Concepts and Technologies for Radioactive Waste Disposal in Rock Salt

Wernt Brewitz*[1], *Tilmann Rothfuchs

Koncepcia a technológie pre ukladnenie rádioaktívneho odpadu v kamennej soli.

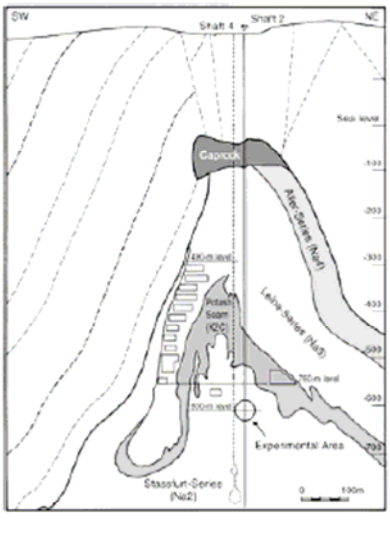
In Germany, rock salt was selected to host a repository for radioactive waste because of its excellent mechanical properties. During 12 years of practical disposal operation in the Asse mine and 25 years of disposal in the disused former salt mine Morsleben, it was demonstrated that low-level wastes (LLW) and intermediate-level wastes (ILW) can be safely handled and economically disposed of in salt repositories without a great technical effort. LLW drums were stacked in old mining chambers by loading vehicles or emplaced by means of the dumping technique. Generally, the remaining voids were backfilled by crushed salt or brown coal filter ash. ILW were lowered into inaccessible chambers through a borehole from a loading station above using a remote control.

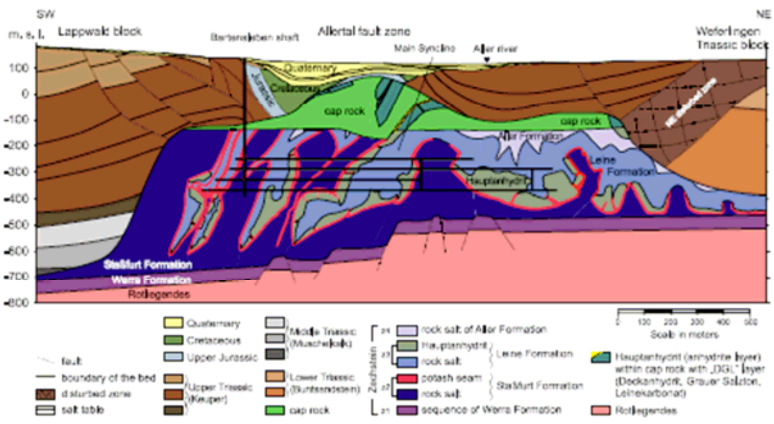
Additionally, an in-situ solidification of liquid LLW was applied in the Morsleben mine. Concepts and techniques for the disposal of heat generating high-level waste (HLW) are advanced as well. The feasibility of both borehole and drift disposal concepts have been proved by about 30 years of testing in the Asse mine. Since 1980s, several full-scale in-situ tests were conducted for simulating the borehole emplacement of vitrified HLW canisters and the drift emplacement of spent fuel in Pollux casks. Since 1979, the Gorleben salt dome has been investigated to prove its suitability to host the national final repository for all types of radioactive waste. The "Concept Repository Gorleben" disposal concepts and techniques for LLW and ILW are widely based on the successful test operations performed at Asse. Full-scale experiments including the development and testing of adequate transport and emplacement systems for HLW, however, are still pending. General discussions on the retrievability and the reversibility are going on.

Key words*: rock salt, Radioactive Waste****,*** *Concept Repository Gorleben*

Introduction

In the northern part of Germany, marine Zechstein deposits are widely distributed. As a result of the salt mobilisation during the Mesozoic and Cenozoic time, salt domes and diapirs with complicated internal structures were formed, being the object of potash and rock salt mining since the end of the 19th century. About 30 years ago, salt was selected to host a repository for all kinds of radioactive waste in Germany because of its excellent mechanical properties allowing the excavation of large openings without an additional support. As a result of its elasto-viscoplastic material behaviour, rock salt creeps at high stresses without a significant fracturing enabling the encapsulation of any waste on a long term. Especially at high temperatures, as caused by a heat generating highlevel waste, the creep capability and high thermal conductivity of rock salt are providing for the acceleration of void closure and heat dissipation.





a) Asse salt mine *b) Bartensleben main cross cut (source BfS).*

Fig. 1. Cross sections of the Asse and Morsleben salt mines.

[1] *Wernt Brewitz, Tilmann Rothfuchs*, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH Repository Safety Research Division, Theodor-Heuss-Strasse 4, 38122 Braunschweig, Germany

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The "Gorleben" salt dome has been investigated since 1979 in order to prove its suitability to host the national final repository for all types of radioactive waste. However, in view of the change in the Federal Energy Policy, in 1998 the German government expressed certain doubts with respect to the suitability of salt as host rock in general and of the Gorleben site in particular. All exploration activities were halted by the end of 2000 and a moratorium was imposed for up to ten years. Within this period of time, all pending issues should be clarified and new formation-independent site selection criteria should be developed in order to identify alternative sites with favourable geological settings.

Before the implementation of the Gorleben moratorium, as in many countries, full-scale testing was conducted in the underground research laboratory (URL) Asse from 1968 until the mid nineties of the last century in order to prove the feasibility of preliminarily selected disposal concepts for all waste types.

Parallel to the activities at the URL Asse, the former salt mine Morsleben has been used as a repository for the lowlevel radioactive waste (Endlager für radioaktive Abfälle Morsleben, ERAM). The waste disposal already started at the time of the German Democratic Republic and was continued after the German reunification under the responsibility of the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) and its repository operator Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE).

This paper provides a summarizing overview about the concepts developed and tested and the achievements obtained at Asse and Morsleben with regard to the radioactive waste disposal in geological salt formations in Germany. A general view of both locations is given in Figure 1. Figure 1a shows a cross section of the Asse anticline with empty excavations on thirteen mining levels in the southern flank remaining from the rock salt mining between 1908 and 1964. A cross section of the Allertal salt structure with the main excavations of the Morsleben mine is presented in Figure 1b.

Development of Concepts and Testing of Disposal Techniques for the Low and Intermediate-Level Waste at Asse

From 1967 to 1978, approx. 124,000 containers with a low-level waste (LLW) and approx. 1,300 containers with an intermediate-level waste (ILW) were emplaced in the Asse mine (Fig. 1) in empty mining chambers remaining from the rock salt mining for testing disposal concepts and technologies for the salt option. The LLW, packed in 200- or 400-l-drums or lost concrete shields, were transported without an additional shielding.

In accordance with the licences granted, the permissible dose rate of the waste packages could amount to 2 mSv/h at the container surface. The waste drums were stacked in old mining chambers made accessible to loading vehicles or were emplaced later by means of the dumping technique. By these tests it was shown that the dumping of 200- and 400-l-drums as well as the subsequent backfilling with crushed salt provides a safe disposal technique. For the waste in concrete shields with weights of up to 3.5 Mg, however, the stacking technique together with the pneumatic backfilling is a most suitable method (Fig. 2). Entrances to the disposal chambers were sealed at the termination of the emplacement operations.

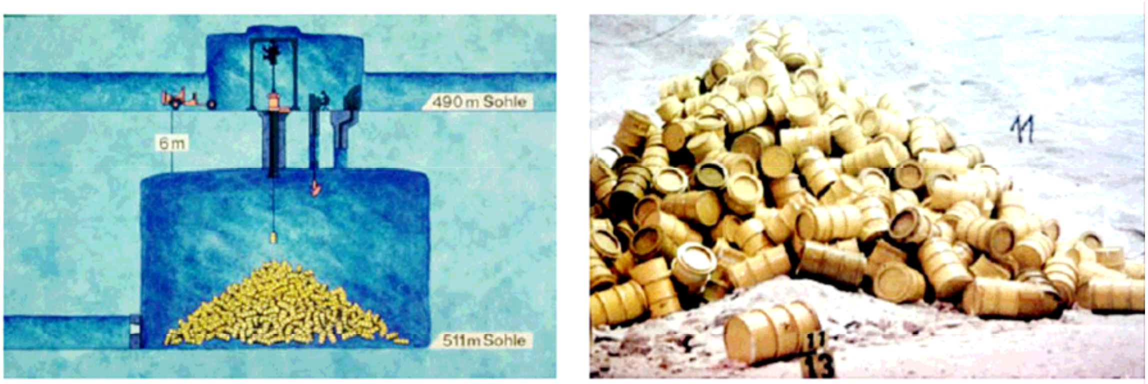
ILW can only be handled and transported in shielded containers due to the high dose rate at the container surface of up to 10 Gy/h. This also applies to the handling of these wastes in an underground repository. Consequently, inaccessible chambers or boreholes need to be selected for a final disposal. For the test in the Asse mine, 200-ldrums containing ILW were delivered in collective transport containers and were transported to the underground in individual shielding containers with a total weight of 9.8 Mg. Using the remote control, the 200-l-drums were then lowered into a sealed chamber through a borehole from a loading station above (Fig. 3).

After 1975, a cavern of 10,000 m³ was excavated in about 1,000 m depth for the disposal of ILW, which was to be filled from a hot cell in the shaft hall directly through a newly sunk shaft. Due to the termination of licences it has not yet been possible to use this installation (GSF, 1985).

During 12 years of practical disposal operation, it was demonstrated that LLW and ILW can be safely handled and economically disposed of in the salt repository without a great technical effort. The labour force employed for the disposal tests was kept under a surveillance with dosimeters. In 1978, when approx. 30,000 containers of LLW were emplaced, the highest personnel dose rate ranged below 10 mSv/a. An estimate showed that the stacking technique of lost concrete shields resulted in a mean overall dose rate of about 6.5 µSv per container and the dumping technique in a mean overall dose rate of 0.35 µSv per drum (Brewitz et al., 1981).

The tests with ILW demonstrated further that the waste can be safely transported and disposed of in a mine when using a suitable shielding. A significant contribution to the personnel dose rate as a result of these tests could not be measured. In 1978, all disposal activities at Asse were terminated due to a change of the legal situation in Germany. Since this time, only radiological tests were planned and carried out where the radioactive material was removed from the site at the end of the experiment and returned to the producer. Testing of concepts and technologies without radioactive waste continued until 1995 and focused on a development and testing of disposal concepts for the high-level radioactive waste (HLW) (see chapters 4 to 6).

Fig. 2. Stacking technique for LLW drums in a mining chamber at the Asse mine (source GSF).



a) Lowering of ILW drums into the storage room *a) Unloaded ILW drums in the sealed storage room*
Fig. 3. Unloading of ILW drums atthe Asse mine (source GSF)

The disposal concepts and techniques for LLW and ILW included in the "Concept Repository Gorleben" (DBE, 1998) are widely based on the successful test operations performed at Asse during more than 10 years of the emplacement between 1967 and 1978.

Disposal of Low- and Intermediate-Level Waste in the Disused Former Salt Mine Morsleben

In the German Democratic Republic, the disused Bartensleben mine was selected in 1970 as a repository for the radioactive waste (Morsleben repository for radioactive waste). The Bartensleben shaft had been sunk in 1910/1912 followed by the potash mining until 1918 and the subsequent rock salt mining until 1969. Together with the neighbouring and connected Marie mine, the total volume of underground workings still accessible today amounts to approx. 5.8 million m³. The first license for the test disposal in the Morsleben repository was issued in 1978. In 1986, the license was renewed for an unlimited time for the disposal of LLW and ILW. After the reunification of Germany, the BfS applied for licensing under §9 of the Atomic Act in order to continue the disposal operation after the year 2000.

The emplacement of radioactive waste was performed mainly at the depth of -372 m NN on the fourth level of the West Field and East Field, and in the deep workings of the South Field of the Bartensleben mine. Small amounts of waste were also emplaced in the Central Part and the North Field of the Bartensleben mine. The concept of waste handling and disposal was mainly based on the adjustment of waste characteristics and appropriate emplacement techniques (Brennecke et al., 2004). Three different disposal techniques were applied: in-situ solidification of liquid wastes, stacking and dumping of solid wastes (BfS, 2001).

a) Stacked 200-l-drums in the West Field

b) Stacked waste drums in the East Field (three drum layers are stacked upon each other and separated by a crushed salt layer of 1 m thickness, respectively)

Fig. 4. Emplacement chambers with stacked waste drums in the Morsleben mine (BfS, 2001).

For the in-situ solidification, the liquid LLW and the brown coal filter ash (BFA) as a binding agent were mixed before placing them in emplacement voids. Solidification, however, proved to be inadequate by this method. Hence, radioactive liquids and BFA were alternately dispersed in the openings leading to a solid product when the liquid permeated the BFA. This technique was stopped when the repository was taken over by the BfS.

The stacking of 200- to 600-l-drums of LLW in empty mining chambers started in the West Field (Fig. 4a). After this area was filled in to a large extent, the emplacement was continued in the East Field (Fig. 4b). Unloading from the transport vehicle and stacking of the waste drums was carried out by a forklift. The maximum stacking height was about 4.50 m corresponding to the upright stacking of five 200-l-drums.

The LLW, ILW, and spent sealed radiation sources were dumped into non-accessible mining chambers in the deep workings of the South Field by means of a remote-controlled equipment. A reusable cask containing the radioactive waste was placed on a dumping rig. Subsequently, the waste was dumped into the chamber. After a radiological inspection, the empty cask was authorised for a reuse. The dumping technique was applied for radiation sources, drums, and non-inflammable waste.

Generally, the remaining voids of the emplacement chambers were completely backfilled by BFA and crushed salt. BFA was used for the backfilling of openings which were hardly accessible or which had to be backfilled over longer distances of about 100 m. The backfilling with BFA was performed pneumatically via pipes. The crushed salt backfill, however, was just dumped into the chambers.

From 1971 to 1991, the Morsleben repository received 14,432 m^3 of LLW and ILW, and 6.227 spent sealed radiation sources with a total activity of 2.9·1014 Bq (BfS, 2001). Most wastes originated from the operation of the nuclear power plants Greifswald and Rheinsberg, and from the research reactor Rossendorf. In February 1991, the emplacement of radioactive waste was stopped temporarily due to the safety and licensing reasons. In January 1994, the emplacement was resumed. Until September 1998, another 22,320 m^3 of solid waste in 200-, 280-, 400-, and 570-l-drums and in concrete containers as well as 394 pieces of spent sealed radiation sources were disposed of. This waste came from the whole Federal Republic of Germany. Altogether, a total activity of 3.8·1014 Bq was emplaced between 1971 and 1998.

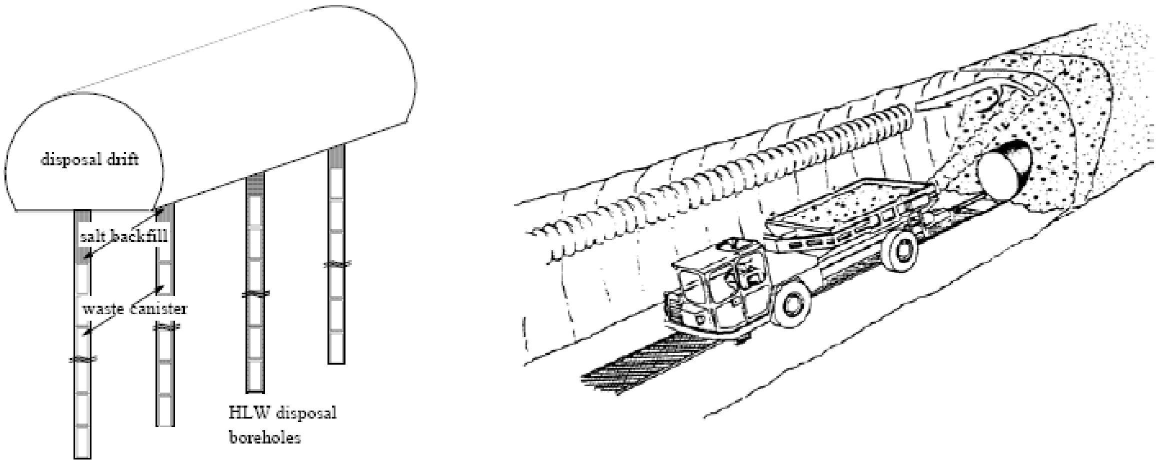
In 1997, this application was changed into the licensing for the closure of the repository. Since that time, on appropriate work has been performed aiming at the proof of the long-term safety of the repository. A concept has been elaborated comprising the almost complete backfilling of the mine workings with salt concrete and the installation of technical barriers (Brennecke et al., 2004). For immediate stabilization of the Central Part of the Bartensleben mine, where the highest degree of excavation is reached, initial backfilling of a selected number of mine workings with salt concrete has been started in 2003.

Disposal Concepts for High-Level Waste

In Germany, two types of heat generating HLW have to be disposed of in an underground repository, namely: (a) steel canisters containing vitrified fission products remaining from the spent fuel reprocessing and (b) Pollux steel casks containing non-reprocessed spent fuel assemblies.

Several disposal concepts for HLW have been developed in Germany for a geological repository in salt formations as a combination of technical alternatives and waste type volumes:

- Borehole emplacement of vitrified HLW (Fig. 4a),
- Drift emplacement of spent fuel in Pollux casks (Fig. 4b),
- Combined drift and borehole emplacement of both waste types.



a) Borehole disposal of HLW canisters *b) Drift disposal of Pollux casks (source DBE)*
Fig. 4. HLW disposal in salt formations.

These concepts have been analysed by different research teams and the results were reported in SAM (1989).

The most promising concept appeared to be a combined drift and borehole emplacement of both HLWcanisters and Pollux casks.

The borehole emplacement concept provides for the disposal of steel canisters containing vitrified HLW in about 300- to 600-m-deep and 0.6-m-wide boreholes. The boreholes will be drilled down from a disposal level at a depth of some 880 m below the ground. About 200 canisters will be disposed in one borehole. In order to stabilize the canister stack and to confine the weight load to permitted limits, the annulus between the canisters and the borehole wall is to be backfilled with crushed salt. This will prevent the destruction of the canisters in the lower part of the borehole. The canisters will be completely encapsulated by the creeping salt. At the top of the borehole, a seal consisting of crushed salt will be placed.

In the drift emplacement concept for the direct disposal of spent fuel, large self-shielding Pollux casks will be disposed of in drifts about 200 m long, 4.5 m wide, and 3.5 m high. The remaining voids will be backfilled with crushed salt. By the creeping of the surrounding rock, this material will be compacted slowly but steadily. In a sound rock mass, this process leads to a complete confinement of the waste in the repository.

First experiments on the disposal of HLW at Asse aimed at the determination of thermal and thermo-mechanical properties of the Staßfurt Halite Series Na^2 rather than on the development of special disposal concepts. The Na^{2-} formation, considered suitable for the waste disposal, is located in the centre of the Asse anticline similarly to the situation in most salt domes in the northern Germany (Fig. 1).

In a later stage from 1980 onwards, a conduction of full-scale experiments simulating specific disposal concepts was started.

Borehole disposal

In 1982, plans were taken up for conducting an in situ-test in regard of the development and testing of safe methods for the final disposal of HLW in boreholes in deep geological salt formations (Rothfuchs, 1987). Thirty highly radioactive canisters containing vitrified amounts of the radionuclides Cs-137 and Sr-90 in quantities sufficient to cover the bandwidths of heat generation and gamma radiation of real HLW were planned to be emplaced in six boreholes at the 800-m-level in the mine. A duration of testing of approximately five years was envisaged. The project was named the HAW-project and the international partners in this project, co-sponsored by the national governments and the European Commission (EC), were the French Agence nationale pour la gestion des déchets radioactifs (ANDRA), the Energie Onderzoek Centrum of the Netherlands (ECN) and the Spanish Empresa Nacional de Residuos Radiactivos, S. A. (ENRESA).

Besides the investigation of the response of the host rock to the thermal load of HLW and the effects of gammaradiation in the natural rock salt, the development of a transport and handling system for HLW-canisters was a major objective of the project. The system developed for the test at the Asse mine is illustrated in Fig. 5.

Because of licensing uncertainties, the project was prematurely terminated by the end of 1992 and the radioactive canisters were never emplaced in the Asse mine. Successful cold trainings of the emplacement procedure and shielding tests with Co-60 sources, however, were performed and the system was finally approved in May 1991 by the responsible mining authority. A detailed information on the documentation and appraisal of the system is provided in Müller et al. (1995).

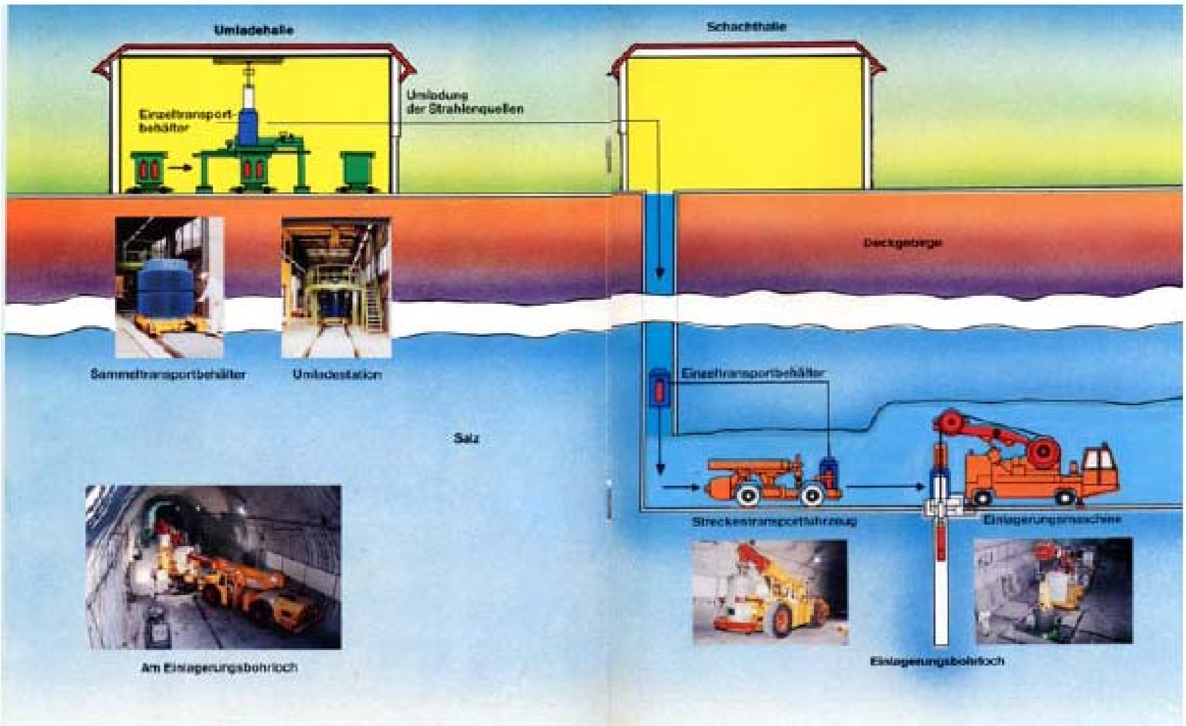


Fig. 5. Transport and handling system for HLW canisters developed and tested at the Asse mine.

Drift disposal

The Thermal Simulation of Drift Emplacement (TSDE) experiment represents the most important in-situ experiment in Germany on the direct disposal of spent fuel in a salt repository. The direct disposal of Spent Fuel became the first option after the revision of the Atomic Act in the early nineties of the last century.

The test, which belongs to a series of demonstration tests dealing with the transport and emplacement technology as well as safety aspects for the direct disposal of spent fuel, was performed in the Asse mine between September 1990 and February 1999 (Droste et al., 2001). Main objectives of the experiment were to investigate the interaction between the heat generating waste canisters, rock mass, and the crushed salt backfill under the repository relevant in-situ conditions and to validate the theoretical models used to predict the compaction and permeability of crushed salt. In addition to the mechanical parameters, the gas development in the pore space of the backfill was monitored and analyzed. In order to study the corrosion behaviour of potential cask materials, 280 material samples were placed on a heater cask at temperatures between 170 °C and 200 °C and in the backfill at temperatures of about 100 °C.

The test field was designed to simulate reference repository conditions for the direct disposal of spent fuel. A general view of the entire test field is given in Figure 6. Two parallel test drifts were excavated on the 800-mlevel.

The drifts were 70 m long, 3.5 m high, and 4.5 m wide and separated by a 10 m wide pillar. In each drift, three electrically heated casks were deposited. In addition to the two test drifts, the test field included several observation and access drifts on the 800 m level and on the 750 m level.

Heating was started in September 1990. After five months, the maximum temperature of 210 °C was reached. In the following, the temperature decreased to 170 °C at the end of the heating period which was more than eight years long. This decrease in temperature was caused by an increase in the thermal conductivity of the crushed salt backfill in consequence of the material compaction induced by a drift convergence. Until the end of the heating period, the drift closure led to a reduction of backfill porosity from initially 35 % to 20 % at a maximum in different parts of the test drifts.

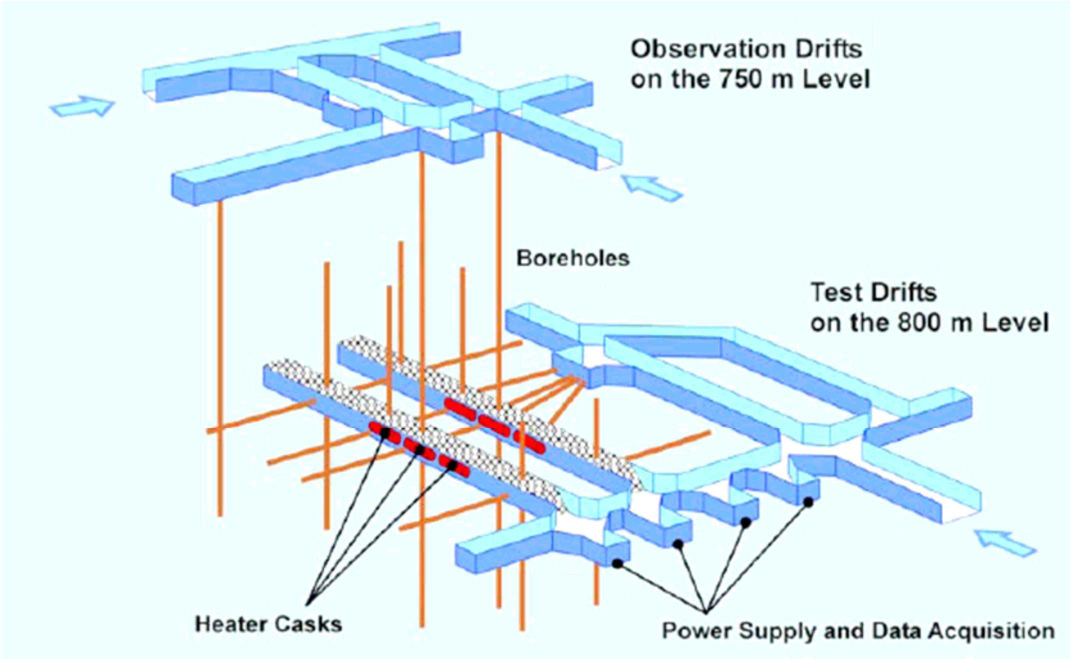


Fig. 6. General view of the TSDE test field..

In the TSDE experiment, the agreement between numerical simulations and measured data was fairly good so that the models used can be considered as adequately verified. It was extremely useful that special measures had been foreseen from the very beginning of the experiments to enable a later uncovering of the test rooms for posttest analyses of the compacted backfill material and of the installed measuring instruments. Since significant deviations between predicted and measured data were observed during the operational period, this issue was of a special importance. Most questions which had been arisen during the test conduction could be answered at the end of the project due to the results from the post-test investigations. A summarising report was published at the end of the project (Bechthold et al., 2004).

Concept Improvements

Despite of favourable parameters of the rock salt as a host rock formation and the fact that the disposal techniques were successfully demonstrated at the Asse mine, general discussions on retrievability and reversibility are still going on. Quite recently, the expert group AkEnd of the Federal Minister for Environment, Nature Conservation and Reactor Safety (BMU) proposed a new site selection procedure based on scientific and socioeconomic criteria.

At a disposal site carefully selected for its long term safety, which provides an isolation of the radioactive waste up to 1 million years, a retrievability is not an issue. Any disposal concept based also on the retrievability should not degrade the overall favourable conditions made up by the geological formations. However, the design and improvement of the technical systems and the concept itself should a enable long-term monitoring and/or adjustments of the concept at a later stage of the repository operation. As shown in an engineering study (Engelmann et al., 1995), the retrievability is basically feasible in the rock salt, if needed.

Additional technical features can make such an exercise more efficient and cost effective. From this point of view, the above alternatives could be adapted to some extent. One possibility is for example to change from heavy weight Pollux casks to smaller casks for individual single spent fuel bundles only. Such long "borehole cans" could be emplaced into medium-length boreholes (approx. 50 m) which are fitted with long lasting liners.

Such liners can provide not only a mechanical stability but also a reduced irradiation of the adjacent rock salt if coated with the respective material such as Polysiloxane Si(OR)4. This system could be adapted to vitrified HLW in steel cans. It should have no negative effects on the long-term isolation of the waste. Borehole seals similar to those developed can be used in order to provide the necessary safety in both the operational and postoperational phases.

Conclusions

In Germany, disposal concepts and techniques for the final disposal of LLW and ILW have been successfully developed during a more than 10 years testing period from 1967 until 1978 at the Asse salt mine and during the emplacement of LLW and ILW in the Morsleben repository between 1971 and 1998. Although being developed more than 30 years ago, these techniques (with minor modifications) are still a part of the national concept for a repository in salt formations in Germany.

Concepts and techniques for the HLW disposal in salt formation are very well advanced as well. Borehole and drift disposal concepts for HLW disposal in salt formations have been confirmed by about 30 years of testing in the Asse mine. Most tests, however, have been performed without a radioactive material and testing of adequate transport and emplacement systems. Thus, full-scale pilot experiments including the development and testing of respective systems under representative conditions are still pending.

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