Optimization of Spent Fuel Direct Disposal Technology for a Geological Repository in Rock Salt in Germany - 10504

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ABSTRACT

In Germany, the reference concept for the disposal of high-level radioactive waste (HLW) and spent fuel (SF) proposes the geological disposal in a rock salt formation. While HLW canisters are supposed to be disposed of in vertical boreholes, the reference concept for SF foresees the horizontal emplacement of heavy self-shielding containers in disposal drifts. Over the past years all operational steps of the reference concept have been reviewed for possible improvements, which led to the development of an alternative disposal concept for SF, the so-called BSK 3 (German acronym for fuel rod canister) concept, that relies on a vertical borehole emplacement technology.

Results of a recently concluded full-scale demonstration program of the BSK 3 emplacement system showed that the BSK 3 concept could be a feasible alternative to the reference concept. Handling procedures and techniques developed for this concept could also be applied for the disposal of HLW canisters. Therefore, its implementation would simplify future repository operations compared to the reference concept. Furthermore, advantages are to be expected for the BSK 3 concept in regard to its implications for the long-term safety of the repository, mainly because the time needed by rock salt to enclose the SF containers will be reduced for the relatively small voids within the emplacement boreholes.

INTRODUCTION

The peaceful utilization of nuclear energy in Germany started in the 1950s. The first nuclear reactors were operated for research purposes only; the utilization for generating power started in 1962 with a pilot nuclear reactor. In the sixties and at the beginning of the seventies the use of nuclear energy expanded. As a result, a total of 21 nuclear power stations were put into operation between 1968 and 1989. Today, 17 nuclear power plants are still in operation.

According to the stipulations in the Atomic Energy Act (AtG) of that time , reprocessing of spent fuel assemblies was the main way to dispose of irradiated fuel assemblies for the German utilities until 1994. To this end, the German utilities signed reprocessing contracts with COGEMA (now AREVA NC, France) and BNFL (now NDA, UK) for a total of about 6,700 metric tons of heavy metal (tHM) with the obligation to take back any waste generated by reprocessing. As part of the so-called consensus agreement between the utilities and the Federal Government of 11 June 2001, all parties agreed on a stop of SF reprocessing. Instead it was decided that after interim storage for the required cooling time, SF was to be directly disposed of in a geological repository. Consequently, fuel assembly transports for reprocessing purposes have not been permitted since the middle of 2005. However, it is expected that the return of all processing waste will continue until 2025.

The German reference concept for the disposal of high-level radioactive waste (HLW) and spent fuel (SF) proposes the geological disposal in a rock salt formation. In 1963, the predecessor of the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe - BGR) issued a recommendation to dispose of the resulting radioactive waste in rock-salt formations. In 1973 and 1974 the Federal Government started to plan the construction of a national center for the reprocessing, conditioning, and disposal of radioactive waste. After a four-stage intense site selection procedure by the Federal Government and the Federal State of Lower-Saxony, during which more than 140 sites were reviewed, these activities led to the selection of Gorleben as the site for a national center for reprocessing, conditioning, and disposal of radioactive waste in 1977. From 1979 on, a comprehensive surface survey program was carried out to characterize the salt dome and the surrounding area which had never been impaired by mining activities.

In view of the very promising surface exploration results which strongly suggested the suitability of the site to host a repository, DBE (German acronym for “German Company for the Construction and Operation of Waste Repositories”) started the excavation of a large-scale exploration mine on behalf of the Federal Government in 1986.

In spite of the technical achievements, a moratorium on underground exploration of the Gorleben site was issued in 2000 due to political decisions taken by the former Federal Government which was formed by a coalition between the Social Democrats and the Green Party. Exploration has not resumed since then. However, after the Federal elections of 2009, the newly formed Federal Government has recently expressed its intention to complete the underground exploration of the site without further delay. It is assumed that completion of the Gorleben exploration could be achieved within five years time. Two more years will then be required to evaluate the exploration results and to draw up the final suitability statement for the site. If the suitability of the Gorleben salt dome is then confirmed, the licensing procedure can be initiated.

Concurrent with site exploration from the surface and subsequent construction of the exploration mine, a large-scale R&D program was carried out to develop the technologies required for the safe operation of a future repository. According to the regulatory framework in Germany, license application for a radioactive waste repository requires the prior demonstration that all facilities and equipment needed for the disposal operation can be provided and safely operated. Consequently, the development of safety relevant repository equipment that was not state of the art has been an important part of the repository-related R&D work for the past decades. The objectives is to have the science and technology available when needed to license and later operate a repository.

A first equipment demonstration program in the early nineties concentrated on the direct disposal of SF. The so-called POLLUX® concept was developed as an alternative to the previous concept of spent fuel reprocessing and disposal of vitrified HLW and later became part of the current German reference concept. In regard to SF, the POLLUX® concept anticipates the packaging of fuel rods of up to ten spent PWR fuel assemblies (about 5 tHM) into a self-shielding cask with a gross weight of about 65 metric tons. Together with the weight of the transport cart and ancillary equipment this requires a shaft hoist for a payload of 85 metric tons. One main aspect of the first equipment demonstration program, therefore, was to convincingly show that the shaft hoisting of such payloads was feasible and could be realized in compliance with nuclear safety requirements. However, the other relevant handling procedures and equipment needed for the direct disposal of SF were also included in the demonstration program. All safety relevant repository equipment that was not state-of-the-art was replaced, and handling procedures were tested in full-scale test facilities above ground.

In addition to the development of equipment for an eventual repository operation, all technical facilities that are necessary for the implementation of the POLLUX® concept, apart from the repository, have been built to prove the feasibility of this concept, i.e. interim storage facilities for casks containing spent fuel, a pilot conditioning plant, and a special "POLLUX®" cask for final disposal.

In spite of the standstill of exploration work at the Gorleben site since 2000, site independent R&D work to optimize the waste emplacement technology and equipment has been ongoing without interruption. One important part of this R&D work carried out during recent years has been dedicated to the optimization of the German reference concept for the disposal of spent fuel.

To optimize the reference concept, all operational steps have been reviewed for possible improvements. This review process initiated the development of an alternative concept for the direct disposal of SF, the BSK 3 concept. In contrast to the POLLUX® concept, the developed BSK 3 concept relies on vertical borehole emplacement technology and was investigated further as it promised advantages in regard to operational simplifications and long-term safety.

In its first part, this paper summarizes the consistent, long-term technological effort of the last decades that has led to a situation where all advanced technologies required to run a repository for spent fuel and HLW are available and have undergone comprehensive testing to demonstrate their approvability in a future licensing procedure. The second part is dedicated to the description of the BSK 3 concept and the results of the recently completed demonstration program which led to the confirmation of the technical feasibility of the BSK 3 concept.

REFERENCE CONCEPT AND TECHNOLOGY DEVELOPMENT

Reference Concept for disposing HLW and SF

While the repository site development in Gorleben was still ongoing, a comprehensive equipment development and demonstration program for spent fuel and vitrified waste disposal started in the early 1990s. The overall objective of this national R&D effort initiated by the Federal Government was to demonstrate the feasibility and safety of spent fuel conditioning, transport to underground, and disposal in a repository mine under full-scale simulated conditions.

The work started with the development of a reference concept for the disposal of spent fuel and vitrified HLW in a repository in a salt formation [1] (Fig. 1).

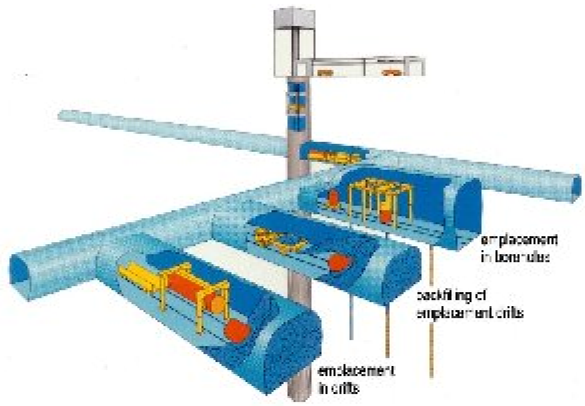

Fig. 1. German reference concept for spent fuel and vitrified HLW in a repository in a salt formation

This concept, which still is the current reference concept for Germany, comprises the so-called borehole concept for the final disposal of waste from SF reprocessing and the POLLUX® concept for the direct disposal of SF in horizontal drifts. The borehole concept for vitrified HLW and other wastes from reprocessing proposes the disposal of waste canisters in up to 300-m deep unlined vertical boreholes with 0.6-m diameter, drilled from the repository drifts. The diameter of these boreholes is slightly larger than the diameter of the waste canisters (43 cm). Up to about 200 canisters could be stacked into one borehole.

The POLLUX® concept was selected from a number of alternatives and anticipates the emplacement of heavy (65 t) self-shielding casks (POLLUX® cask, Fig. 2; POLLUX® basket, Fig.3) containing the fuel rods of up to ten disassembled spent fuel elements (~5 tHM). Thus, it requires a conditioning facility where the fuel rods can be separated from the structural parts of the fuel assembly. The first conditioning plant in the world was built by GNS (German acronym for "Company for Nuclear-Service") to demonstrate the waste conditioning process. It was licensed for an initial pilot operation of 35 tHM and became technically ready for spent fuel acceptance in 2000. Currently, the plant is in stand-by operation to be used in case damaged CASTOR® casks require repair work. The execution of actual spent fuel conditioning for research purposes depends on further decisions on the Gorleben repository project and on the availability of acceptance criteria for disposal.

According to the POLLUX® concept, the casks will be disposed of in horizontal drifts in a repository mine at a depth of about 870 m. The void space around the casks will be backfilled with crushed salt shortly after emplacement.

In Germany, obtaining a license to construct a repository requires prior demonstration to the competent authorities that the technological ways and means selected to build and operate the repository are state-of-the-art technology. Thus, by pointing to existing installations, it can be shown that the proposed system or equipment can be constructed and operated in the required way. In the early 1990s neither the required waste encapsulation nor the transport of the resulting heavy payloads in a shaft had ever been demonstrated before. Therefore, a large-scale demonstration program had to be carried out.

The objectives of this demonstration program were to:

- develop and provide a POLLUX® cask for transport, storage and disposal
- develop and provide facilities for spent fuel conditioning for disposal
- develop and test a hoisting system for the required payload of 85 t
- develop and test all necessary equipment for underground transportation and emplacement

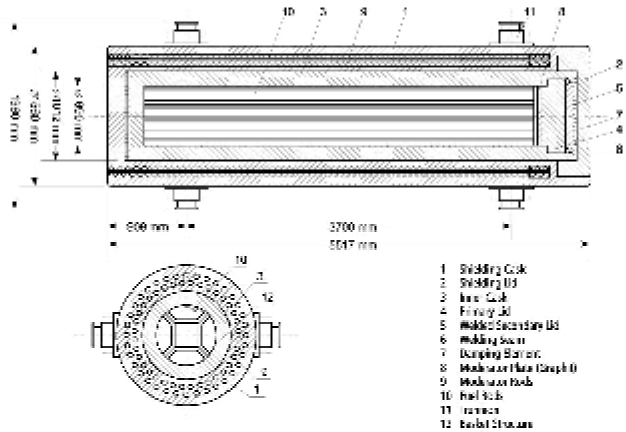

Fig. 2. POLLUX® cask

Fig.3. Fuel rods being loaded into one of a total of five POLLUX® baskets

Spent Fuel Hoisting to Underground

The hoisting of SF to underground was one major component of the reference concept that was not state-of-the-art and therefore had to be developed and demonstrated in a full-scale test program. A comprehensive, worldwide review of heavy-duty hoisting facilities operating in mines carried out at the beginning of the demonstration program showed that the technological limit at that time was in the area of a payload of 40 tons for loads conveyed from underground to the surface. In contrast to this, the German reference concept requires the hoisting of a payload of about 85 tons (cask and transport cart) from the surface to underground. Correspondingly, the feasibility of hoisting such payloads to underground with the level of safety required in the nuclear industry was highly questionable.

Development and testing of a suitable hoisting system for the required payloads was assigned to DBE. After a detailed design of the hoisting system fulfilling the required payload and mining and nuclear safety specifications, all internal systems and components were identified that were not state-of-the-art at that time. For comprehensive testing of these components, a full-scale demonstration facility was designed (Fig.4) and constructed (Fig.5) which integrated all safety-relevant systems and components that were to be tested.

About 1000 cycles of loading and unloading the shaft-hoisting cage were demonstrated at a surface test facility to obtain reliable data on the performance of the safety-relevant equipment which was needed for a risk-informed safety analysis and for the license application. A subsequent probabilistic safety analysis of the shaft hoisting system showed that shaft transportation was safe for the conveyance of spent fuel to underground. It further demonstrated the clear superiority of this transportation method to accessing the underground areas of a repository via a ramp. The estimated probabilities of occurrence of catastrophic events were of the order of 10^{-9} per year. With these values such incidents are clearly in the range of rest-risks and they do not need to be considered in the design. This probabilistic safety analysis was the first of its kind in the world for repository equipment important to safety, and it was based on reliability data derived from full-scale tests.

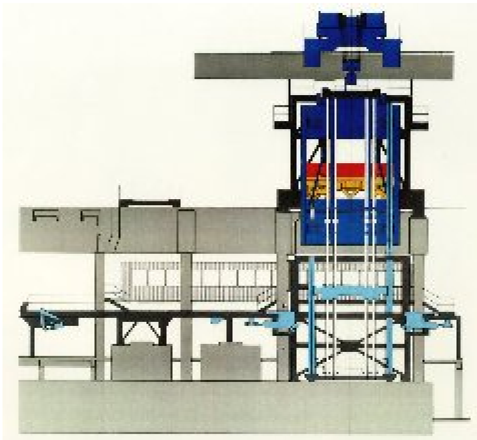

Fig. 4. Sketch of hoisting test facility **Fig. 5. Test facility with full-scale shaft hoisting equipment**

One of the components of particular importance tested at the SST facility (Simulation of Shaft Transport) was the protection system against accidental overwinding. If the engine control system or the hoisting engine brakes fail to stop the cage as designed (called "overwinding"), such a protection system must mitigate the consequences to non-severe effects to prevent the cage from damaging the shaft station structures and endangering the integrity of the hoisting cables.

In the SST facility, both a novel overwinding prevention system proposed by DBE for this purpose and a traditional system required by the mining supervisory authority were tested. The SELDA (Strain Energy Linear Ductile Arrestor) arrestor proposed by DBE performed excellently in repeated tests, so that now a suitable overwinding prevention system for the required payload range is available and is to be used in all future German mines. The second system, consisting of tapered wooden shaft cage guides, is the one traditionally used worldwide in the mining industry, although for much lower payloads. The system was completely unable to arrest the cage as intended, resulting in serious damage to the test facility. The total failure of this traditional system confirmed the critical importance of equipment demonstration projects for final disposal purposes.

Underground Transportation and Disposal

Upon reaching the underground shaft landing station, the waste packages are unloaded from the shaft cage, conveyed into the disposal drift, and disposed of there. The final operation is the backfilling of void space around the cask. For the underground transport and disposal, it is important to minimize the height of the equipment, i.e. the loaded transport cart and the emplacement device, as they determine the drift height and thus have a strong impact on rock excavation needs. Moreover, a compact repository layout that minimizes host rock volume needs would require the smallest possible curve radii. For transportation safety reasons, track-bound transport was selected, and it was intended to make use of standard systems and components of the railways industry whenever possible. DBE, in close cooperation with equipment manufacturers, designed and procured a system for these tasks.

Safety and maintenance needs' optimization excluded the use of external power, and a modular, battery driven locomotive was designed. The 65 tons weight of the POLLUX® disposal cask required a transport cart running on 8 wheels. Furthermore, a compact repository design could be achieved by a skewed layout with 60-degree curves having a radius of 20 m. The latter specification was fairly stringent in combination with the height limitation.

The transport, handling and emplacement equipment of the POLLUX® cask reference concept were subject to successful full-scale demonstration in a dedicated surface facility, a view of which is shown in Fig 6.

Fig. 6. Test facility with full-scale prototype of underground transportation and emplacement system

Transportation and disposal tests were repeated 1000 times to gather data on the reliability of the equipment. For the waste emplacement device, a single control equipment failure was registered during the tests, with the machine automatically going into safe stand-by condition, as designed. In summary, DBE's first series of full-scale demonstration tests was very successful and led to an amendment of the Atomic Energy Act in 1994, accepting direct spent fuel disposal as a viable alternative to reprocessing and HLW disposal.

BSK 3 CONCEPT

For the past few years, alternative technical approaches for both, vitrified HLW and spent fuel emplacement have been investigated to harmonize and optimize future disposal operations. Among others, borehole emplacement, the reference technique for HLW, was also considered for consolidated spent fuel. After initial promising studies, the German industry (GNS) decided to investigate a new disposal canister to support the further development of a borehole concept. The new canister was named "BSK 3" according to the acronym for the German word for fuel rod canister and can contain the fuel rods of 3 PWR fuel elements or 9 BWR fuel assemblies [2]. The corresponding BSK 3 concept, jointly developed by GNS and DBE, still relies on the separation of fuel rods from the structural parts of the fuel assemblies, but - different to the POLLUX® reference concept - fuel rods are packed into a BSK 3 canister which has the same diameter as the reference HLW canister.

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 program for the concept to confirm the expected advantages. In detail, the main advantages that are supposed to be gained from the implementation of the BSK 3 concepts are:

- Complete isolation of the waste in the impermeable host rock by the converging salt is an important safety feature of a salt repository. Due to the small void around the BSK 3 canisters in the borehole, this situation will be achieved relatively fast compared to enclosure of the POLLUX® casks that 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 extensively harmonized and standardized emplacement technology and will use essentially the same equipment for hoisting to underground and transport for all waste designated for disposal in a repository for HLW and SF.
- Earlier disposal and/or higher specific thermal loads of the waste with a potential to reduce the intermediate storage periods to less than 10 years as was estimated by GNS due to the lower HM content compared to the POLLUX® cask.
- Improved control of the heat transfer to the host rock by well-directed combination of heat-generating waste (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 concurrently reducing the exploration effort.
- Reduction of gas source term due to significantly reduced amount of metal without self shielding cask

Technical approach for transport and emplacement of BSK 3

In view of these advantages, an R&D project with financial support from the German Federal Government and the German nuclear industry was launched to develop and test the systems and components for the transport, handling and disposal of BSK 3 canisters. The main objective was to demonstrate the functionality and reliability of the equipment and to obtain the data and information required for licensing this new back-end technology. The project was also embedded into ESDRED (Integrated Project Engineering Studies and Demonstration of Repository Designs), a larger effort with thirteen partner organizations from nine European countries financially supported by the European Commission [3, 4] in the context of the EURATOM 6th Framework Program.

The system for the handling and emplacement of BSK 3 canisters was developed by DBE TECHNOLOGY GmbH[1] in cooperation with GNS and equipment manufacturers and comprises: 1) a transfer cask which provides appropriate shielding during transport and emplacement, 2) a transport unit consisting of a mining locomotive and transport cart, and 3) an emplacement device. Fig 7 outlines the components of the entire transport and emplacement system in an underground emplacement drift.

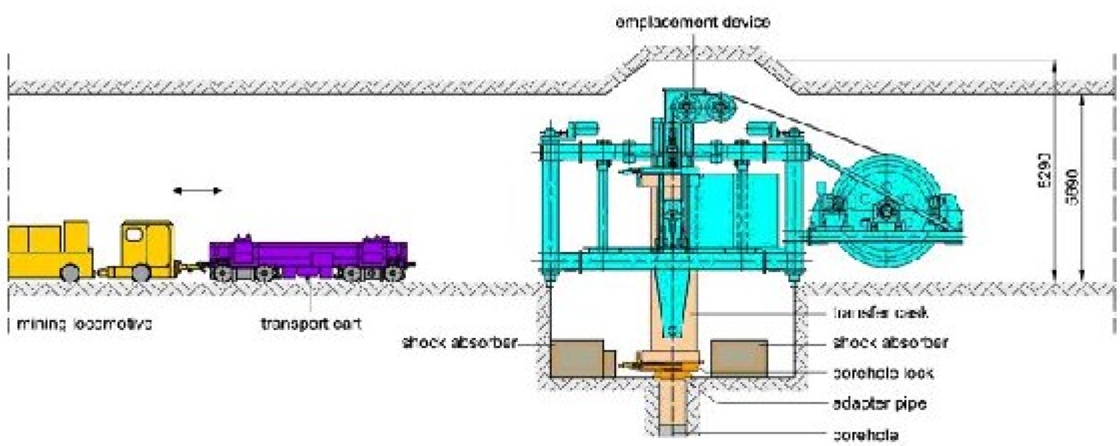

Fig. 7. Outline of the BSK 3 disposal system

The BSK 3 canister will be inserted into a transfer cask in a hot cell at the surface, for instance at the conditioning plant, shipped to the repository, hoisted to underground on a transport cart, and towed into the disposal drift. The emplacement device, positioned on top of the emplacement borehole, carries out the emplacement operation as described in detail below. For the demonstration tests, a BSK 3 canister mock-up with the geometry and weight of the original canister but without radioactive material content was procured.

[1] For statutory reasons all R&D work after 2000 was assigned to DBE TECHNOLOGY GmbH, a subsidiary of DBE mbH, the German Company for the Construction and Operation of Repositories for Waste, Ltd.

The transfer cask was designed to provide mechanical strength and gamma and neutron radiation protection to allow workers to approach the cask in case equipment repair becomes necessary. The transfer cask body is a thick-walled cylinder made of nodular graphite cast iron (GJS). Neutron moderation and shielding is provided by polyethylene. Two locks made of stainless steel are screwed to the cask body. The flat slide latches integrated into the locks work like drawers and run in slide bars. When in locked position, the flat slide latch is kept in place by two locking bolts set into the sidewalls. The transfer cask is not fitted with a mechanism to operate the locks. Lock opening and closing is carried out at the base by the borehole lock mechanism and at the lid by the emplacement device (shielding cover). The emplacement device is equipped with all means for safe transfer cask handling and BSK 3 canister emplacement.

In the course of an emplacement sequence, the BSK 3 canister is transported inside a transfer cask on a transport cart to its designated position in an emplacement drift. The transfer cask is then lifted off the transport cart by the emplacement device and turned into an upright position after the transport cart has been removed. In the next step, the cask is lowered onto the borehole lock and locked in position. A shielding cover is lowered onto the upper transfer cask lock before the top of the cask can be opened and a grab can take hold of the BSK 3 canister. The lock at the transfer cask base and the borehole lock are opened simultaneously, and the BSK 3 canister – held by the canister grab – is lowered into the borehole. The canister grab is then removed and the transfer cask and the borehole lock closed. After turning the transfer cask back into horizontal position, the transport cart is hauled again into the emplacement device and the transfer cask is placed on the cart. Finally, the transport cart with the transfer cask is driven out of the emplacement drift and back to the surface for reloading.

The BSK 3 system demonstration and test program

All full-scale demonstration tests were performed in the same facility as the afore mentioned demonstration tests for the reference POLLUX® system. It is a former turbine hall of a power station in Landesbergen near Hanover in the Northern German state of Lower-Saxony. Within less than 2 years, all components had been designed in detail, manufactured, and delivered to the test site and had been evaluated and approved by external experts. The components of the emplacement system were assembled on a platform 10 m above the ground floor. A 10-m long vertical steel metal casing simulated the emplacement borehole. For the test program, the BSK 3 canister was lowered into the "borehole" by the grab of the emplacement device and, unlike in a real repository, removed again thereafter for the next test run.

Fig. 8 shows a photo of the full-scale test site with all the components required for transport and emplacing BSK 3 canisters.

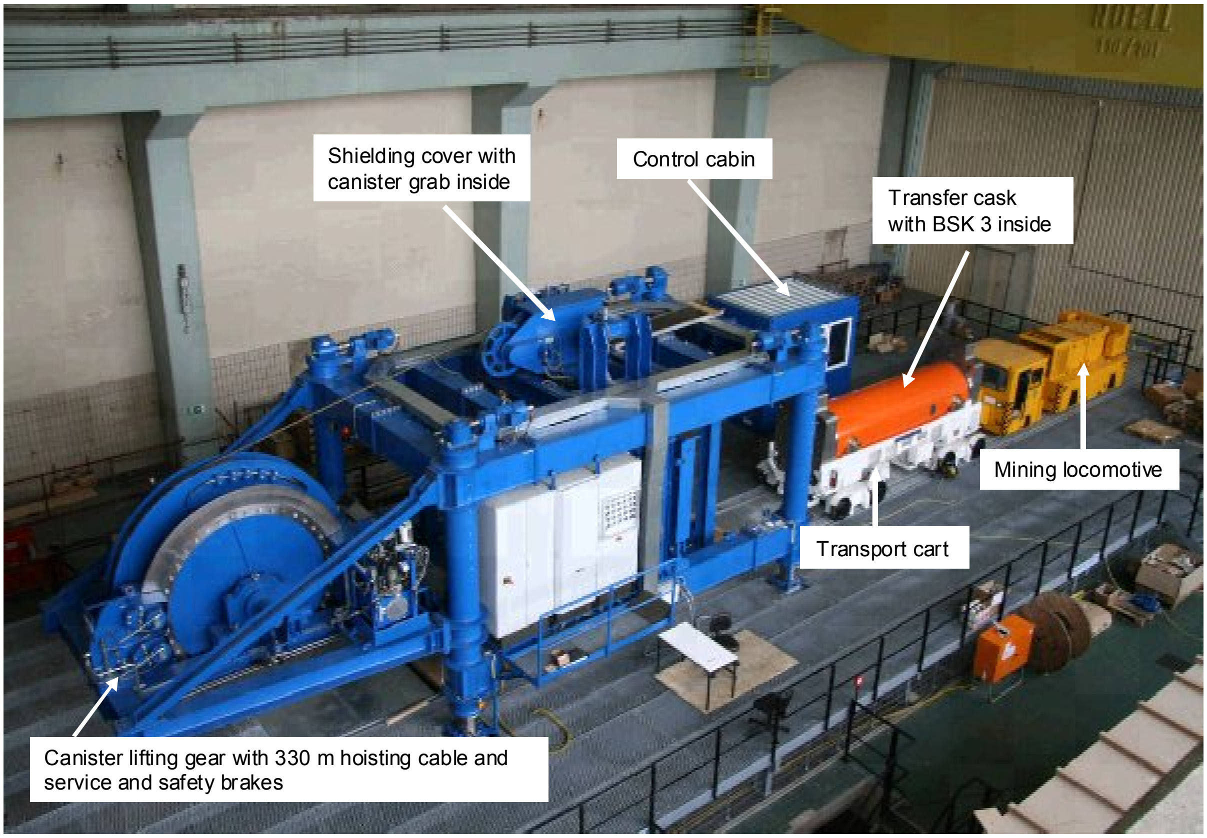

Fig. 8. BSK 3 full scale test stand with components
(Photo of the Test Site in Landesbergen, Germany)

The demonstration program started in July 2008 and continued until July 2009. It comprised demonstration tests, simulation tests, and tests to identify potential operating failures and to develop preventive and corrective measures. 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 mentioned above beginning with the acceptance of the BSK 3 canister and concluding with the emplacement of the canister into the vertical borehole. In total, more than 1,000 complete emplacement operations had been carried out by the end of the test program. 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 test of operational disturbances

Several technical and safety-related features were tested additionally. To simulate more realistic conditions within the borehole, the BSK 3 dummy and – in a second series of trials – a canister with three HLW canisters were lowered on a salt layer covering the head of a previously "emplaced" canister. Fig. 9 describes three different situations in the borehole, all of them showing the top of an already emplaced BSK 3 canister. The challenge was to safely open the grab after the canister has been emplaced, even if the canister is not in a strictly upright position.

Fig. 9. Simulating crushed salt backfill before emplacing the next canister

It was demonstrated that the grab of the emplacement device could safely be unhooked from the canister in all cases although the canister was not in a strictly vertical position but touching the wall of the borehole (Fig. 10).

Fig. 10. Opening of the grab in the borehole

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 (Fig. 11). The safe transport of the emplacement device back to the top of the borehole cellar could be demonstrated as well.

Fig. 11. Transport of the emplacement device by means of the transport cart

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 (Fig. 12). Corresponding demonstration tests were performed successfully.

Fig. 12. Re-railing of the transport cart (left) and standard equipment (right)

Additional emplacement tests with HLW canister dummies

The full-scale demonstration program 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 applied for BSK 3 canisters. For this purpose a so called triple pack was designed and fabricated; a steel envelop containing three HLW dummies with the same outer diameter and the same weight as the BSK 3. Another large number of emplacement processes (approx. 120) was successfully performed with this triple pack confirming the reliability of the emplacement system for this type of canisters as well.

Demonstration tests on technique 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 the demonstration test was to show 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 maximum grain size of the crushed salt was 8 mm. The test showed that the space between BSK 3 canister and borehole wall can be completely filled. This is of particular importance for the degree of accuracy of safety assessments.

CONCLUSIONS AND OUTLOOK

Several years after the demonstration of all the elements of the German reference concept for spent fuel disposal, a new, alternative system was proposed and tested comprehensively. In addition to this, a feasibility study focusing on the direct emplacement of large transport and storage casks is currently being carried out. It can therefore be summarized that in spite of the standstill with regard to the exploration of the future HLW repository site in Gorleben, conceptual work taking into account the whole line from interim storage to disposal is still going on.

The reliability of the handling technologies has been confirmed for the POLLUX® and the BSK 3 concept in above-ground “cold” full-scale demonstration tests while the testing of the related conditioning technologies is still pending. It is recommended to carry out full-scale demonstration tests underground for both concepts in order to simulate typical “mining conditions” with higher temperatures in a dustier atmosphere.

ACKNOWLEDGMENTS

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