THE BAMBUS PROJECT IN THE ASSE MINE (GERMANY) FULL SCALE TESTING OF THE DIRECT DISPOSAL OF SPENT FUEL ELEMENTS IN SALT FORMATIONS

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ABSTRACT

In Germany a reference concept for the disposal of spent nuclear fuel elements in deep geological salt formations was developed. The concept considers the emplacement in self shielding POLLUX-disposal casks in parallel underground drifts. These disposal drifts are backfilled with crushed salt remaining from the excavation of underground disposal rooms to stabilize the underground repository and to seal the waste from the biosphere.

In the nine years TSDE (Thermal Simulation of Drift Emplacement) in-situ experiment simulating the direct disposal of spent fuel in self-shielding POLLUX-disposal casks the thermo-mechanical behavior of rock salt and crushed salt backfill was investigated. From 1990 to 1999, the TSDE test had been conducted 800 meters below ground in the Asse research salt mine to simulate the expected conditions of a nuclear waste repository. Six 65-tonnes containers had been placed in two parallel drifts and electrically heated to reproduce the heat generation of spent fuel. The temperature on the container surface was between 170 and 200°C. Thermal and mechanical effects on backfill and rock salt were monitored by an extensive set of measuring sensors. In order to verify the predictive capabilities needed for long-term safety analyses, the in-situ measurement results were compared with model predictions based on preceding laboratory investigations.

For the confirmation of the measuring results one of the backfilled drifts was uncovered after termination of heating to enable determination of the remaining porosity and permeability of the backfill material. The analysis of removed backfill material confirmed the measured reduction of porosity and consequently an increase of the isolation capability. It was found that 2D-modelling was adequate only to simulate the backfill compaction around the central heater where plane symmetry prevailed. By the application of complex 3D-models the whole test under consideration of end effects could be analyzed.

Post-test analyses of the retrieved measuring instruments and corrosion specimen were performed and provided extremely useful results for the improvement of measuring techniques and container materials in future repositories. Post-test investigations included investigation of the excavation disturbed zone (EDZ) in the rock mass around the test drifts as well. Post test-analyses and modeling work were combined in the BAMBUS project (Backfill and Material Behavior of Underground Salt Repositories) which was sponsored by national organizations and the Commission of the European Communities (CEC).

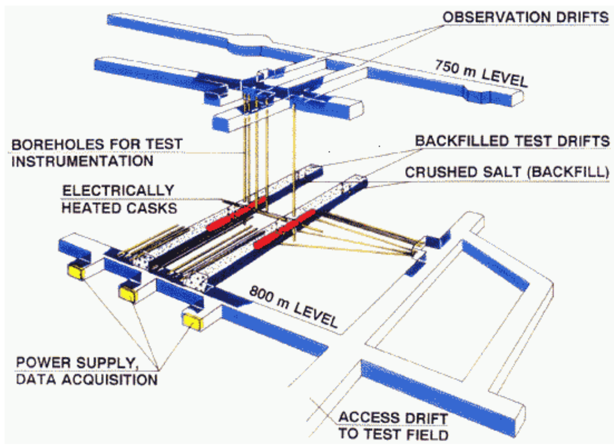
INTRODUCTION

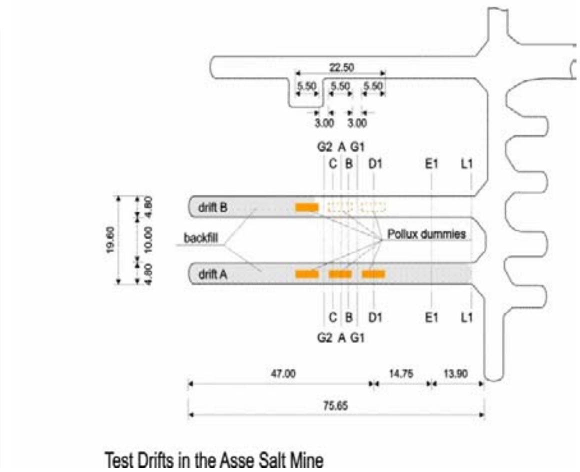
According to the German reference concept for the direct disposal, light water reactor (LWR) spent-fuel elements encapsulated in self-shielding POLLUX-casks will be disposed of in underground drifts in a salt repository. To stabilize the underground repository, to seal the waste from the biosphere, and to limit the temperature increase in the repository (by improved dissipation of the decay heat of the waste) the disposal drifts are backfilled with crushed salt remaining from the excavation of underground disposal rooms. As a consequence of the creep behavior of the rock salt under the combined effects of stress and heat, the crushed salt backfill is compacted and the initially high material porosity (approx. 35%) decreases with time to very low values thereby improving the backfill sealing capability. Thus, modeling of the sealing behavior of the compacting crushed salt is a very important task of safety analyses. The credibility of the used model significantly increases if the results of which are in reasonable agreement with actual measuring results from full-scale field experiments performed under representative conditions.

The "Thermal Simulation of Drift Emplacement (TSDE)" experiment in the Asse mine in Germany lasting for almost nine years is such an outstanding example for a representative underground experiment. Within the BAMBUS project [1], which was funded by national institutions of Germany, France, Spain , the Netherlands and the Commission of the European Communities (CEC), the temperature and stress dependent compaction behavior of crushed salt backfill was studied by improved numerical modeling and post-test analyses of the TSDE backfill. The data obtained from such studies are needed to extend the basis for optimizing the repository design and construction. To achieve these objectives, the work program consisted of in situ investigations in the Asse research mine, laboratory studies on retrieved material samples (backfill, instruments and corrosion specimen), modeling and desk studies. Post-test investigations included EDZ investigation in the rock mass around the test drifts as well. In addition, the long-term behavior of the EDZ was investigated at two other locations in the Asse mine.

TSDE-TEST FIELD IN THE ASSE MINE

The TSDE-test field was located in the anticlinal core of the Asse salt dome inside the Stassfurt Halite of the Zechstein Series. The test field comprised two parallel test drifts on the 800-m level and several observation and access drifts on the 800m and 750m -levels (Fig. 1a).





a) Test field overview **b) Ground plan (one drift dismantled)**

Fig. 1 TSDE-test field in the Asse mine at the 800m-level

The geometrical dimensions of the test drifts as well as the heater power were selected in order to generate representative repository conditions. In each test drift which was 3.5-m-high, 4.5-m-wide and 70-m-long, three simulated and electrically heated waste casks (type POLLUX) of 1.5 m diameter, 5.5 m length, and a mass of 65 Mg were deposited. The nominal heater power of each cask was 6.4 kW.

For monitoring purpose about twenty cross sections in the TSDE experiment were equipped with appropriate measuring instruments to monitor the rock salt and backfill material behavior over time. Instrument fabrication and in-situ installation had to take into account the harsh environment in the repository (backfill emplacement procedure by slinger technology and high temperatures). The instruments were installed either via boreholes in the rock or around and between the heated casks in the backfill material. The installation of the instruments and the electrically heated casks (Fig.2.) was done in a stepwise approach according to a precisely defined time schedule. The remaining space between the casks and between casks and the drift walls was backfilled with crushed salt once a cask has been completely installed.

In September 1990, the test field installation was accomplished and the heaters were switched on. In January 1999, after almost 8 and a half year of operation, heating was terminated and preparation work for the evaluation phase began. Before dismantling and removal of instrumentation and heaters could start, an additional year was spent for cooling down the rock and air temperature in the test drift environment to an acceptable temperature level for mining activities. Thus, backfill excavation and dismantling of heaters and instrumentation began in August 2000 and lasted until May 2001.

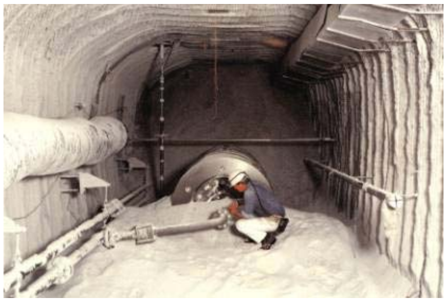


Fig. 2 Installation of casks and instrumentation 1990 (left) and dismantling of a cask (right) 10 years later

The scientific investigation program performed during the test operation included geotechnical (temperature, deformation, and stress) measurements in the backfill and the surrounding rock salt. Post-test dismantling of the TSDE experiment made it possible to study the achieved compaction of the backfill and the EDZ in the surrounding rock. Studies were done both in situ in the dismantled drift and in the laboratory on samples, corrosion specimens, and instruments that had been retrieved from the opened drift. These studies helped to substantially improve the understanding of processes related to backfill and host rock behavior in a repository in rock salt and to extend the basis for optimizing the repository design and construction and for predicting the long-term performance of the most important barriers in the repository.

RESULTS OF BACKFILL INVESTIGATIONS

One of the main objectives included further clarification of backfill properties. Re-entry into the test drift provided the opportunity to obtain samples that were exposed to simulated repository conditions over nearly one decade. Samples of the compacted backfill material were taken at several cross sections and analyzed in the laboratory. Of special interest was the situation in the central part of the test field at cross section B (Fig. 1b) where from the viewpoint of 2D-modelling adequate plane symmetry prevails. Here, complete vertical and horizontal profiles were analyzed for their remaining porosity. Though significant variations were detected along the profiles, the porosity decreases slightly towards the roof in case of the vertical profile and from the pillar towards the drift wall in case of the horizontal profile.

Generally, the porosity in the centre of the test field was found lowest with average porosities of about 0.2, which corresponds to a drift closure of about 0.37 m. This agrees fairly well with the results of improved 3D-models. Further examination of these samples illustrated the mechanisms of compaction at higher temperatures. It could be shown that the models applied for mechanical compaction behavior of crushed salt were reasonable, within the range of application.

The thermo-mechanical behavior of the host rock itself was of interest as well. The mechanisms of deformation and the constitutive models applied have been well established for rock salt, in general. Elevated temperatures expected in repositories for high-level radioactive wastes will give rise to accelerated creep processes. In BAMBUS measurements between the TSDE test field and the surrounding rock salt quantified these phenomena at a repository scale. At the beginning of the project, it was postulated that the long-term heating cycle may influence strength-deformation response of the rock salt. Suitable samples were obtained and tested at room temperature and at 70°C. The strength investigations showed similar results as obtained from formerly tested rock salt specimens which had not experienced a heating period.

RELIABILITY OF INSTRUMENTATION AND MEASURED DATA

Originally, the instruments had been designed for a 5 years lifetime (3 years experiment duration plus an optional extension of 2 years). However, most instruments provided data during the almost ten years of realized experiment duration. Some of them failed and were replaced by new ones; other had to be left after failure and were subject to a post-test analysis. The opportunity to retrieve instruments from an in-situ experiment is rare in geomechanics and allowed a credible assessment to be made of the instrumentation array. First, these activities provided an assessment of the accuracy and reliability of measurements recorded during the TSDE experiment and second, these post mortem examinations provide a firm basis for recommendations of monitoring instruments for future deployment. Fig.1.b shows a ground plan of the TSDE test field with indicated measuring cross-sections at the end of the excavation phase. When the program for the TSDE evaluation phase was set up, two main reasons were found for the decision to retrieve instruments and to conduct post-test examinations.

- Instrument accuracy and reliability are significant features in repository design and construction. As far as similar instruments will be used in the TSDE experiment and in a later repository the failure analysis will help to derive recommendations for improved measurement methods and instruments quality.

- The comparison of experimental results and numerical predictions strongly depends on the accuracy of the measured data. Even though symmetry, redundancy and diversity were applied in the instrumentation design, instrument drift over time and systematic errors may occur. That is why the actual boundary conditions of the instruments in and around the drifts should be investigated. A comparison of these findings with the recorded data during the experiment can be used to determine parameter values for backfill and rock salt.

During the excavation phase from August 2000 to May 2001 a representative number of temperature sensors, convergence sensors, displacement transducers, backfill pressure cells, one stress monitoring station and gas filters were retrieved from the compacted backfill. Table 1 shows the amount and type of recovered instruments which have been forwarded to post test analysis and recalibration tests.

Table I List of recovered measuring instruments

Organisation	Number	Type of instruments
BGR	1	Stress monitor station
DBE	6	Convergence measuring device
	12	Temperature gauges
GRS	4	Convergence measuring device
	3	Backfill settling devices
	70	Temperature gauges
	15	Backfill pressure gauges
	43	Displacement transducers
	12	Gas filters (gas sampling)
	3	AWID gauges

During the removal activities, first a visual inspection of cable and instrument damage was done. Some visible mechanical damages were caused by creep deformation in the rock and the backfill. Only a very limited number of instruments showed corrosion. Within the existing measuring time of approximately 10 years, the determined corrosion did not impair the functioning of the construction units. The investigation results showed the suitability of the applied materials as well as the applied measures for sensor protection under the harsh in situ conditions (plastic host rock material, corrosive atmosphere, temperature, measuring time). The bending of some convergence measuring rods caused by floor uplift was assessed to yield measuring errors below 1%. In order to exclude that malfunctioning of the measuring instrumentation during the testing period affected the measurements, post-test investigation and re-calibration of measurement devices were also performed.

The in-situ test and the post-test investigations revealed that the robust gauge design and the used sensors were very successful despite of their harsh environment application. The re-calibration results revealed a high reliability of the applied sensors and a low sensor drift. After up to 12 years of operation, the linearity of most gauges was still within the manufacturer's respective limit of tolerance. Especially, the linearity of the extensometer sensors hardly changed during operation proving that the reverse extensometer design with the displacement transducers inside a tight instrument head in the deepest part of the borehole can be recommended for further application in heated areas. But even at high temperature of up to 90°C, the sensor drift was largely within the limit of tolerance. Significant deviations were only observed for the drift convergence devices which had been installed directly above the heater casks. For backfill pressure measurements, the robust Glötzl hydraulic pressure cells proved to be very reliable in the prevailing pressure range. The used intricate AWID measuring equipment (Kessels, 1984), however, is only reasonable for special applications.

For future long-term in-situ measurements of stresses and stress changes, it is recommended to use installation boreholes which allow a safe and protected leading of all measuring lines to the central data acquisition systems. To this aim, installation boreholes should be drilled from access and observation drifts around the test drifts to avoid exposition of measuring lines to high temperatures, stresses, and deformation. To avoid or to reduce long-term effects of corrosion of pressure cells, measuring valves, and measuring lines, it is recommended to use common stainless steel or special materials, e.g. Hastelloy, for all components of the stress monitoring system.

On basis of the results obtained during the post test analysis and the experiences gained during the in situ experiment the following additional recommendations can be summarized:

- The possibility to apply wireless data transmission systems should be studied and tested
- The application of temperature resistant cables with an outer steel liner or the complete laying of cables into protective tubes up to protected rock areas is strongly recommended

Generally, dismantling of the test field and retrieving of the measuring equipment is recommended for any in-situ experiment with no maintenance possibilities. For quality assurance, sensor calibration before and after an in-situ test is indispensable. Basing on the post-test analyses, the in-situ measurements of the TSDE test could be assessed as very confidential. Most of the applied measuring systems proved to be suitable for the long-term monitoring of a final repository.

INVESTIGATIONS ON THE EXCAVATION DISTURBED ZONE (EDZ)

Deviatoric stress situations around underground disposal rooms in rock salt may lead to the development of excavation disturbed zones (EDZ), the permeability of which being significantly higher than that of the undisturbed rock. These zones represent potential pathways for liquids and consequently radionuclides released from waste canisters may be transported along this pathway. Hence, healing of these zones after the installation of geotechnical barriers or the emplacement of backfill material would be advantageous. Therefore, the permeability in the rock salt around the TSDE-test drifts was investigated by GRS before heater shut down. Two boreholes with a diameter of 86 mm were drilled parallel to the walls of the northern and the southern TSDE test drifts, at distances of 1.5 m and 0.5 m, respectively. Measurements were carried out both in the non-heated area and the heated area beside the test drifts.

For the permeability measurements, a four-packer probe was used with a 0.8-m-long central test interval and two control intervals of 0.3 m length each at both sides of the test interval. The packers had a length of 0.4 m and were pressurized individually with hydraulic oil up to about 8 MPa. Test fluid was nitrogen. Low permeability values were expected. Thus pulse injection tests were performed in all cases.

During the injection phase, a constant nitrogen gas flow of 500 to 550 ml/min was applied. During the injection phases, no measurable gas flow into the surrounding rock was detected. The following shut-in phases lasted up to fourteen days. By the application of an industrial calculation tool from the oil industry the measured data were transferred into permeability values. All permeability values determined from the four measurements in the EDZ were in the order of 10-22 m^2. Permeability values in this range correspond to non-disturbed rock salt, thus indicating that if an excavation disturbed zone had existed after drift excavation, it was healed during heating. Healing is also indicated by re-crystallization of the rock salt in the heated area resulting in very large salt crystals which were observed in the cores from both boreholes. However, the zone very close to the drift walls could not be examined in these tests. But at the end of the dismantling phase, approx. 2 years after heater shut down, respective tests were performed by the École Polytechnique–G.3S. with a new designed equipment. Measurements were performed both in the middle of the heated zone and in the area not influenced by the thermal load at the entrance of the test drift. The results showed a significant increase of the permeability (k = 2 · 10-15 m^2) compared to the above given value for undisturbed salt rock mass. These results might lead to the conclusion that the EDZ is amplified due to the thermal loading. However, it is very likely that a significant part of the additional disturbance comes from the rapid cooling phase due to heater shut off. Indeed, the sudden interruption of the heating in the TSDE experiment may have induced tensile stresses leading to fracturing and growth of the initial EDZ around the drift. Since the decrease of the temperature would be much slower in a real repository, such stresses should not occur in reality.

In two additional locations in the ASSE mine permeability measurements were performed as well. Around the lined part of a drift where a cast steel bulkhead had been emplaced and backfilled with concrete in 1914, permeability of the EDZ reduced to about 10-20 m^2 to 10-18 m^2. This reduction can be regarded as a result of an induced stress state of high, normal or mean stress and negligible deviatoric stress. In a 40 year old pillar between two large chambers measurements showed a larger zone of increased permeability.

CORROSION INVESTIGATIONS

To identify corrosion resistant materials for long-lived containers, shielding containers and canisters, 280 material specimens were exposed to repository conditions in the TSDE test drift over about 10 years. 140 of them were placed in the backfill close to the first heater cask at temperatures of 90 °C. The other 140 specimens had been installed on the top of the central heater in the northern drift. Here, a maximum temperature of 210 °C which until the end of the experiment decreased to 170 °C was measured. In the course of the backfill removal activities, all specimens were retrieved and shipped to FZK/INE laboratories for further examination. The post-test analysis showed that the average corrosion rate of all materials was negligibly low. Some pitting corrosion was detected for unalloyed and low-alloyed steels, but the maximum pit depths after 10 years was less than 100 µm (Table 2.). In general, the observed corrosion rates in the in-situ experiment were significant lower than the values detected in previous laboratory immersion experiments. This is due to the negligible amount of water/brine in the backfilled test drift.

Table II Corrosion results after almost 9 years at in-situ testing at 180°C (source: FZK-INE)

Material	**Average corrosion rate (µm/a)**	**Pitting corrossion (µm)**
Ti99.8-Pd	0.02 ± 0.002	-
Hastelloy C4	0.04 ± 0.001	-
Hastelloy C22	0.05 ± 0.002	-
TStE355 carbon steel	0.07 ± 0.03	-
15MnNi6.3 low alloyed steel	0.05 ± 0.03	-
TStE460 low alloyed steel	0.04 ± 0.01	60
Castiron	0.08 ± 0.06	-
Stainless steel 1.4306	0.03 ± 0.001	-
Stainless steel 1.4833	0.02 ± 0.001	20

COMPARISON OF PREDICTED AND MEASURED TEMPERATURES AND POROSITIES

The main objective of the modeling exercises within the BAMBUS project was to develop material models adequately describing the thermo-mechanical behavior of rock salt and backfill to allow reliable long-term assessment of repository performance. Very detailed models of the TSDE in situ test were developed within the BAMBUS project. Comparisons of measuring and calculation data included evaluation of temperature, deformation and stress fields in the backfill and the host rock. Several varied modeling techniques implemented by the different modeling teams exemplify a breadth of tools available to address complicated time-dependent thermo-mechanical salt repository analyses. Several models have been validated against the measurements from the TSDE test. Once the three-dimensional geometry was incorporated, the models provided results which compare favorably with measurements.

The history of the TSDE experiment was to be taken into account for a precise description of the test boundary conditions. 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 termination of the more than eight and a half year long heating period. This was due to the increase of thermal conductivity of the crushed salt backfill in consequence of the material compaction induced by drift convergence. Until the end of the heating period, drift closure led to a reduction of backfill porosity from initially 35 % to 20 % in the heated area and down to 31 % in the non heated area.

The compacted backfill was uncovered after termination of the heating phase in order to enable post-test investigation of the achieved degree of backfill compaction in comparison to the results of model predictions. Model analyses were done with regard to the temperature distribution and the rock mechanical interaction of the backfill in the drifts and the surrounding rock. For the temperature calculation, a 3D-model was used which led to an acceptable agreement of measurement and modeling results (Fig. 3).

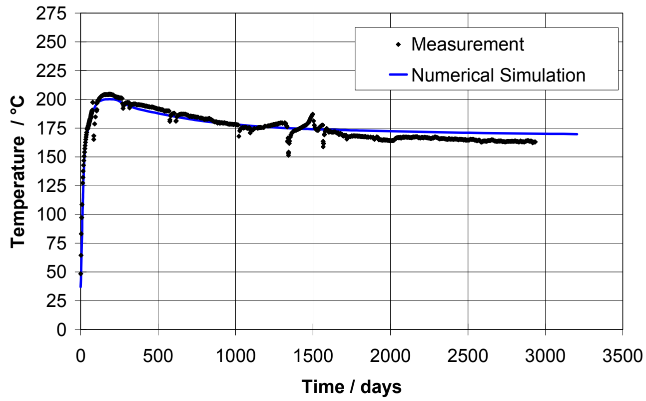


Fig. 3 Measured and predicted temperature evolution at cask surface in the TSDE experiment

Because of limitations in computation time needed, in some of the model teams the calculation of drift closure and backfill compaction was performed as a 2D-calculation. A plane-strain model for the central cross section of the test set-up was used. Figure 4 shows reasonable agreement between measured and predicted backfill compaction. However, some deviations were obvious and it was thus decided to uncover the test field after termination of the experiment in order to enable post-test investigation of true backfill compaction. It was found that the post-test data determined in the laboratory agree very well with the porosities determined during the in-situ measurements.

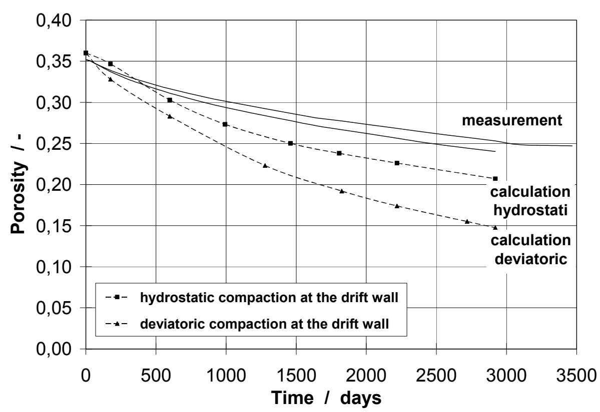


Fig. 4 Decrease of porosity in the heated backfill in the TSDE experiment

Generally, it can be stated that the model approaches produced results that compared favorably with the TSDE in-situ measurements. In particular, the incorporation of three-dimensional geometry provided a remarkable improvement relative to the previous results in the BAMBUS project.

RETRIEVABILITY DESK STUDY

The mechanical and thermal boundary conditions have been addressed for the reference drift disposal concept for spent fuel and a borehole concept for vitrified waste. The main conclusions with respect to the drift disposal concept is that the temperature of the host rock in the surroundings of the disposed containers is the main constraint for retrievability. For the (deep) borehole concept, it will be very difficult or almost impossible to retrieve the containers with vitrified waste if the convergence of the borehole is not counteracted by a liner and if no measures are applied to avoid container damage by the weight of the pile of containers on top of them.

For the drift emplacement concept a number of measures that limit the temperature increase in the disposal fields have been considered. Most feasible measures are the extension of the interim storage period (to approx. 80 years), and the reduction of the number of spent fuel elements per disposed container. The technical equipment to retrieve emplaced and backfilled containers can be developed by modifications on existing devices. Given that modifications the time window for retrieval operations is merely determined by conventional mining issues. Experiences show that mines in rock salt can be in operation for a century.

For the borehole emplacement concept, a desktop design has been performed that adds to existing designs a steel casing, that counteracts the convergence of the borehole, and an overpack that can carry the weight of the stack of (overpacked) containers in the borehole. A thermo-mechanical calculation has been performed to show that the steel casing can resist the thermal induced stresses that will occur after emplacement of the heat producing vitrified waste. The results of an illustrative performance assessment addressing the potential radiological consequences of the accessibility to the waste showed that the dose limits recommended in ICRP 60 were met.

CONCLUSION AND OUTLOOK

The thermo-mechanical behavior of crushed salt backfill was investigated in an almost nine years in-situ experiment simulating the direct disposal of spent fuel in self-shielding disposal POLLUX casks in disposal drifts. In order to verify the predictive capabilities needed for long-term safety analyses, the in-situ measurement results were compared with model predictions based on preceding laboratory investigations. To confirm measuring and modeling results one of the two backfilled drifts was uncovered after termination of the experiment. The analysis of uncovered backfill material confirmed the reduction of porosity and consequently an increase of the isolation capability with time. It was found that 2D-modelling was adequate only to simulate the backfill compaction around the central heater where plane symmetry prevailed. Modeling of the whole test under consideration of end effects was done as well, but required the application of complex 3D-models. Post-test analyses both of the compacted backfill material and the measuring instruments were extremely useful for the confirmation of the applied models and measuring techniques.

Originally, the electrically heated casks and the measuring equipment had been designed for a three to five years testing period, but were operated over almost ten years under final repository conditions. The heaters provided the requested thermal load up to the end of the experiment. As expected, an increasing number of instruments failed during the long testing period. Therefore, however, the layout of the measuring systems had been designed redundantly allowing for failures what is recommended for any monitoring. For quality assurance, sensor calibration before and after an in-situ test has been done. In-situ test and post-test investigations revealed that the robust gauge design and the used sensors were very successful despite of their harsh environment application. Most failures were caused by damaged measuring lines. The re-calibration results revealed a high reliability of the applied sensors and a low sensor drift. After up to 12 years of operation, the linearity of most gauges was still within the manufacturer's respective limit of tolerance. The applied measuring systems proved to be suitable for the long-term monitoring of a final repository.

The post-test analysis on retrieved corrosion specimens showed that the average corrosion rate of all materials was negligibly low. In general, the observed corrosion rates in the in-situ experiment were significant lower than the values detected in previous laboratory immersion experiments. This is due to the negligible amount of water/brine in the backfilled test drifts. There are several container materials available which could be recommended for the application as waste package material in a repository in rock salt.

In a desk study on retrievability the mechanical and thermal boundary conditions have been addressed for the reference drift disposal concept for spent fuel and a borehole concept for vitrified waste. The main conclusions are that retrievability is in principle feasible for the drift disposal concept. For the (deep) borehole concept, it will be very difficult or almost impossible to retrieve the containers if borehole convergence/closure is not avoided by a borehole liner.

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REFERENCES

1 BECHTHOLD, W. et al.:. Backfilling and sealing of underground repositories for radioactive waste in salt (BAMBUS Project). Nuclear Science and Technology, EUR 19124 EN. Luxembourg: European Commission, 1999

2 J. DROSTE & T. ROTHFUCHS: Long-term instrument performance – experience from a large scale test in rock salt. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Germany, 2003