrication failure which can be identified by initial quality assurance
5	Secondary failure
6	Irrelevant failure Unexplainable, sporadic, noncritical phenomena

During the demonstration tests, only class 1 failures are unrecoverable random failures. The results of the classification and evaluation are compiled in Table 6-2.

Table 6-2: Failures during operation of the Emplacement Device

	Emplacement Operation	Recovery Operation
Class	**Number**	**Number**
1		
2		
3	20	
4	17	411
5		
6	10	
Σ	47	411

A total of 458 failures occurred during the demonstration tests. 47 occurred during the emplacement sequence and 411 during the retrieval sequence. The retrieval sequence is not relevant to the emplacement operation in the repository but during the reliability tests, failures that occurred during the retrieval sequence were classified as class 4 failures. These 411 failures were due to fabrication failures (failures of the control programme) and one of them was due to an assembly error at the drive of the shielding cover.

With emplacement sequence no. 111, the control of the emplacement device was switched from manual to automatic operation. As a lot of control programme failures occurred, a comprehensive reprogramming of the control system was carried out at emplacement sequence no. 310.

Of the 47 failures that occurred during emplacement operations, 4 occurred during manual operation. Three were class 3 failures (1. premature starting of the winch after safety brake engagement (error message), 2. manual lifting of the shielding cover until emergency break engaged, 3. telescopic corner supports were not stopped during lowering of emplacement device) and one was a class 4 failure (emergency stop did not engage after failure of telescopic corner supports).

After the operation had been switched from manual to automatic, 38 failures occurred during the emplacement operations until the reprogramming at sequence no. 310. Of these 38 failures, 17 were class 3 failures (overload of the emplacement device because more than twice as many emplacement sequences were performed than expected in reality in order to accelerate testing. As a consequence, the telescopic corner supports overheated.). 16 were class 4 failures (six times the canister grab touched the emergency stop due to a sagging cable, four times the canister grab touched the emergency stop due to control failure, one programme failure at the beginning of a sequence, three times the shielding cover did not reach the start position, once breakdown of canister lifting gear, one drive failure due to fabrication failure). The remaining 5 were class 6 failures (three times error message regarding frequency converter, once software breakdown, once shielding cover twisted).

After emplacement sequence no. 310, 5 failures occurred (breakdown of canister lifting gear, failure of safety circuit because oil temperature was too low (6°C) at start of operation, failure during closing of upper cask lock, shielding cover twisted, cable length counting failure of the canister lifting gear).

There were neither random failures nor any design failures that had to be corrected.

6.2.2 Drift Transport of the Emplacement Device

When a borehole is filled to its capacity and backfilled with crushed salt, the emplacement device is moved to the next emplacement borehole. In preparation of the move, a two-piece support beam is swivelled in, which allows the emplacement device to be set onto the transport cart. The corner supports are moved to their highest position and the battery locomotive pushes the transport cart underneath the emplacement device using an additional extended coupling bar. Then, the emplacement device is lowered down and positioned on the four support points of the transport cart. Next, the four corner supports of the emplacement device can be lifted off their base plates. Now, the mining locomotive can move the emplacement device to the next emplacement borehole. All the processes described above are monitored from the control cabin and have been tested during the demonstration tests.

Figure 6-6 shows the intended drift transport of the emplacement device.

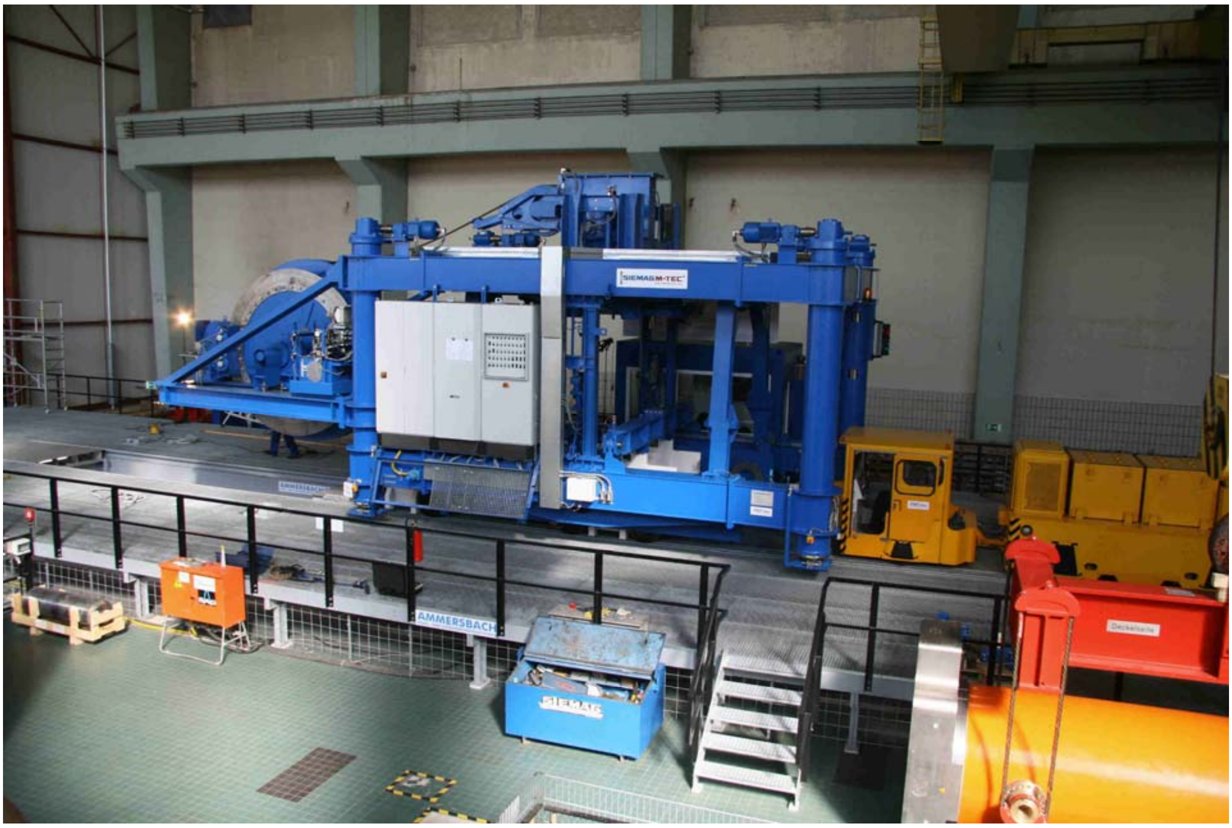


Figure 6-6: Drift Transport of the Emplacement Device

7 Additional Tests and Results

Three additional tests and two calculations were carried out and evaluated:

- emplacement of a long canister containing 3 COGEMA Canister Dummies
- re-railing device for the transport cart
- backfilling technique for boreholes
- stability analyses for the borehole cellar
- load impacts from the rock on the canister

7.1 Emplacement of a Long Canister containing 3 COGEMA Canister Dummies

To reduce emplacement time and effort, it was decided to test if it is possible to simultaneously emplace several containers. For this purpose, a long canister containing 3 COGEMA canister dummies was developed. Again, the canister was designed to withstand the lithostatic and thermomechanical pressure at the emplacement level The idea was to show that the emplacement device would be able to handle a canister with a weight of 2,770 kg and a different balance point. In total, 55 double operating cycles corresponding to 110 emplacement sequences were successfully performed. Figure 7-1 shows a sketch of the long canister while Figure 7-2 shows a picture of the canister dummy.

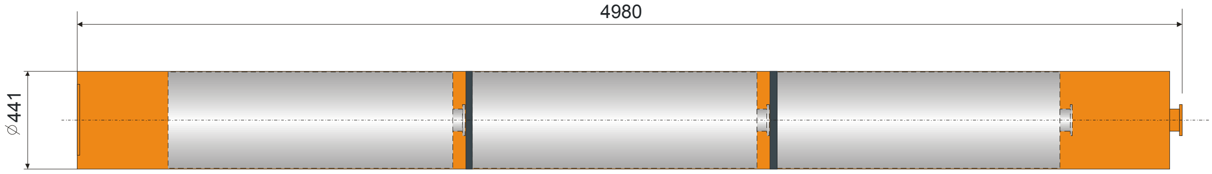


Figure 7-1: Sketch of the long canister with 3 COGEMA canister dummies

Figure 7-2: Long canister with 3 COGEMA canister dummies

7.2 Re-railing Device for the Transport Cart

In case of derailment, the loaded transport cart must be put back on the tracks. For this purpose, special mountings are attached at the ends of the upper carriage where lifting consoles can be screwed on to provide application points for the lifting jacks of the re-railing equipment. The re-railing operation is carried out with a standard re-railing device from the FAG Company, the LUKAS model (Figure 7-3). The equipment has already been tested and is also used by the German national railway company. It consists of the following components:

- Re-railing bridge
- 2 roller carriages
- 2 roller carriage sliding plates
- Retrieving device
- Control panel with folding frame
- Hydraulic power unit with three-phase alternator motor (220/380 V - 50 Hz)
- 2 telescopic jacks HP 40/ T 320 R
- Axel pusher, mass 26 kg
- 2-stage hand pump 530 bar
- Two way distributor valve with plug coupling units

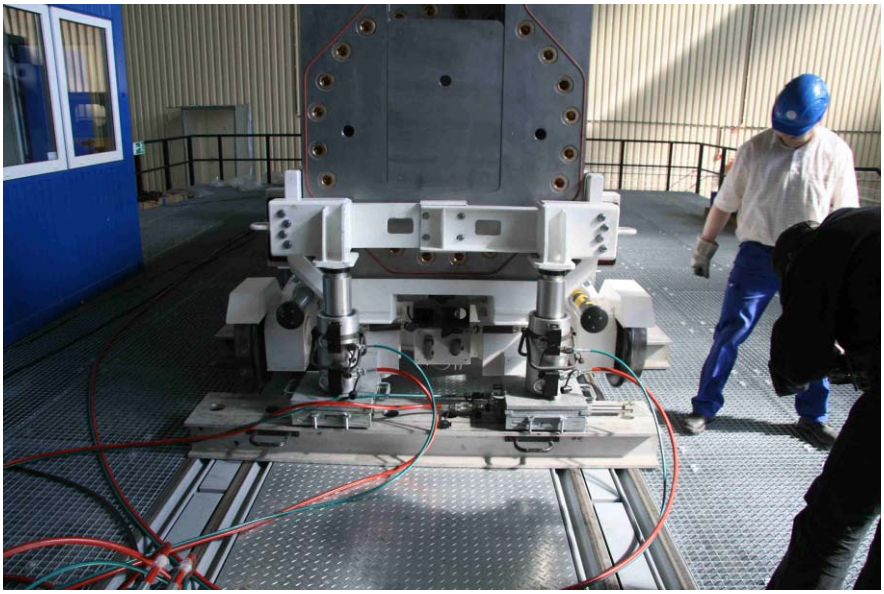


Figure 7-3: Transport cart with re-railing equipment

The re-railing of a transport cart onto the rails is performed as follows:

- The transport cart is secured against unintentional rolling by drag shoes or wedges
- The re-railing bridge is positioned under the mountings at the transport cart so that the telescopic jacks can be applied. Four employees are required for this process as this is very heavy.
- Connection of the hydraulic power unit and control panel energy supply.

- The roller carriages are placed onto the re-railing bridge.
- The roller carriage sliding plates are positioned. The sliding plates between the roller carriages and the telescopic jacks compensate for lateral movements during the lifting and positioning operation.
- Engaging of the telescope jacks.
- Connection of the hydraulic hose fittings.
- Lifting of the transport cart until the lower edges of the running wheels are above the upper edges of the tracks.
- Connection of the roller carriages to the control panel.
- Manoeuvring of the transport cart until it is positioned above the rails and can be set back onto the tracks. For this purpose, the roller carriages are moved with a shunting cylinder and a claw which fits into holes in the re-railing bridge. After the extension of the claw and the relocation that this causes, the cylinder is retracted again. At the same time, it is pulled out of the first hole and lowered into the next one. Thus, a further hole spacing can be negotiated. The sliding plates do not have any drive mechanism. They move as passive trailers due to the frictional connection caused by the weight of the lifted load.
- If the transport cart is moved too far, it can be fetched back by means of the retrieving device. If the running wheels of the transport cart are positioned on the upper side of the tracks due to inaccurate positioning, they are pushed into place with the aid of the axel pusher.
- Dismantling of the re-railing device

It could be shown that the re-railing of the transport cart by means of this equipment is feasible.

7.3 Backfilling Technique for Boreholes

Taking into account radiological and thermal aspects, the borehole disposal of BSK 3 and HLW canisters with vitrified waste demands the backfilling of the free space around the canister with a backfill material. Crushed rock salt is the designated material for backfilling. In a series of tests, the filling of the free space around the more than 5-m-long canisters was investigated.

For the technical testing of the backfilling concept, a prototype backfilling flask was developed. A mechanical load bearing element was integrated in the borehole which divides the individual canisters. Figure 7-4 shows the complete backfill system.

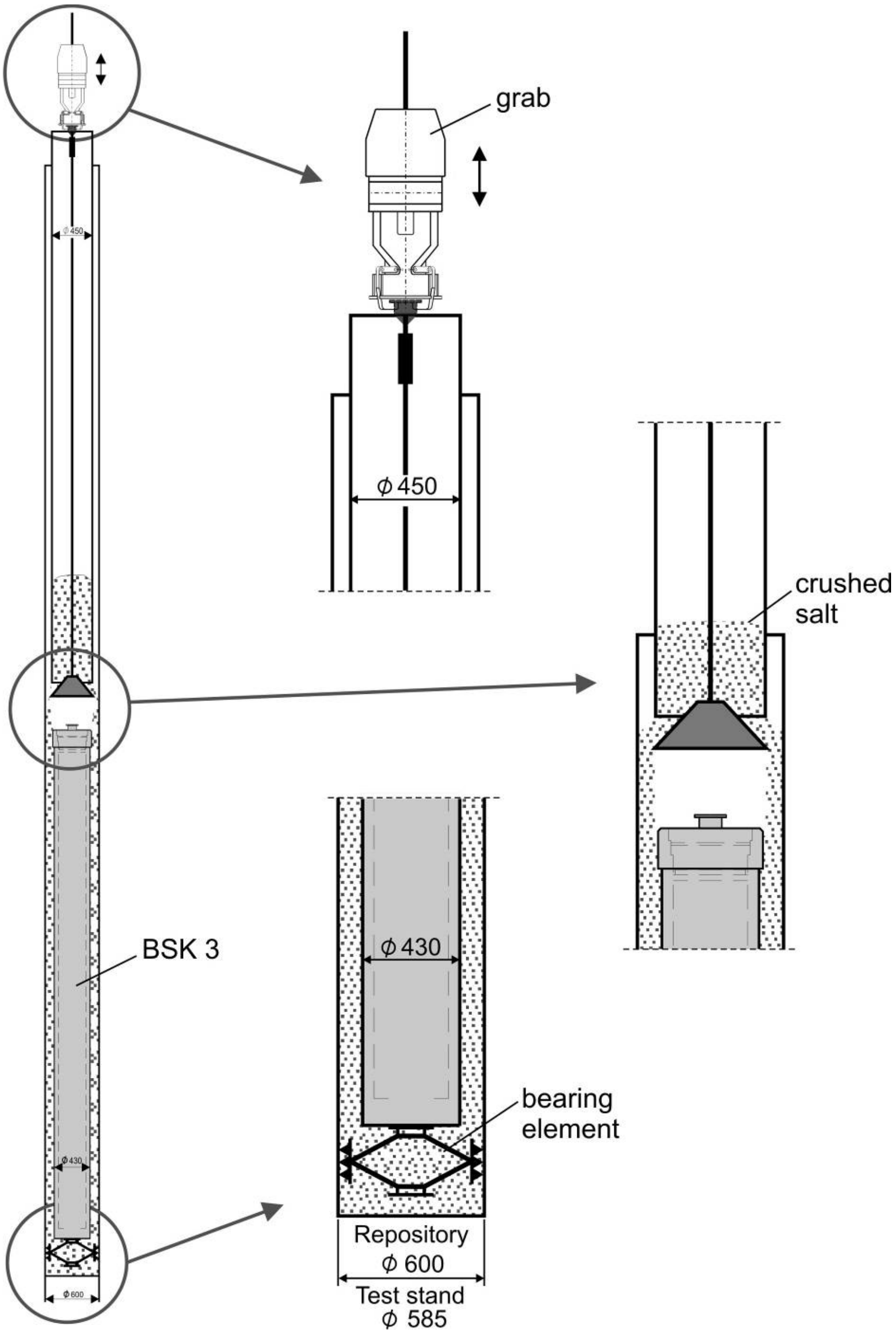


Figure 7-4: Complete backfill system

Table 7-1: Grain size distribution reference backfill /5/

Grain Size	mm	0.063	0.125	0.25	0.5	1	2	4	8
Through fraction	%	1.6	5.7	12	20	34	57	89	100

As the reference backfill was not available, commercial crushed rock salt with a mixture between 4 mm grain and 8 mm grain was used. The porosity in the tests was between 41 and 45%.

It could be shown that, except for a triangular space where the head of the BSK 3 leaned against the borehole wall (Figure 7-5), the BSK 3 and the bearing element were almost completely surrounded by crushed salt. Figure 7-6 shows a view of the BSK 3 during the backfill operation.

Figure 7-5: Triangular space resulting from the head of the BSK 3 leaning against the borehole wall

Figure 7-6: BSK 3 during backfill operation, seen through a window

7.4 Stability Analyses for the Borehole Cellar

For the emplacement of spent fuel canisters (BSK) in vertical boreholes it is necessary that enough space is available at the emplacement location in order to be able to swivel the transfer cask into a vertical position. The drift alone does not provide this space, thus it is necessary to enlarge the cross-section of the drift and to construct a borehole cellar.

From a geomechanical point of view, the excavation of the borehole cellar has the highest impact on the stress state apart from the excavation of the drift. Damage and partial failure of the cellar walls are to be expected, primarily of the walls parallel to the drift axis, thus, the borehole cellar needs to be protected during the duration of the emplacement process. The borehole wall is damaged down to a depth of approx. 0.5 m below the floor of the borehole cellar. More than 50% of the surface designated for the borehole lock is stable in the long term.

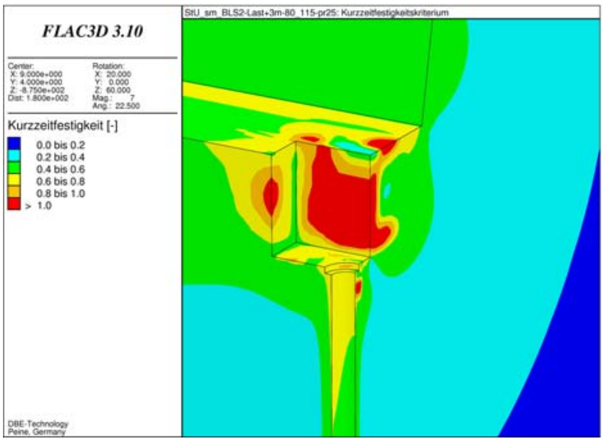


Figure 7-7: Short-term stability (failure criterion) 3 months after drilling of the borehole (failure occurs for values >1.0)

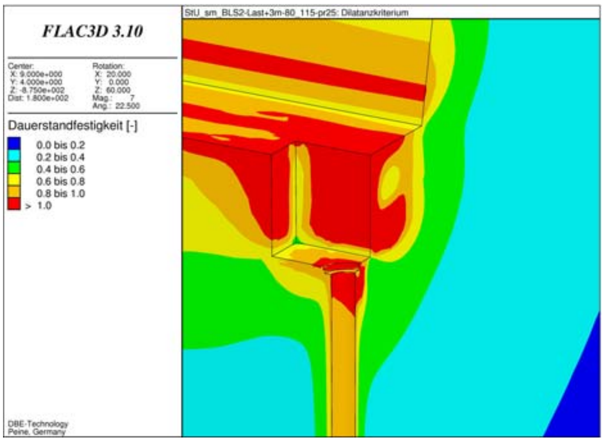


Figure 7-8: Long-term stability (dilatancy criterion) 3 months after drilling of the borehole (damage occurs for values >1.0)

Additional loads arise during emplacement due to the operation of the technical components. Two essential load states arise: one when the emplacement device lifts the loaded transfer cask, and the other when the loaded transfer cask is set down onto the borehole lock. If large enough foot prints are chosen for the emplacement device, the surface pressure is low compared to the stress state of the rock. On a free surface, low pressures on the surface suffice for an improvement of the stress state. This is also true in case of a damaged rock state. Here, a state improvement can also be determined, nevertheless, a healing process cannot be taken into account.

Choosing a wide enough spacing for the corner supports of the emplacement device ensures that the device is positioned in an area that is stable in the long term. The borehole lock will be placed in an area where the stress has already been reduced through the floor of the borehole cellar and through the borehole. As a consequence, a damaged area occurs at the borehole mouth which can be protected for the duration of the emplacement period by installing an accurately fitting adapter pipe. An additional concrete layer to support the borehole lock can improve the positioning accuracy of the borehole lock, if needed.

As a conclusion, it can be stated that the most significant geomechanical loads are due to the necessary mining works, especially the excavation of the borehole cellar, and not to the operation of the technical equipment.

7.5 Load Impacts from the Rock on the Canister

The concept for the emplacement of radioactive waste in boreholes in rock salt proposes to emplace spent fuel canisters and canisters containing vitrified waste in vertical boreholes of up to 300 m depth. The void space remaining in the borehole after emplacement will be backfilled with crushed salt. Due to the creep properties of rock salt, the rock mass converges over time, thus compacting the crushed salt. As a result, the canisters in the boreholes are subject to increasing pressure. In addition to this process, further aspects that result in additional pressure have to be considered. As the emplacement process will take a certain time until it is completed, the heat input of the first canisters to be emplaced will already affect the rock mass while the emplacement process is still ongoing. The resulting thermal expansion of the rock mass will place an additional load on the waste canisters. This additional load will not only affect the immediate vicinity of the heat source but will also be noticeable at longer distances and will thus affect boreholes farther away.

/11/ describes how overlapping temperature fields may lead to the effect that, after a first temperature maximum has been reached in a borehole and the heat input by the waste is generally decreasing, a second temperature maximum is reached at a later time. This second maximum may be even higher than the first one. This causes an additional load increase at the reference point due to the heating of the rock mass and its resulting thermal expansion.

Depending on the heat flow, a period of increasing load may be followed by a period of decreasing load at a specific location. Due to the viscoplastic behaviour of the rock salt, a uniform compressive stress acts on the canisters in the long term. In the short term, however, the two aspects mentioned above and the mutual interference of the boreholes lead to an anisotropic load.

If the rock and emplacement conditions are similar to those in the Gorleben exploration mine, the lithostatic rock pressure at the bottom of a borehole will be approx. 25 MPa. Taking into account the limit of 30 MPa for isotropic loads assumed in the past, the margin for additional thermal loads is only 5 MPa. It was thus to be investigated by means of numerical calculations if this margin is exhausted when making assumptions relevant to practice. The reference fuel was a UO_2 PWR fuel assembly with a uranium enrichment (U235) of 4 % and 50 000 MWd/tHM average burn-up and an interim storage time of 10 a, alternatively 15 a. It was assumed that the fuel assemblies were emplaced in boreholes of 300 m depth. One emplacement field consisted of 36 boreholes distributed over 6 drifts (Figure 7-9). The borehole-to-borehole distance was varied between 50 m and 75 m. Prior to the calculations regarding the finite field, individual effects were investigated by means of simplified models. /12/ gives a detailed description of the calculation models and the results achieved.

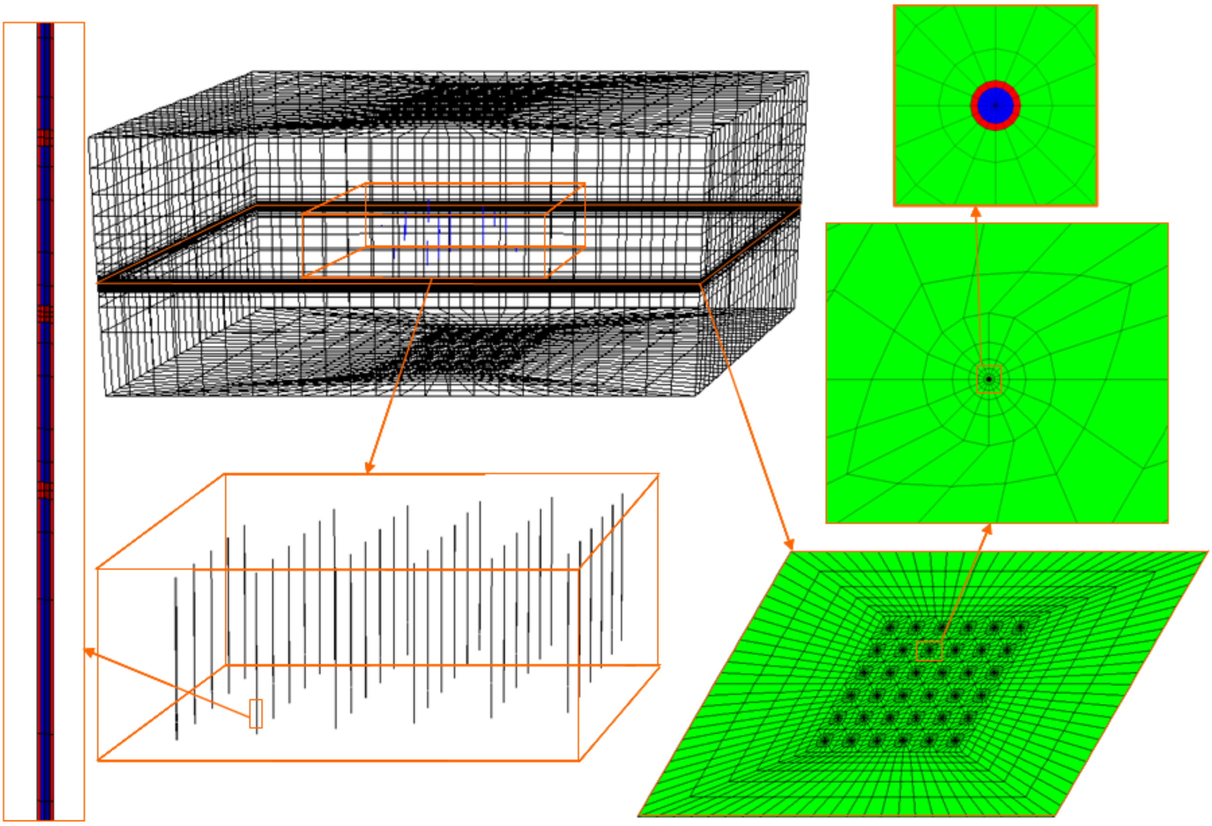


Figure 7-9: 3D model and several partial models

Prior to the results from a complex 3D-model, Figure 7-9, some further results from more simple models were achieved:

- A modified interim storage time from 10 a to 15 a leads to a reduction in the maximum load by approx. 1 MPa.
- A reduced interim storage time of 4 a, which is the shortest possible interim storage time for the reference design /13/, increases the load in the borehole by approx. 6 MPa.
- Enlarging the borehole diameter from 0.6 m to 0.8 m results in a stress reduction of approx. 3 MPa if the interim storage time is 4 a.
- Enlarging the borehole spacing from 50 m to 60 m leads to a decrease in maximum load by approx. 1.5 MPa.

Even though the emplacement process is completed after approx. 3 a, the stress does not decrease continuously after having reached a first maximum but there will be overlapping with thermally activated additional stress from the other boreholes. This overlapping may result in an increase in stress. The possible stress increase due to overlapping is shown in Figure 7-10. The figure shows the evolution of the maximum stress over time in the evaluation level for each of the six boreholes in the six drifts. It shows that after a first stress maximum has been reached, canister loads may occur – especially in the boreholes closer to the centre – that are significantly higher than the first stress maximum. The total maximum load is approx. 40 MPa.

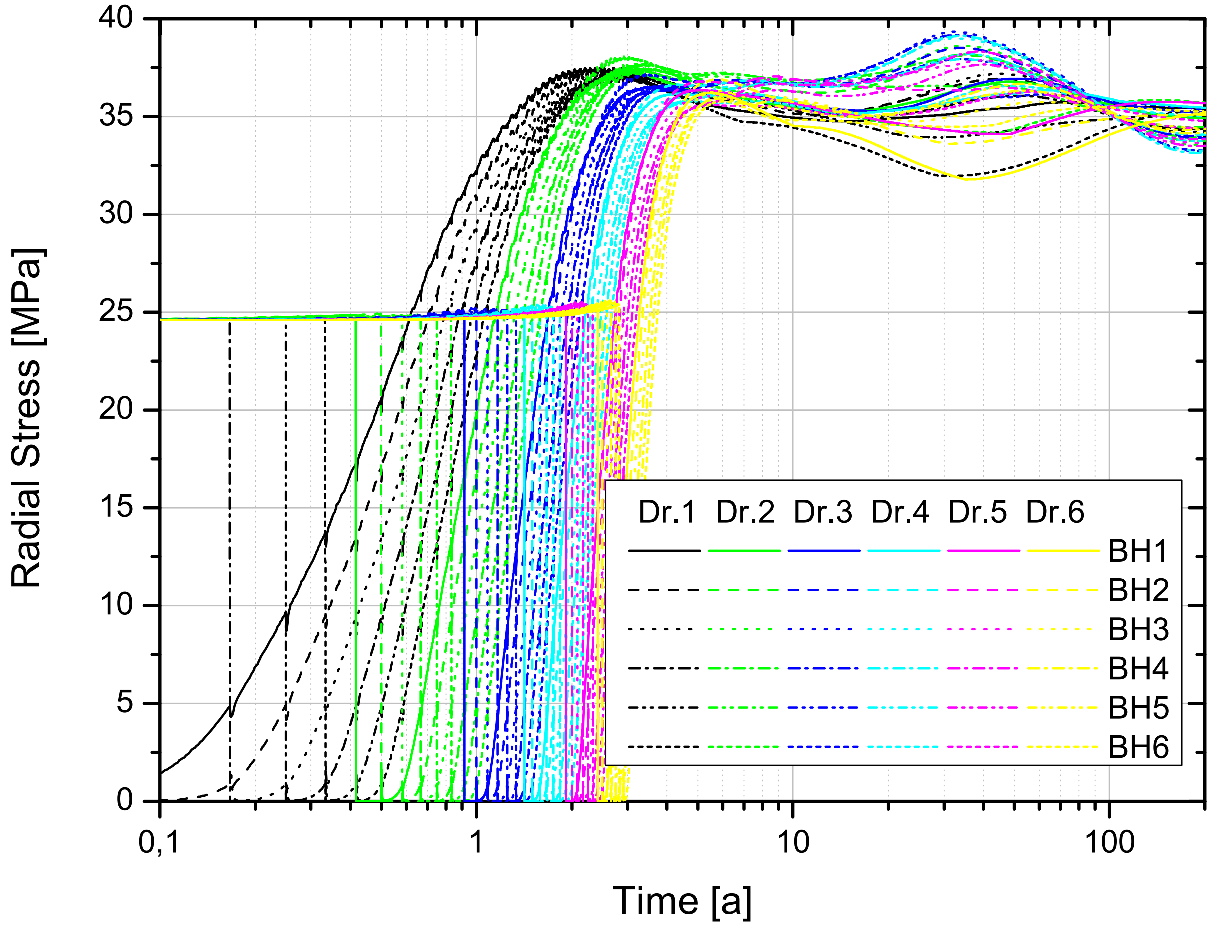


Figure 7-10: Maximum radial stress in the individual boreholes as a function of time

The ratio between maximum load value and minimum load value is called anisotropy factor. In case of isotropy, this value equals 1. Figure 7-11 shows the evolution of the anisotropy factor depending on the maximum load value of a point in time. The starting point is the isotropic stress state at approx. 25 MPa. Even at this point, it can be seen that emplacement in the first boreholes will cause an anisotropic state in the boreholes that will be drilled subsequently. This may be of interest for the drilling of the boreholes. Every time a borehole is drilled, the stress state will initially decrease until there is complete stress relief. Subsequently, the stress increases slowly. However, a high anisotropy factor can only be seen at the beginning of the compaction process. When the stress has reached a value of approx. 10 MPa, the anisotropy factor is only approx. 1.1. Due to the highly viscous behaviour of the rock salt, the isotropic initial state at approx. 25 MPa will have to be reached in the long term. During the period under consideration, i.e. 200 a, however, this state was not reached, Figure 7-11.

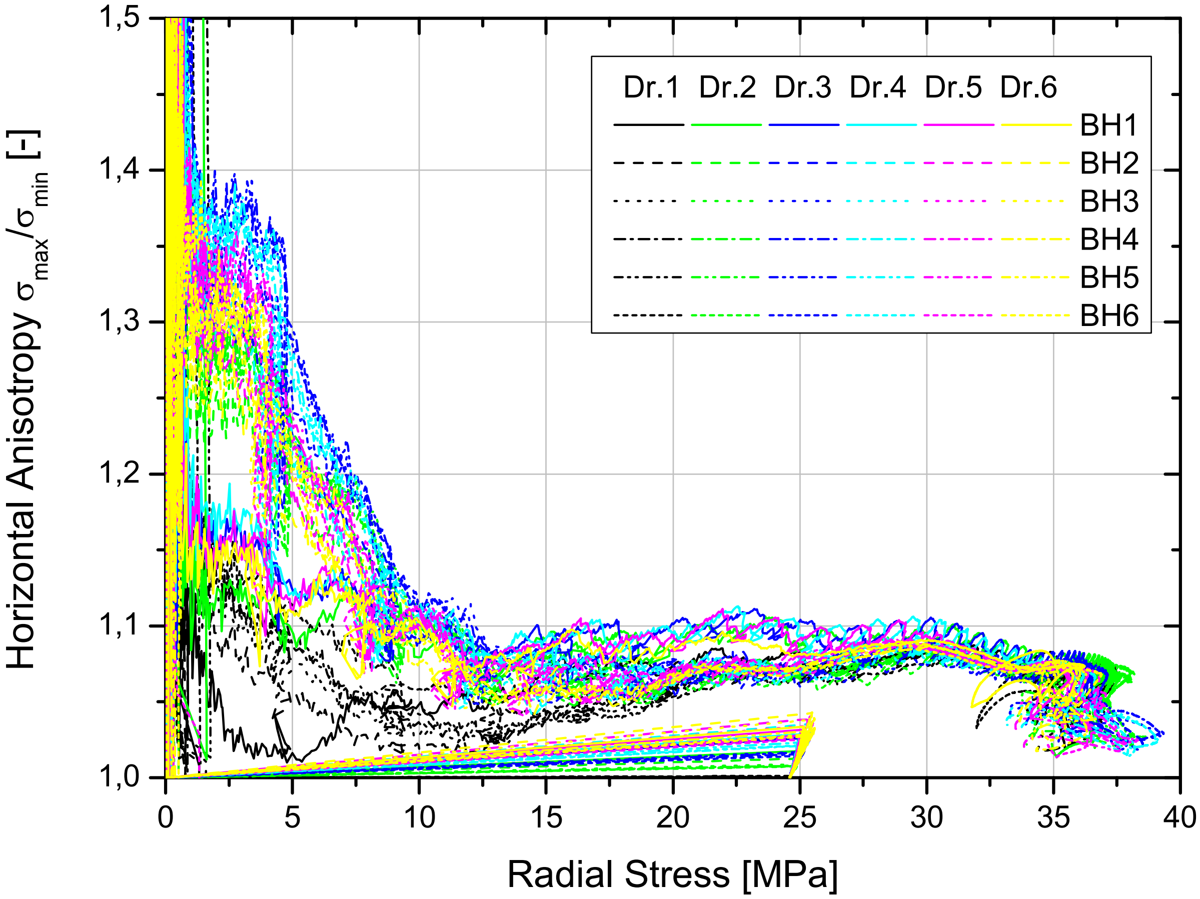


Figure 7-11: **Anisotropy factor in the canister loads in the individual boreholes depending on the maximum radial stress**

The discretization of the three-dimensional model, which – due to numerical reasons – was relatively rough, could be improved. Likewise, the constitutive models to describe the mechanical behaviour of rock salt could be improved. For crushed salt, this concerns the behaviour of the material at porosities of less than approx. 10 % /14/. For rock salt, this concerns uncertainties in the material behaviour at low deviator stresses. This stress state is reached when the rock salt movement due to the convergence of void spaces has mostly subsided. Thus, this state is also related to the description of the compaction ability of crushed salt at low residual porosities.

The results of the calculations of the load impact on the canisters indicate that – based on the assumptions made in the existing borehole concept concerning the canister design – the requirements concerning canister integrity cannot be met. Thus, changes either in the design or in the concept have to be made. Changes in the design concern the stress level of the canister load as well as the homogeneity of the load. Concerning the repository design, the borehole depth of 300 m, the borehole diameter of 0.6 m, the almost complete and uninterrupted filling with BSK 3 canisters, and the interim storage time of 15 years should be mentioned. If the requirements on the canisters are not to be increased, the repository design has to be adjusted. However, an adjustment of the design was not done within the scope of this project. The question is whether a reduction in borehole length – which seems to be obvious at first – should be the first option or whether a change in design could be a feasible alternative. One possible design change could be a thicker layer of crushed salt around the canisters. Other possibilities could be measures to reduce the energy density in the rock mass, e.g. by reducing the number of canisters per borehole, by increasing interim storage time, or by alternating canisters with different inventories. Furthermore, increasing the borehole spacing should be investigated in a further project. Furthermore, it has to be assumed that additional loads from neighbouring emplacement fields will have to be taken into account.

This investigation considered the disposal of UO_2 PWR fuel assemblies with known burn-up. The results do not apply to the final disposal of HLW canisters, canisters containing MOX fuel assemblies, or of UO_2 fuel assemblies with different burn-up. The calculations carried out assumed an ideal, i.e. centric, positioning of the canisters in the borehole. The demonstration tests carried out in this project showed, however, that this "ideal" position is hardly ever achieved /15/. In this case, a further anisotropic influence is possible.

8 Conclusions and Outlook

In spring 2008, the platform for the demonstration tests was erected, followed by the delivery of the components of the emplacement system in the summer of the same year. All the components were assembled at a level 10 m above the ground floor, while a 10-m-long vertical steel metal casing was installed below the demonstration floor to simulate the emplacement borehole. The BSK 3 was lowered down by the grab of the emplacement device into this artificial borehole and – unlike in a real repository – removed again for further tests.

In a series of demonstration tests, the feasibility of the handling process and other processes planned for the underground emplacement process were successfully demonstrated over a time period of approx. 10 months between September 2008 and the end of the project in July 2009. Due to the late start of the test series, the demonstration tests were performed in two shifts per day, i.e. 8 to 10 emplacement processes were performed per day. All the components which are relevant to the system's function and control were taken into account. In combination with a specific test programme, experimental data on the reliability of the underground emplacement process were obtained. In this context, it was observed that there is a permanent need to continuously monitor all the movements of the different components during the transfer and emplacement process. By doing so, experience regarding the maintenance of the emplacement device was gained and recorded.

The demonstration tests comprised all the process steps, starting with the acceptance of the BSK 3 canister and concluding with the emplacement of the canister into the vertical borehole. In total, 1,004 complete emplacement operations had been carried out by the end of the test programme. The entire system and each component proved to be safe, reliable, and robust. The masses involved in the BSK 3 concept are slightly lower than those in the POLLUX® concept. It can thus be assumed that all shaft transport and hoisting devices developed for the POLLUX® concept are applicable for the BSK 3 concept as well.

Several technical and safety-related features were tested additionally. To simulate more realistic conditions within the borehole, the BSK 3 dummy was lowered onto a salt layer covering the head of a previously "emplaced" canister at the bottom of the simulated emplacement borehole. The challenge was to safely open the grab after the canister had been emplaced, even if the canister was not in a strictly upright position but touching the wall of the borehole. It was demonstrated that the grab of the emplacement device could safely be unhooked from the canister in all cases.

After one borehole has been filled, the emplacement device needs to be transported to the next borehole by means of the transport cart. This process was also simulated at the test facility. The safe transport of the emplacement device from borehole to borehole could be demonstrated as well.

In case of derailing, the transport cart loaded with the transfer cask needs to be set back onto the rails by means of conventional equipment. Corresponding demonstration tests were carried out successfully.

The full-scale demonstration programme was extended by additional tests with HLW dummies. The idea was to demonstrate the technical feasibility of handling HLW canisters with the same equipment as was used for BSK 3 canisters. For this purpose, a so-called triple pack was designed and fabricated; a steel envelop containing three HLW dummies with almost the same outer diameter and the same height as the BSK 3. A further series of emplacement processes (110) was successfully performed with this triple pack, confirming the reliability of the emplacement system for this type of canisters as well.

From the point of view of radiation protection and with regard to thermal aspects, the gap between an emplaced BSK 3 and the borehole wall needs to be backfilled, even in the area close to the borehole cellar. In a repository in salt, crushed salt will be used as backfill material, and it is vital that the crushed salt completely fills the voids. Thus, a further demonstration test was carried out with the objective to develop the technology and to investigate whether the space around the BSK 3 could be completely filled or not; just to confirm existing assumptions. A prototype backfill canister was fabricated and the crushed salt inserted into the borehole. The grain size of the crushed salt was between 4 and 8 mm. The test showed that the space between BSK 3 canister and borehole wall can be filled completely.

8.1 Analysis of Main Achievements

It can be stated that the development, the fabrication, and the demonstration tests of the BSK 3 emplacement system were a success. All the components were designed in detail, the drawings and reports evaluated by external experts confirming the compliance with the regulatory requirements of the German Mining Regulations and the Atomic Energy Act. The components were fabricated on a full-scale basis between winter 2006 and spring 2008. The construction work to prepare a suitable test platform was successfully completed by April 2008. The individual components (mining locomotive, transport cart, BSK 3 dummy, transfer cask, emplacement device and borehole lock) were delivered to the test site between April and June 2008. After the individual components had been accepted on site, the demonstration programme – performed in two shifts because of unforeseen delays in fabrication and installation of the emplacement device – was started in September 2008 and lasted until the end of the project. The reliability of the emplacement system was confirmed by means of a large number of demonstration tests and conclusions and recommendations were drawn for the industrial application in a real repository.

The successful demonstration programme led to the decision not to dismantle the entire transport and emplacement system after the end of the ESDRED project but to use the system for a second type of waste canister. The idea was to investigate its reliability for handling and emplacing a so-called "triple-pack" of HLW canisters instead of a BSK 3 canister. Accordingly, additional demonstration tests were performed in the spring of 2009, beyond the scope of the ESDRED Project. In this case, three canister dummies were encapsulated by a thin steel envelope thus providing a geometry similar to the BSK 3 canister. This encapsulation is the prerequisite for the emplacement process with the same transport and emplacement system already successfully tested for the BSK 3 canister.

One lesson learned during the fabrication of the different components of the BSK 3 emplacement system was that it is necessary to not only provide very precisely formulated technical specifications and detailed drawings but to control and/or monitor all steps of a component fabrication process on an ongoing basis as well.

In conclusion it can be stated that the reliability and the robustness of the designed and fabricated emplacement system for spent fuel canisters of the BSK 3 type was proven by the various demonstration tests implemented.

8.2 Possible Design Improvements

It is recommended to repeat the demonstration tests in situ under real conditions in order to investigate the influence of temperature and dust and to eliminate possible impacts on the functionality and reliability of the technical components of the BSK 3 emplacement system, preferably in a salt environment.

The results of the calculations of the load impact on the canisters indicate that – based on the assumptions made in the existing borehole concept concerning the canister design – the requirements concerning canister integrity cannot be met. Thus, changes either in the repository design or in the concept have to be made. Concerning the repository design, the borehole depth of 300 m, the borehole diameter of 0.6 m, the almost complete and uninterrupted filling with BSK 3 canisters, and the interim storage time of 15 years should be mentioned. If the requirements on the canisters are not to be increased, the repository design has to be adjusted. However, an adjustment of the design was not done within the scope of this project. The question is whether a reduction in borehole length – which comes to mind first – should be the first option or whether a change in design could be an alternative. One possible design change could be a thicker layer of crushed salt around the canisters. Other possibilities could be measures to reduce the energy density in the rock mass, e.g. by reducing the number of canisters per borehole, by increasing interim storage time, or by alternating canisters with different inventories. Furthermore, increasing the borehole spacing should be investigated in a further project. It should also be investigated if additional loads from neighbouring emplacement fields have to be taken into account.

This investigation considered the disposal of UO_2 PWR fuel assemblies with known burn-up. The results do not apply to the final disposal of HLW canisters, of canisters containing MOX fuel assemblies, or of UO_2 fuel assemblies with different burn-up. The calculations carried out assumed an ideal, i.e. centric, positioning of the canisters in the borehole. The demonstration tests carried out in this project showed, however, that this "ideal" position is hardly ever achieved /15/. In this case, a further anisotropic influence is possible.

Abbreviations

ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs (French National Radioactive Waste Management Agency)
BMWi	Bundesministerium für Wirtschaft und Technologie (*Federal Ministry of Economics and Technology*)
BOP	Blowout Preventer
BSK	Brennstabkokille (*Spent Fuel Canister*)
BWR	Boiling Water Reactor
CASTOR®	**Ca**sk for **S**torage and **T**ransport **o**f **R**adioactive Material
COGEMA	Compagnie Générale de Matières Nucléaires
CSD-C	Colis Standard de Déchets Compactés
ESDRED	Engineering Studies and Demonstration of Repository Designs
EU	European Union
EURATOM	European Atomic Energy Community
FKZ	Förderkennzeichen (*Project Number*)
GNS	Gesellschaft für Nuklear-Service mbH
HLW	High Level Radioactive Waste
NRG	Nuclear Research & Consultancy Group, The Netherlands
PWR	Pressurized Water Reactor
R&D	Research and Development
SF	Spent Fuel

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