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Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt, Phase II

(BAMBUS II)

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ABSTRACT

This report presents results of the BAMBUS II project (Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt), undertaken as a joint project by FZK (DE, co-ordinator), BGR (DE), DBE (DE), G.3S (FR), GRS (DE), IfG (DE), NRG (NL), UPC (ES), and US DOE/CBFO (USA) between August 2000 and April 2003. The project was funded by the European Commission and the national governments and authorities.

The principal scientific objective of the project was to extend the basis for optimising the repository design and construction and for predicting the long-term performance of the following barriers in a repository for radioactive waste in rock salt: (i) the host rock including the Excavation Disturbed Zone (EDZ) around emplacement rooms, (ii) the backfill (crushed salt), and (iii) the materials used for constructing durable waste containers. The work was divided into in situ studies, laboratory investigations, modelling studies, and desk studies.

In situ investigations were carried out in the Asse salt mine subsequent to completion of the large-scale TSDE (Thermal Simulation of Drift Emplacement) in which two simulated emplacement drifts had been electrically heated to between 170 and 200 °C by disposal cask mock-ups over more than eight years. In one drift, backfill, two heaters, and measuring instruments were recovered. Local conditions in backfill and surrounding rock were examined and samples of native salt and consolidated backfill were studied in laboratories. Instruments were retrieved for analysis of their performance during the experiment execution and for re-calibration. Extensive geophysical studies characterized the development of the EDZ around excavations.

Laboratory tests measured properties of specimens extracted from the backfill in the dismantled drift as well as cores from the surrounding rock. Physical, mechanical, and hydrological experiments quantified parameter values requisite for material models and described attributes of backfill and rock salt at advanced stages of compaction and deformation. An extensive array of 280 candidate container material samples was recovered and examined to evaluate their state of corrosion, which was minimal after more than ten years of exposure in the TSDE experiment.

A suite of modelling studies analysed the thermo-mechanical evolution of the TSDE and evaluated the predictive capabilities available to address complex modelling demands associated with long-term repository predictions. These computational studies helped to refine models and codes based on forensic investigations in the dismantled experimental drift and from laboratory tests. Advancements recognized in a breadth of applications improved comparisons between computational results and in situ experimental results from the TSDE. Post-test investigations served to reconcile lingering differences between experiments and calculations witnessed at the conclusion of the BAMBUS-I project. The primary results encompass comprehensive computational approaches that demonstrate successful prediction of temperature profiles, stress distributions, displacements, and the attendant properties of compacted backfill, intact rock salt and the EDZ.

In a desk study the boundary conditions for the retrievability of highly active waste and spent fuel were investigated. The consequences of the accessibility of the waste during the retrievability period were assessed. In addition, the technical and scientific results of the TSDE project (1985 to 2002) were reviewed and documented. For use in future repository design and construction, an easily accessible data acquisition system was developed.

EXECUTIVE SUMMARY

I Background and scope

The BAMBUS II project was an international research project addressing the behaviour of host rock and backfill in a geological repository for heat-generating radioactive waste in rock salt. The principal scientific objective of the project was to extend the basis for optimising repository design and construction and for predicting the long-term performance of the following barriers in a repository:

- the host rock including the Excavation Disturbed Zone (EDZ) around emplacement rooms,
- the backfill (crushed salt), and
- the materials used for constructing durable waste containers.

In the framework of the European Atomic Energy Community's R&T Specific Programme "Nuclear Fission Safety 1994-1998", the project BAMBUS I was carried out, in which full-scale in situ experiments addressing backfill and rock-salt behaviour were combined with laboratory tests and modelling studies. The studies completed in the BAMBUS I project demonstrated that the relevant physical processes are qualitatively well understood and the models describing these processes can be extrapolated over wide ranges. However, difficulties still remained in quantitatively predicting the rates of room closure and backfill consolidation. To resolve these issues the follow-up project BAMBUS II was undertaken.

Other objectives of the project included investigation into performance of monitoring instruments, an evaluation of corrosion specimens exposed to typical repository conditions for more than ten years, and an assessment of retrievability issues in the light of the findings from the TSDE experiment.

To achieve the objectives, the work carried out in BAMBUS II consisted of four major parts:

- in situ investigations,
- laboratory studies,
- modelling studies, and
- desk studies.

These activities were carried out as summarised below.

I.1 In situ studies in the Asse salt mine

In the TSDE experiment heating was initiated on 25 September 1990 and terminated 1 February 1999. The experiment had been designed in the late 1980s to support development of the so called drift emplacement concept. According to this concept, fuel assemblies would be containerized in self-shielded casks which would be placed horizontally on the repository floor in drifts about 3.5 m high and 4.5 m wide. The drifts would then be backfilled immediately with crushed salt. In the TSDE experiment measurements were monitored since 1990 in and around two simulated repository drifts, each containing three electrically heated mock-ups of the disposal casks. Weight, dimensions, and heat capacity of the containers as well as the drift dimensions matched the preliminary layout of the drift emplacement concept. Thus, the test field simulated a portion of a full-scale repository emplacement panel. During the project duration, temperatures, stresses, backfill density and permeability, rock deformation, and gas generation and transport were measured. The in situ measurement results were compared with calculation results of the computer codes and models developed and implemented by the modelling groups.

In the BAMBUS II project, one of the two TSDE experimental drifts was dismantled after the temperatures in the drift had decreased to a level acceptable for working in the drift. The backfill material was removed in the first half of the drift up to the third heater cask. Two heater casks were removed from the drift and instruments in the backfill and in the rock were recovered for further inspection and evaluation. During the excavation work examination was made at representative locations along the drift and samples were taken for further laboratory tests.

The aims were to

- study in detail how the drift closed by salt creep, how the EDZ developed, and how the backfill compacted during more than eight years of heating,
- compare the actual findings post mortem with measurements recorded during the conduct of the experiment,
- extract samples from the backfill and surrounding rock salt for further laboratory tests,
- study the performance of the instruments in the dismantled drift and retrieve instruments for further examination and re-calibration,
- retrieve 280 corrosion samples for laboratory investigation of the corrosion behaviour of selected container materials, which had experienced simulated repository conditions.

The results were used within the project to

- improve and verify the parameter values in material models for predicting long-term rock salt and backfill behaviour,
- verify and optimise the design of the instrumentation for in situ measurements and repository surveillance and quality assurance,

- provide an experimental basis for studies of the retrievability of heat generating waste from a salt repository.

The scope of work performed during TSDE dismantling included studies of the EDZ around the drift. In addition to the EDZ studies associated with the TSDE experiment, investigations into the long-term behaviour of the EDZ were conducted at two other locations: (1) in the pillar of a large mining room (volume about 86 000 m^3) which was excavated in the 1950s and (2) in a drift which was lined with a cast-iron structure in 1914.

The aims were to

- measure EDZ properties around a heated emplacement drift as well as long-term performance and healing processes in the EDZ around non-heated drifts and rooms to advance repository design and construction,

- develop and test procedures for measurements of EDZ parameters.

The results were used in the project to

- determine parameters for material models for calculating EDZ evolution,

- examine empirical relationships between rock stress and EDZ permeability,

- test and improve techniques to measure EDZ permeability and depth.

I.2 Laboratory tests

Whereas in situ tests were carried out to study the complex performance of backfill, rock salt, and EDZ, laboratory tests on samples from the dismantled test drift were used to measure specific properties, such as compaction behaviour, permeability, and thermal conductivity. In these tests material parameters were obtained under simulated in situ conditions and at compaction states approaching residual porosity. In the BAMBUS I project similar tests carried out in various laboratories yielded variable results. To investigate possible reasons for the differences, selected tests were conducted in a laboratory benchmark among participating laboratories utilizing prescribed and equal conditions.

To study the corrosion behaviour of potential disposal cask materials, in the TSDE experiment 280 material specimens were placed on one heater cask at temperatures between 170 °C and 200 °C and in a backfill region in which temperatures near 100 °C were predicted. After ten years exposure to simulated repository conditions, these specimens were retrieved and analysed using methods of gravimetry, surface profilometry, pitting measurements, scanning electron microscopy, and X-ray diffraction.

During the TSDE experiment, measurements were obtained remotely with no access for inspection or maintenance of the instruments. To study their performance, instruments located on the heater casks, in the backfill, and in the surrounding rock salt were retrieved and the recorded data from the TSDE heating phase were compared with the actual conditions in the drift to assess the validity of the data obtained during the experiment and to evaluate reasons for failures.

The aims of the laboratory studies were to

- determine mechanical, hydraulic, chemical, and thermal properties of backfill and rock salt at simulated in situ conditions and at conditions resulting from further compaction,
- compare in a benchmarking exercise the methods and instruments of the laboratories,
- evaluate the corrosion behaviour of five selected container materials,
- determine accuracy and reliability of the instruments installed in the TSDE drift.

The results were used to

- provide a firm basis for establishing parameter values in material models for rock salt and crushed salt,
- make available improved measuring techniques for laboratory tests, in situ investigations, and long-term repository surveillance and provide greater confidence in measurement results,
- select suitable disposal container materials and enhance the basis for predicting their long-term performance.

I.3 Modelling studies

Based on the findings of the investigations in the dismantled test drift, models and codes of backfill, rock salt, and EDZ were developed and improved. These process models were implemented by the modellers in a variety of computational approaches to provide tools for repository performance assessment. The computational work was facilitated by close collaboration with colleagues performing in situ studies and with laboratory personnel engaging the supporting experiments. Modelling progress was enhanced by the opportunity to compare results among the participating groups.

The aims were to

- verify, test, and advance models of the thermo-mechanical behaviour of backfill and rock salt,
- refine models for EDZ evolution,
- improve computer codes and reduce CPU time,
- improve models and codes by comparing results.

The outcome was

- models for repository performance assessments with a high predictive capability,
- improved tools for repository design calculations.

I.4 Desk studies

Based on the findings of the in situ investigations, a study was performed to address issues associated with retrieval of heat generating waste from a salt repository. In addition, the technical and scientific results of the TSDE project carried out from 1985 to 2002 were documented.

The aims were to

- assess the mechanical and thermal boundary conditions for retrieval of heat generating waste from emplacement boreholes and drifts,
- assess the safety and radiological consequences of the accessibility of the waste during the retrievability period,
- compile the results of the TSDE project obtained during the time period 1985 to 2002.

The outcome was

- the basis for planning retrieval of heat-generating waste from a repository in salt,
- the documentation of the scientific and technological results of the TSDE project.

II Project organisation

The BAMBUS II project started on 1 August 2000 and lasted 33 months, until 30 April 2003. It was jointly carried out by nine partners from five countries:

FZK	Germany (coordinator)
BGR	Germany
DBE	Germany
NRG	The Netherlands
GRS	Germany
G.3S	France
IfG	Germany
UPC	Spain
USDOE	USA

The contributions of the partners to the major project parts are presented in the table below:

Project part	**Contribution**
In situ investigations	BGR, DBE, G.3S, GRS, IfG
Laboratory investigations	BGR, FZK, G.3S, GRS, IfG, USDOE
THM modelling studies	BGR, DBE, FZK, G.3S, GRS, DBE, UPC, USDOE
Desk studies	DBE, NRG
Coordination	FZK

III Results

III.1 In situ studies in the Asse salt mine

The primary geotechnical questions posed for in situ studies included creep closure, EDZ development, and backfill compaction and characteristics. In the process of excavating the experimental field, samples of backfill and salt, including sections within the EDZ, were extracted for laboratory studies. In addition, hundreds of corrosion samples of selected container materials were recovered and their durability assessed by several laboratory techniques. A considerable number of gauges, instruments and cable lines were also recovered for recalibration and performance determination.

The rock stresses in situ were measured by pressure cells and by the hydraulic fracturing method. The stress history recorded by the pressure cells could be interpreted in terms of test activities, such as drift excavation, heating, cooling, and removal of the backfill. The measured stress paths corresponded to the results of model calculations and therefore add credence to the modelling applications. Hydraulic fracturing tests were performed in two horizontal injection boreholes in the heated and unheated areas. The results tracked the magnitude and orientation of the minimum principal stress as it changed with test conditions.

The field tests evaluating the EDZ comprised a significant contribution toward objectives of the BAMBUS II project. The EDZ was evaluated proximal to the heater test itself and at two other test sites, to measure permeability under various in situ stress conditions. The conduct of these tests advanced the practical application of experimental configurations for testing in the very-near field. Fracture patterns ascertained from TSDE cores compared favourably to similar measurements on WIPP salt, and illustrated the finite extent of the damaged zone.

Increased permeability was found up to a depth of 1.5 m below the floor and not more than 0.5 m into the walls. Permeability may rise to values of 10^{-16} to 10^{-15} m^2, in comparison to around 10^{-21} m^2 for undisturbed salt. The drift floor was highly disturbed in the formerly heated region, which was attributed to the cooling process. The experimental work near the rock surface included development and successful application of innovative techniques that allowed assessment of permeability in the extremely near field. These permeability measurements were supported and augmented by other tests in ambient portions of the mine at different depths. These data were used to assess a mathematical function relating permeability to stress as well as to evaluate new approaches to modelling the EDZ.

Healing of the EDZ is an important issue with respect to repository performance, for example, in the sealing strategy. In this work, the EDZ was measured behind a bulkhead constructed almost 100 years ago. Although healing was qualitatively shown from the permeability tests, the original permeability of undisturbed salt was not re-established.

III.2 Laboratory investigations

Laboratory investigations quantified mechanical, hydraulic, chemical, and thermal properties of backfill and rock salt after experiencing the thermo-mechanical environment of the TSDE. Specimens of both materials were characterized as well as tested further for stress-strain behaviour in the case of rock salt and for consolidation behaviour in the case of backfill. Several of these laboratory studies were benchmarking in nature, as comparisons from various test methods were made. Laboratory investigations also comprised a significant effort with respect to instrument re-assessment.

The function of crushed salt backfill proved fundamental to the analytical needs, and a considerable effort was expended toward advancing the state of knowledge. Characteristics of backfill salt were documented in detail by optical and electron microscopy. The physical mechanisms of compaction involved minor brittle processes and mechanical translation of grains, as contrasted with more highly effective compaction processes of pressure solution/reprecipitation or crystal plasticity. Laboratory testing produced satisfactory agreement between the compaction behaviour of loose backfill and that of drilled cores from the TSDE backfill salt. It was concluded that the heating cycle did not alter the crushed salt material in a discernable extent. In turn, mechanical compaction behaviour was modelled reasonably over the applicable range.

Re-entry into TSDE drift B provided the opportunity to obtain in situ backfill samples for laboratory tests and petrological examination. Oedometer tests demonstrated that the backfill resistance in situ was less than that experienced in laboratory compaction. Thus, backfill resistance under in situ conditions could be lower than that measured in the laboratory. Some issues remain concerning consolidation of dry salt, particularly at the higher densities. Some recommendations are also made to reduce scatter in the σ–ϕ diagram via triaxial testing, which could include deviatoric states of stress.

Elevated temperatures expected in repositories for high-level radioactive wastes will give rise to accelerated creep processes in rock salt. The creep process accounts for the considerable stress distribution experienced and was comprehensively monitored in the TSDE. Rock stresses were compared to periodic minimum stress measurements obtained using the hydraulic fracturing method as well as compared to the predictions of the thermo-mechanical model calculations.

Samples of the Staßfurt salt were obtained and tested in two series of strain-controlled strength tests performed at room temperature and at 70 °C to determine if the heating cycle had any perceptible influence on strength and deformability. Investigations on rock-salt specimens extracted from the pillar between the two heater drifts show similar results as formerly tested Staßfurt rock-salt specimens which had not experienced a heating period. Substructural features of the heated salt provide evidence of recovery. However, these microstructural changes are not significant enough to realize mechanical differences in the laboratory tests.

Strain rates employed in standard testing procedures are generally orders of magnitude higher than experienced in situ. Therefore, special relaxation tests were performed to extrapolate to in situ conditions. Strength dependence on deformation rate can also be measured in creep tests after reaching the stationary phase. Such tests were performed and the results compare favourably the reference BGRa creep law.

One of the critical components of the BAMBUS II strategy involved the forensic examination and recalibration of instruments. These investigations provided an assessment of the accuracy and reliability of measurements recorded during the TSDE experiment. Furthermore, the post mortem examinations provide a firm basis for recommendations of monitoring instruments for future deployment in a salt repository. General categories of instruments included pressure, temperature and displacement. A majority of stress monitoring gauges remained functional. However, the cable system was susceptible to damage. Recommendations are provided to improve cabling and the instrumentation system in general.

Performance of the displacement measuring devices can be categorized as good. The linearity of the extensometer sensors hardly changed during operation and remained reliable even after more than a decade of operation. Some of the deformation instruments exceeded their range, but appeared to produce good quality data up to the limit. Thereby, this work has provided solid recommendations regarding selection of deformation gauges for salt repository applications.

Temperature was monitored via a large and redundant array of gauges, such that failures were negligible. The majority of recalibrated temperature gauges exhibited acceptable accuracy, with a few noted exceptions. Temperature sensors in the heated area displayed corrosion damage, which did not impair the function of the sensors. The sensors in the non-heated area were not corroded.

The corrosion results obtained from the TSDE experiment are in agreement with the findings of previous investigations. Corrosion rates of the unalloyed/low-alloyed steels and cast iron determined in situ are negligibly low and significantly lower than the values observed in previous laboratory immersion experiments. The studies confirm that the alloy Ti99.8-Pd and the unalloyed/low-alloyed steels have a high resistance to general and pitting corrosion in salt environments, and therefore, they are very promising materials for the manufacture of long-lived containers for the disposal of HLW/spent fuel in rock salt.

III.3 Modelling studies

The essence of modelling studies was to assess the viability and capability to model the thermo-mechanical behaviour of backfill and rock salt in a long-term field experiment. Modellers were allowed to exercise their own computational platforms and to a great extent determine their own approaches to the system evaluation within certain prescribed boundary conditions and material properties. Thus, assessment could be made of the utilities, such as CPU time, in addition to the prediction of thermo-mechanical response.

Several different, but equally viable approaches including four 3-D thermo-mechanical models, two 3-D thermal 2-D mechanical models, one 2-D thermo-mechanical model were applied to the TSDE analysis. Modelling results were compared quantitatively against a set of benchmark TSDE measurements. The overall comparisons included temperature profiles, closure magnitudes, backfill pressure and porosity. These results are displayed in a consistent set of plots within the main text. The several and varied modelling techniques implemented by the collaborators exemplify a breadth of tools available to address complicated, time-dependent, thermo-mechanical salt-repository analyses.

The thermal response was generally reproduced, as might be expected. With only a few exceptions, relative errors between calculated and measured temperatures are within 10 %. This essentially means that thermal conductivity for both the rock salt and for crushed salt are well constrained. The greatest uncertainty continues to reside with thermal properties of the backfill, and temperature profiles exhibit strong dependence on the conductivity of crushed salt. The modellers developed a higher level empirical relationship for conductivity as a function of porosity, which fit the data more accurately and over a greater range.

Drift closure predications displayed the largest errors ranging from 10 to 90 %, and these calculations usually over-predicted the results from the field. Several possible explanations are put forward for the various results, although once again, the mechanical properties of the consolidating salt backfill comprise a vital element in these computations. Thus, it would appear that some additional consideration of backfill constitutive behaviour for dry consolidation might improve predictions.

The several modelling approaches produced results that compared favourably with TSDE measurements. Once the three-dimensional geometry was incorporated, the models demonstrated a marked improvement relative to the previous experience in BAMBUS I.

III.4 Desk studies

The results of the study relating to the issue of retrievability of heat generating waste show that in view of the mechanical and thermal boundary conditions, for the drift disposal concept temperature is the main constraint, whereas for the borehole disposal concept it is nearly impossible to retrieve the waste canisters if the borehole closure is not counteracted by a borehole liner. A desktop design was developed that adds to existing designs a steel liner and an overpack that can resist the thermally induced stresses. For drift emplacement, the most feasible measures that limit the temperature increase in the disposal field would be extension of the interim storage period or reduction of the number of spent fuel elements per container.

To assess the potential radiological consequences of the accessibility of the waste during the retrievability period, an illustrative performance assessment was performed. The results show that even if the repository is flooded before the access galleries and shafts have been backfilled and sealed, the estimated dose level in the biosphere is well below the dose limit for accepted practises recommended in ICRP-60.

Documentation was established of the scientific and technical results achieved in the TSDE project from 1985 to 2002. The intention was to develop a systematic approach for the compilation of documents which were produced during the entire project duration and to develop an easily accessible data acquisition system. The database is a basic literature- and documentation administration which comprises all reports, publications and documents of the TSDE experiment.

IV Conclusions and recommendations

The BAMBUS II project was a first-of-its-kind undertaking that disentombed a long-term thermo-mechanical test conducted to simulate the expected environments of a nuclear waste repository. Although experiments of equal complexity and duration have been completed within the salt sciences community, for example at the WIPP site, no previous experiment of this nature made use of the opportunity to perform a comprehensive forensic evaluation of the test results post facto. Much of the vital information was gained from studies of the backfill and instruments produced by dismantling the TSDE. In view of the advancement of scientific knowledge gained by the BAMBUS II research, a suitable first recommendation is that future field tests consider post-test evaluations as an integral part of the planning to the extent feasible.

It is recognized that most field tests do not lend themselves to such examination, however, in repository science applications the long-term monitoring needs are unique. Instrument robustness and dependability will be essential in the regulatory environment and for performance confirmation. This recommendation pertains to future experimental programmes, and the payoff will be realized when the first salt repository is operational. With appropriate planning, the geotechnical instrumentation associated with a repository can also provide important validation of conceptual models.

One of the key technical issues addressed in BAMBUS II concerned the constitutive behaviour of crushed salt backfill. In addition to stress-displacement models, important properties, such as permeability and thermal conductivity, are functions of the state of consolidation. To this end, the TSDE backfill was placed at an initial porosity of approximately 35 % and consolidated an additional 10 % or so. The most important conditions of crushed salt backfill occur when the porosity becomes very low and the bulk properties approach those of intact salt. Because the high-density properties are most relevant to performance assessment of nuclear waste repositories, it is recommended that future investigations focus a portion of the research on this domain.

Projects such as BAMBUS II require considerable investment of technical and monetary resources. These investments are essential not only to advance repository sciences, but to engage the technical community and thereby retain the acquired knowledge in a corporate memory. A consistent and continuous effort is essential for a viable future for repository sciences.

Finally it must be stated that the results obtained here are both general and specific. Each site will, of course, demand attention to the specific features pertaining to that site alone. However, the processes and means of executing site-specific characterization can draw upon the considerable success of projects such as BAMBUS II.

V Acknowledgements

In this project a significant part of the work continued that had been performed in the EU-funded project BAMBUS (1996 to 1998). The long-term TSDE project terminated after more than 15-years duration and the final evaluation was carried out. Of great benefit to the performance and outcome of the project was the cooperation of scientists from different scientific and technical fields and from different countries.

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