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Proceedings of the 6th US/German Workshop on Salt Repository Research, Design, and Operation

Fuel Cycle Research & Development

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The authors greatly appreciate the inexhaustible care provided by Laura Connolly of Sandia National Laboratories in preparation of these Proceedings. Participants offer a special tip-of-the-hat to Walter Steininger for his considerable work arranging the Dresden venue and providing continuous positive support to our collaboration efforts. As with any endeavor of this magnitude, scope, and complexity, progress is testimony to dedication and contribution of participants.

These Proceedings represent a sum of several parts that advance the foundation of salt repository science and engineering. This document comprises individual chapters, reflecting significant contributions from numerous colleagues as follows:

Chapter 2: SALT REPOSITORY RESEARCH AGENDA

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Chapter 3: GEOMECHANICS ISSUES/JOINT PROJECT

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Chapter 4: DRIFT SEALS MADE OF CONCRETE – STATE OF THE ART IN GERMANY

N. Müller-Hoeppe (DBE TEC)
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Chapter 5: A COMPARISON OF BEDDED AND DOMAL SALT

F. Hansen (SNL)
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Chapter 6: MODULAR BUILD AND CLOSE SALT REPOSITORY CONCEPT

C. Gadbury (Carlsbad Field Office/DOE)
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Chapter 7: UNDERGROUND RESEARCH LAB PRIORITIES

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The US/German Workshops are made possible by federal/ministry funding, which validates the spirit living in an overarching Memorandum of Understanding between DOE and BMWi.

ABSTRACT

The 6th US/German Workshop on Salt Repository Research, Design, and Operation was held in Dresden. Germany on September 7-9, 2015. Over seventy participants helped advance the technical basis for salt disposal of radioactive waste. The number of collaborative efforts continues to grow and to produce useful documentation, as well as to define the state of the art for research areas. These Proceedings are divided into Chapters, and a list of authors is included in the Acknowledgement Section. Also in this document are the Technical Agenda, List of Participants, Biographical Information, Abstracts, and Presentations. Proceedings of all workshops and other pertinent information are posted on websites hosted by Sandia National Laboratories and the Nuclear Energy Agency Salt Club.

The US/German workshops provide continuity for long-term research, summarize and publish status of mature areas, and develop appropriate research by consensus in a workshop environment. As before, major areas and findings are highlighted, which constitute topical Chapters in these Proceedings. In total, the scientific breadth is substantial and while not all subject matter is elaborated into chapter format, all presentations and abstracts are published in this document. In the following Proceedings, six selected topics are developed in detail.

1. Salt Repository Research Agenda. Building blocks of the research agenda were conceived at the 5th US/German Workshop on Salt Repository Research, Design, and Operation in 2014 and reached a mature level for project forecasts in 2015. This contribution identifies future common research and extensive discussion and referencing provides structural framework to the issues. Remaining among previous research issues are the minimum stress criterion, granular salt properties at low porosities, constitutive model development, and other matters of mutual interest and pertinence to the salt safety case.

2. Geomechanics Issues and Joint Project. The overall goal of the Joint Project, which initiated in 2004, is to further develop tools for demonstrating safe, final disposal of heat-generating radioactive waste in salt formations. The *tools* in this particular case include constitutive models, numerical calculation codes, and modeling procedures. Modeling in the Joint Project has evaluated proficiency against *in situ* test results obtained in the Asse mine (domal) and Waste Isolation Pilot Plant (bedded) salt. The most recent simulations of unheated Room D and heated Room B are examining large-scale thermomechanical effects on closure. In concert, a large testing program on Salado Formation bedded salt was completed to avail additional parameter quantification. In the end, the Joint Project will identify the best available resources for salt repository design, analysis, operations, and closure.

3. Concrete Drift Seals. Drift seals provide important functions for operations and closure of salt repositories. In Germany, drift seals made of salt-saturated concrete have been evaluated at full-scale. These efforts included development of specialty concretes with cement or MgO as the binding agent and the brine saturated with NaCl or $MgCl_2$, construction experience, and functionality testing. Investigations of pilot drift seals encompassed the primary elements of drift seals: construction materials, the excavation damage zone, and the contact zone.

4. Comparison of Bedded and Domal Salt. There is a desire within advanced salt repository programs to compare and contrast bedded and domal salt as applied to disposal of heat-generating nuclear waste. Relevant research and application in the United States has concentrated on bedded salt while similar efforts in Germany emphasized geologic domal salt. At this time, each nation is once again considering possible repository choices, which presents a need and an opportunity to compare repository-relevant differentiating characteristics of bedded and domal salt. Differences and similarities exist for bedded and domal salt and they manifest at different scales when applied to nuclear waste disposal.

5. Modular Build and Close. Events in February 2014 at the Waste Isolation Pilot Plant sharpened the focus of operational safety. One means to mitigate potential risk is to design the underground workings in such a way as to minimize exposure during operations. Advances in our knowledge of salt reconsolidation coupled with analogue examples support a concept of sequential sub-unit certification and closure in large-scale salt repositories. Recent changes to the Waste Isolation Pilot Plant panel closure and concurrence by the Environmental Protection Agency were based on recognition that crushed salt panel closures will return to a physical state similar to native salt. These advances suggest a future salt repository featuring modular design, sequential licensing, and complete isolation.

6. Underground Research Lab Priorities. Full-scale test results play important roles in licensing and performance assessment. Salt repository science and engineering has the benefit of several decades of applicable field experiments—to such an extent that there has not been a defined test that must be conducted before a safety case can be prepared for salt disposal of heat-generating nuclear waste. Nonetheless, if an underground facility were to become available, the salt repository community is capable of defining high-value test priorities. Based on break-out sessions of this workshop, the consensus for highest priority field testing included large-scale consolidation and drift-seal demonstration.

Descriptions above comprise the core of the Proceedings of the 6th US/German Workshop on Salt Repository Research, Design, and Operation. Collaborative efforts continue on virtually all of these subjects, and several others. For example, a universal salt catalogue for Features, Events, and Processes continues compilation toward a comprehensive list. Differences and similarities between bedded and domal salt are being examined by way of modeling, background assembling of information, and new testing. Emphasis of the ongoing workshops remains on issues pertaining to salt repository research, design, and operation. The group strives to advance the technical basis for salt repository systems. Joint publications provide evidence of such advancements, including shared goals of state-of-the-art co-authored reports and identification of an appropriate research agenda. Our collaborations provide a forum to evaluate arising issues and support the Nuclear Energy Agency Salt Club.

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ACRONYMS

BAMBUS	Backfill and Sealing of Underground Repositories for Radioactive Waste in Salt
BfS	Bundesamt für Strahlenschutz (Federal Loffice of Radiation Protection)
BGR	Federal Institute for Geosciences and Natural Resources (Germany)
BMU	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (German Federal Ministry for the Environment, Building, Nature Conservation, and Nuclear Safety)
BMWi	Federal Ministry for Economic Affairs and Energy (Germany)
CDM	Composite Dilatancy Model
CRZ	Containment-providing Rock Zone
DBE TEC	Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe GmbH (The German Society for the construction and operation of waste repositories)
DOE	US Department of Energy
DRZ	Damaged Rock Zone
ECN	Netherlands Energy Foundation
EDZ	Excavation Damaged Zone
EIS	Environmental Impact Statement
ELSA	Project: Shaft Seals for HLW Repositories
EPA	US Environmental Protection Agency
ERAM	Endlager für Radioaktive Abfälle Morsleben (Repository for RadioactiveWaste Morsleben)
FEP	Features, Events, and Processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) GmbH
HAW	High-Activity Waste
HFCP	Heated Free Convergence Probe
HLW	High-Level (Radioactive) Waste
HPC	High-Performance Computing
IFC	Isothermal Free Convergence
IfG	Institut für Gebirgsmechanik
KIT	Karlsruher Institut für Technologie
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
PTKA-WTE	Water Technology and Waste Management
R&D	Research and Development
SME	Subject Matter Expert
SNL	Sandia National Laboratories
THM	Thermal-Hydrological-Mechanical
TUBS	Technische Universität Braunschweig
TUC	Technische Universität Clausthal
URF	Underground Research Facility
USA	United States of America
VSG	Vorläufige Sicherheitsanalyse für den Standort Gorleben (Preliminary Safety Analysis for the Gorleben Site)
WIPP	Waste Isolation Pilot Plant

Proceedings of the 6th US/German Workshop on Salt Repository Research, Design, and Operation

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Dresden, Saxony, Germany
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1 INTRODUCTION

Once again, it is a pleasure to present Proceedings of collaborations between German and United States (US) scientists on salt repository research, design, and operation. The 6th US/German Workshop on Salt Repository Research, Design, and Operation was held in Dresden, Germany and totalled 73 participants, including representatives engaged in salt research from Poland and the Netherlands. The cross-section of participants encompassed regulatory authorities, branches of the US Department of Energy (DOE), members of Federal Ministry for Economic Affairs and Energy in Germany (BMWi), The State Authority for Mining, Energy and Geology, German and US universities and research companies, and a particularly appropriate contribution by the Technical University Freiberg on their 250th Anniversary. The ongoing workshops are underwritten by a Memorandum of Understanding between DOE and BMWi and extend benefit to the Organisation for Economic Co-operation and Development's (OECD´s) Nuclear Energy Agency (NEA) Salt Club. The Workshop was initiated by Welcome Addresses from Mrs. U. Borak on behalf of BMWi and Dr. T. Lautsch of Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe GmbH (DBE) (the German Society for the construction and operation of waste repositories (DBE TEC). The complete addresses are found in Appendix B.

Mrs. Borak – Welcome Address

The Federal Ministry for Economic Affairs and Energy has the lead responsibility for project funding for research on the disposal of radioactive waste that does not focus on a particular site and is supported by the Project Management Karlruhe to determine the strategic and technical direction of the research activities. During the current phase of the project funding for the next four years, the **Federal Ministry for Economic Affairs and Energy** plans to clarify conceptual issues concerning the final disposal in bedded rock salt. In this context, the continuation of our cooperation with the United States is particularly valuable.

All previous workshop Proceedings can be found at the NEA website[1] and the Sandia National Laboratories (SNL) website[2]. The current series of workshops was started in 2010, by mutual agreement between lead salt researchers in Germany, Mississippi State University, and SNL. Since the initial meeting in Clinton, MS, the workshop locations have alternated between the US and Germany. These collaborations help ensure documentation of the state of the art, which is tantamount to creating a knowledge archive. Conduct of the workshops encourages open discussion in a mentoring atmosphere. These elements combine to illuminate a contemporary state of the industry and thereby identify the most fruitful salt repository research, development and demonstration. Germany and US salt researchers have worked together since the 1970s. These Proceedings comprising technical presentations and abstracts, as well as external, co-authored technical reports are distinctions of mutually beneficial salt repository progress.

The number of attendees and topics has grown appreciably. An observation made at the Dresden workshop was that owing to the number of participants and the diversity of subject matter, the venue took on appearances of a symposium. Thus, coordinators will attempt to return to a workshop/breakout structure with a more focussed portfolio. The group will continue to document and report on elements that have history and substantial scientific basis, as a means to preserve that knowledge. Mature issues will be balanced with elements of arising concerns to render progress on matters of interest on both sides of the Atlantic Ocean.

2 SALT REPOSITORY RESEARCH AGENDA

2.1 Introduction

The content of this Chapter was developed at the 5th US/German Workshop on Salt Repository Research, Design, and Operation held in Santa Fe in 2014. A cross-section of the geomechanics issues was summarized in the Proceedings of the 5th Workshop and published externally (Hansen and Popp 2015). A *Thesenpapier* or discussion paper from which this material is extracted represents a living document, presenting concise information, data and justification for science and engineering in the framework of the US/German workshops and collaborations. The authors decided to include a majority of the *Thesenpapier* as a Chapter in these 6th Proceedings, which involved format changes, some shortening and minor text revision. This Chapter identifies future common research foci, which were formulated in working groups for specific topics. This working group was heralded “Integrity Analysis” and its identified research is summarized here.

According to the safety requirements issued by the BMU (German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety) (BMU 2010), the main safety principle for the final disposal of radioactive waste is to contain the waste and its contents as quickly as possible and in a permanently safe way in a containment-providing rock zone (CRZ) during the post-closure phase. In repository concepts in salt, safe containment must be ensured by the properties of the rock salt in the CRZ combined with the properties of the geotechnical barrier system. The integrity of the geological barrier is established against the dilatancy criterion and minimum stress criterion. Effectiveness of drift and shaft seals is required for the period in which crushed salt backfill develops its full sealing function.

As part of the system analysis, the corresponding integrity analyses of the geological barrier (1) and of the geotechnical barriers (2) in the reference period are a central element of every safety analysis for a

[1] NEA website: https://www.oecd-nea.org/rwm/saltclub/

[2] US/German Workshop website: http://energy.sandia.gov/energy/nuclear-energy/ne-workshops/usgerman-workshop-on-salt-repository-research-design-and-operation/

repository and are thus also necessary for a comparative site assessment within the framework of a repository site selection process (Figure 2.1).

The corresponding demonstrations can only be carried out by means of numerical model calculations. Due to the complex boundary conditions (e.g., geologic environment), the resulting models should be three-dimensional where necessary. This requires a basic understanding of the safety-relevant impacts and processes as well as their description in a theoretical model including constitutive relations in the form of material laws that link impacts and consequences. Furthermore, the material parameters necessary for the application of the models have to be known, and suitable calculation programmes for implementing the model-based theoretical approaches must be available.

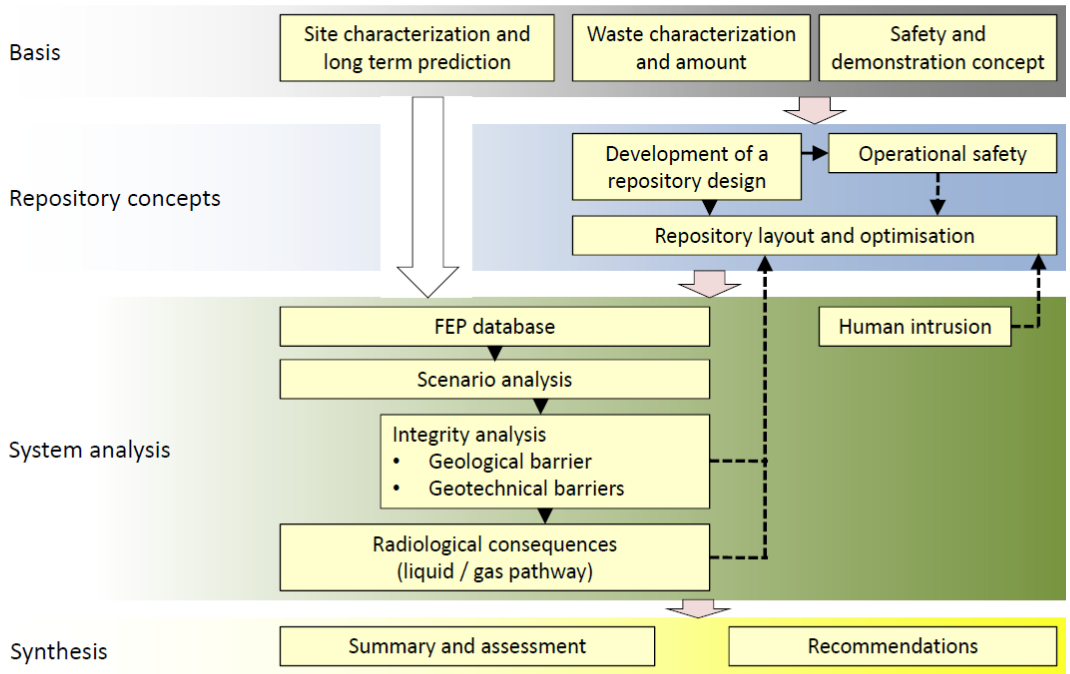

Figure 2.1. Scheme of the VSG safety demonstration.

For the description of the boundary conditions prevailing during the reference period, the Features, Events, and Processes (FEP) methodology and the scenario development based thereon (Beuth et al. 2012) have been refined in recent years to procedures that are applicable to the German regulatory requirements. Within the framework of the already existing US/German cooperation, NEA-FEP data bases for rock salt are to be developed that differentiate between salt domes and bedded salt formations.

They are directly related to the integrity analyses of the host rock and geotechnical barriers, which are the central safety assessment focus. However, in the view of the authors, their performance based on the state of the art in science and technology is challenged as there still are open questions and knowledge deficits. Uncertainty in the following, three work priorities are identified as necessary research and development (R&D) work taking into account an intensified US/German cooperation. They also include the R&D recommendations identified within the scope of the Vorläufige Sicherheitsanalyse für den Standort Gorleben (Preliminary Safety Analysis for the Gorleben Site) (VSG) project (Thomauske et al. 2013).

2.2 Consequence analysis of violating the minimum stress criterion

2.2.1 State of knowledge

There is a high level of knowledge about the mechanical behavior of rock salt, which – based on the generally accepted criteria, dilatancy and minimum stress criterion – has been used for integrity assessments; e.g., in the VSG project. From a scientific point of view, it should be pointed out that there is no unique term for the dilatancy criterion. Depending on the constitutive law applied, there are different approaches to this criterion. Furthermore, the minimum stress criterion in its simple form contains such rough simplifications regarding the underlying flow model, such as interactions of the stress tensor components with the fluid pressure, that it does not reflect the actual conditions. Merely the fact that it is employed conservatively justifies its use. Within the scope of a multi-stage Joint Project on the topic "Vergleich aktueller Stoffgesetze für Steinsalz" (*Comparison of current constitutive models for rock salt*) (Joint Project I to III 2004-2016, Hampel et al. 2013, 2015), existing constitutive modelling approaches are compared and examined regarding their suitability for repositories for chemo-toxic and heat-generating radioactive waste. This research includes different constitutive models (e.g., phenomenological models or models based on a purely physical description of the deformation processes). In addition to this, theoretical and technical concepts (some of which have been studied at pilot scale) for the construction of sealing structures (drift, shaft) are available. Furthermore, the results of studies of experimental sealing structures in rock salt in the former Asse research mine and in anhydrite for the Endlager für Radioaktive Abfälle Morsleben (Repository for RadioactiveWaste Morsleben) (ERAM) are available, which have been carried out *in situ* at a scale of 1:1.

These studies showed that the engineering-based model representations underlying these concepts do not yet simulate conditions adequately, even if some of the results on various experimental structures were positive. Even though they have not yet been finally validated, these positive results of *in situ* investigations on the experimental structures "Asse-Vordamm" and "Pilotströmungsbarriere A1" are part of the current theoretical state of knowledge which was the basis for the VSG, among others, while the results of the *in situ* experiment "Abdichtbauwerk im Steinsalz" (ERAM *in situ* Test Seal) were the basis for the long-term safety analyses for the ERAM. (For more details see Chapter 4.)

With regard to the assessment criteria, it turned out that due to the range of the pressure-driven fluid infiltration, the minimum stress criterion is especially decisive for both the integrity assessment of the geological barrier (far field) and for the assessments of the geotechnical sealing systems. In VSG, areas in the rock salt barrier were identified more than 100 m below the salt top, where – according to the models applied – the minimum stress criterion was violated (Kock et al. 2012) due to thermally-induced stress redistributions. However, the consequences of a pressure-driven fluid infiltration could not be adequately assessed (Figure 2.2) because coupled hydro-mechanical modelling was not possible.

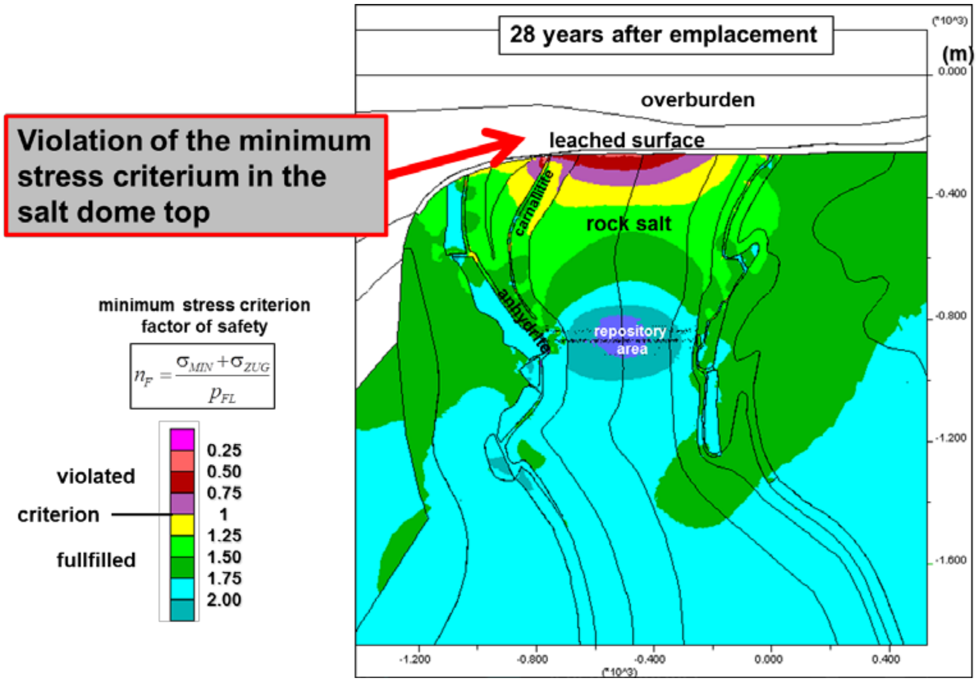

Figure 2.2. Violation of the minimum stress criterion in the salt dome top Gorleben 28 years after repository closure (Eickemeier et al. 2013).

As noted previously, the minimum stress criterion is based on simplifications and represents a conservative approach. During the evaluation of this criterion only the magnitudes of the smallest principal stress component and of the hydrostatic pressure are compared. Due to the assumption of hydrostatic conditions the flow resistances are not estimated. The minimum stress criterion currently applied does not include any directional dependence; i.e., the directions of the principal stress components are not set in relation to the orientation of the fluid impact. If flow processes are taken into account in the calculations at all, they are mostly based on a porosity model, which is due to the predominantly specific grain-to-grain contacts representing hydraulically effective connected pore spaces. This approach is not adequate for rock salt. Taking into account the microstructure of rock salt, the geotechnical approach of a fractured network seems to be more applicable when conducting the analysis on a micro-level. Depending on the stress component directions as well as the kinematic constraints, different grain boundaries can open or close at the same time. If this does not result in a connected network of fractures, this does not necessarily lead to an increase in permeability, even in case of dilatant behavior. For example, according to numerical calculations, there should be brine intrusions in some parts of the ERAM but these particular parts of the repository are dry. In this case, the conservative assumptions applied for the criterion have to be analysed in more detail (ESK 2013).

During the VSG, the effectiveness of the sealing constructions could not be demonstrated completely because brine intrusion at the unavoidable contact zone between sealing and abutment elements and the surrounding rock could not be described (Müller-Hoeppe et al. 2012) due to lack of knowledge. Using the engineering-based model representations applied so far, this is also not likely to be successful. In this case, detailed knowledge is required about the contact zone, which consists of the zone close to the contour of the sealing construction, the excavation damaged zone (EDZ), and potentially a necessary improvement of the contact zone by means of injections such as MgO or agents based on sodium silicate, and about the geometrical and material-specific interactions in order to be able to take into account brine penetration in a coupled hydraulic-mechanical model. First indicative laboratory data that take into account brine in the contact and EDZ are currently being provided in the project described by Czaikowski and co-workers (2015).

This applies in particular to the assessment of the impact "earthquake" while formally applying the depth-specific fluid pressure criterion. Due to the short duration of an earthquake, the integrity violations indicated for the shaft seal probably have no real significance because the fluid does not penetrate to any significant depth during this short time and the minimum stress criterion is re-established after the earthquake. These effects would only be relevant if there was permanent damage (Neubert 2014).

Currently, there are various approaches and model concepts that take into account coupled hydro-mechanical processes and have been used for integrity verifications in commercial projects (e.g., integrity assessments for caverns, underground material utilisation/underground landfill) or within the scope of research projects (e.g., VSG):

- Continuum approaches based on porous materials:
  - with coupling of FLAC/TOUGH, e.g., Technische Universität Clausthal (TUC), GRS Köln
  - within a software package: e.g., CODE_BRIGHT (GRS Braunschweig), OpenGeoSys Code (UfZ Leipzig, BGR), JIFE (BGR), FLAC (Institut für Gebirgsmechanik (IfG), DBE TEC)
- Discontinuum approach UDEC/3DEC: IfG, DBE TEC

The different approaches have different advantages and disadvantages. For example, TOUGH can take into account 2-phase flow parameters while the discontinuum approach can simulate single directional fluid migration in accordance with the effective stress field. Unlike the constitutive laws for rock salt, these calculation approaches to demonstrate integrity have not yet been compared methodologically nor have they been sufficiently verified by means of benchmark. Furthermore, there is a considerable need for their application within the framework of safety analyses because in addition to a conservative assessment of the stress-based criteria, an assessment of the time-dependent development of the barrier integrity during the reference period needs to be carried out.

In principle, these calculation approaches are also suitable to assess sealing construction (as shown e.g., by the use of CODE_BRIGHT during the VSG), however, in addition to modelling issues, there are significant uncertainties regarding the assessment of the contact zone between sealing construction (dam) and rock salt, which is considered to be essential for the demonstration of functionality. Additional work is, thus, required.

2.2.2 Actions

Verification of the representativeness of geomechanical constitutive laws and calculation methods and their further development, e.g., to assess pressure-induced fluid intrusion or percolation while taking into account thermal-hydrological-mechanical (THM) processes is needed to demonstrate the integrity of the geologic barrier or of geotechnical sealing constructions. Based on this, more realistic flow models should be developed, and the minimum stress and the dilatancy criteria should be developed further. This is a prerequisite for the analysis of consequences if the minimum stress criterion is violated locally, which may happen in the early post-closure phase of a repository, e.g., due to a fluid pressure acting from outside or due to an increase in gas pressure in the repository. In this context, the data base for the dilatant behavior of rock salt should be expanded with the aim to standardize the various existing approaches to determine the dilatancy boundary.

This should be done in a cross-institutional collaboration similar to the Joint Project "Vergleich aktueller Stoffgesetze für Steinsalz," taking into account the approaches described above.

In view of a potential site in bedded salt, the knowledge about the mechanical behavior should be expanded, and a comparison with the behavior of domal rock salt should be carried out. Generally, it is to be expected that due to the different origins of the rock salts after sedimentation, they will also have different creep and stress-strain behaviors. For an assessment of these differences, the data base is not yet adequate.

Improvement of the existing data base from laboratory and *in situ* tests to describe the hydro-mechanical integrity of sealing structures, should focus on

- initial tightness after installation
- development over time during convergence (restitution of the EDZ sealing material consolidation)
- effects of improvement measures (injections)

2.2.3 Priority

These are high priority options because they are essential for an integrity assessment based on the current state of scientific and technical knowledge.

2.2.4 US/German cooperation

Cooperation already exists between TUC and the Lawrence Berkeley National Laboratory. Furthermore, the SIERRA code used by SNL as well as CODE_BRIGHT can be applied for the numerically very complex THM calculations.

In the USA, focus for the Waste Isolation Pilot Plant (WIPP) repository was on shaft sealing construction where crushed salt compaction plays an important role. Contemporary circumstances at WIPP have now focused further attention on reconsolidating granular salt for drift seals. (See Chapter 6 of these Proceedings.) In addition, the US/German collaborations have vetted relative merit of potential field testing. (See Chapter 7.)

2.3 Hydraulic and mechanical properties of compacted crushed salt

2.3.1 State of knowledge

The hydraulic and mechanical properties of crushed salt affect the long-term containment of radionuclides and are, thus, important for the safety of a repository. The results of comprehensive research work in this field (e.g., REPOPERM Phase 1 (Kröhn et al. 2009)) and the knowledge about the processes gained therein (Popp et al. 2012) show that the mechanical and hydraulic properties at low porosities of only a few percent cannot yet be sufficiently quantified. It is known that especially at low porosities, microstructural processes are effective that are catalysed by moisture (e.g., pressure-solution creep) and that – by efficiently reducing the porosity – lead to tightness. However, their dependence on time is not yet sufficiently known (Figure 2.3).

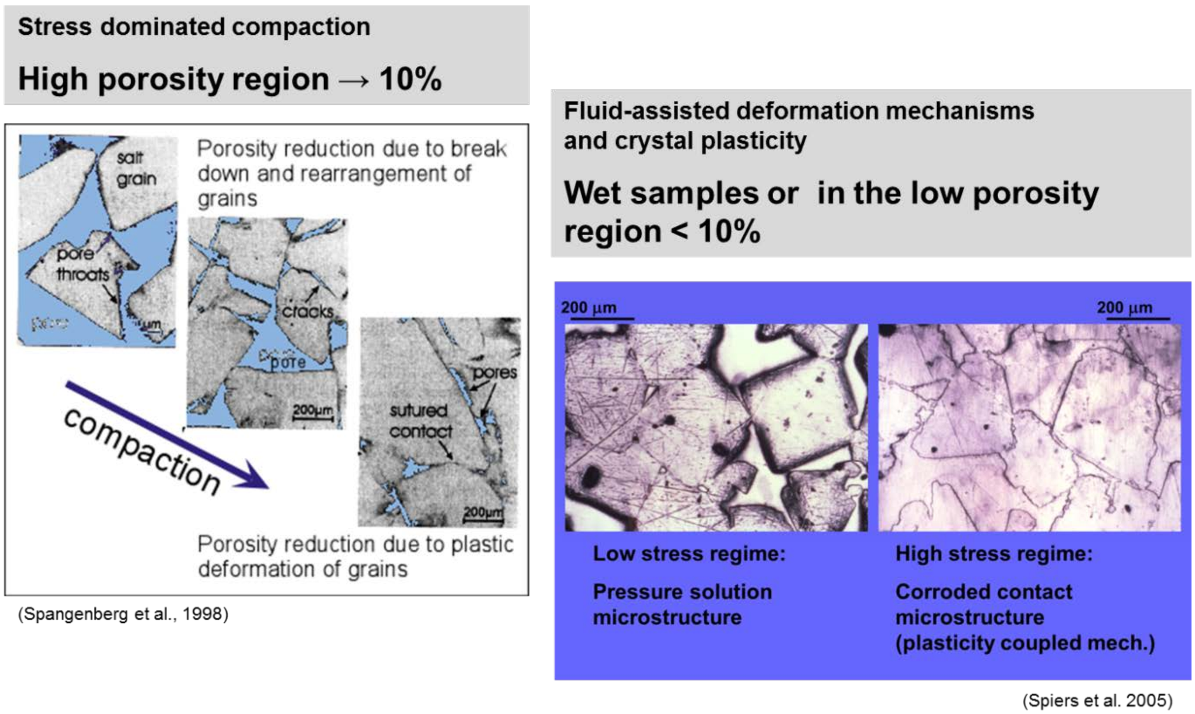

Figure 2.3. Microstructural processes during compaction of crushed salt.

It is beyond dispute that due to the influence of rock convergence the crushed salt backfill will be compacted to low porosities. To narrow the time period necessary, a reliable prediction of the long-term development of the crushed salt backfill based on advanced and calibrated constitutive laws for crushed salt needs to be made. The existing laws do not meet the requirements for sufficient verification and calibration. According to the latest findings, this is not only true for moist crushed salt backfill but for dry crushed salt backfill as well (Kröhn et al. 2015). An improvement of the data base requires that especially experimental long-term studies on a statistically assessable basis and natural analogues be included.

2.3.2 Actions

Due to the scope of the study, which covers laboratory experiments, the characterization of natural or technical analogues as well as the development of constitutive laws, a number of individual actions are recommended:

- Further development of geomechanical constitutive laws and calculation methods to describe the stress-, porosity-, and time-dependent crushed salt compaction taking into account THM processes. This includes hydro-mechanical interactions (pore pressure build-up in case of delayed drainage) as well as microstructural processes influenced by moisture (e.g., pressure-solution creep).
- Long-term compaction tests using possible backfill material under defined stress boundary conditions to identify hydraulic parameters (e.g., 2-phase flow parameters – a first test has successfully been carried out within the scope of the R&D project REPOPERM 2). If necessary, suitable concepts have to be developed further.
- Analysis of natural analogues (e.g., salt piles with a height of several 100 m, Dead Sea sediments from deposits where no significant porosity can be determined starting at depths of only 30 m (Warren 2005)).

- Backfill and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS): More than 10 years have passed since the follow-up tests were carried out within the scope of BAMBUS II, and due to convergence, the crushed salt has compacted even further. The fact that the boundary conditions (e.g., stress state, convergence) are known provides the possibility of calibrating existing constitutive laws for crushed salt against the current state of the salt by characterizing the current crushed salt properties.
- Within the scope of the Asse decommissioning activities, IfG will probably carry out a geomechanical site characterization (stress and permeability measurements) of the Thermal Simulation of Drift Storage field test and take samples. The aim is to characterize the compacted crushed salt material again in order to obtain a further reliable reference point for the calibration of the modelling approaches to be used. So far, no particular research programme has been specified for the core samples that will be taken so that – after approval by Bundesamt für Strahlenschutz (Federal Loffice of Radiation Protection) (BfS) – the residual sample material could, for example, be used for investigations of the microstructures.

2.3.3 Priority

- Development of constitutive laws / laboratory investigations / BAMBUS – high. Without corresponding laboratory investigations, it is not possible to develop constitutive laws; as long-term large-scale test, the BAMBUS setting is particularly suited for calibration.
- Analogues – medium, because boundary conditions are not always known. However, due to the limited duration of the lab and field tests, analogues are indispensable for the acceptance of assumptions.

2.3.4 US/German cooperation

Since BAMBUS II, there has been longstanding knowledge exchange with SNL regarding the general compaction mechanisms and properties of crushed salt; e.g., joint NEA report (Hansen et al. 2014). In addition to the development of constitutive laws, it would be possible to plan and carry out experiments (e.g., mock-up tests of shaft and drift sealing constructions) sharing a joint underground laboratory (Chapter 7).

2.4 Joint Project: Further development and qualification of the rock mechanical modelling for the final HLW disposal in rock salt

2.4.1 State of knowledge

As a result of the work regarding the verification and comparison of constitutive laws and the modelling of the thermo-mechanical behavior of rock salt that has been carried out since 2004, a number of efficient instruments to demonstrate the integrity of the geomechanical barrier are available at the various institutions. These tools have been compared and largely validated by back-calculating comprehensive, systematically completed series of laboratory experiments and various *in situ* arrangements, focusing on the salt properties to be modelled.

In the course of the work, R&D needs have been identified for the following specific issues. In this case, the focus should be on (I) the further development and qualification of existing constitutive laws and modelling procedures and (II) on a comparative analysis with a record of their suitability.

2.4.1.1 Deformation behavior at low deviatoric stresses

One process that can lead to a release of radionuclides from the underground repository is convergence of the underground cavities. Within the scope of the long-term safety analysis, rock mechanical predictions covering the reference period of 1 million years have, thus, to be made, although the effective deviatoric stresses in the repository are then very small. From an experimental point of view, this means that creep experiments with differential stresses of $\Delta\sigma = \sigma_1 - \sigma_3 \leq 5$ MPa have to be carried out. *In situ* observations indicate, however, that the creep rates at room temperature can be expected to be approx. 10^{-11} 1/s (Figure 2.4). Thus, they are several orders of magnitude higher than the rates resulting from the modelling with constant stress exponent (e.g., n = 5). It is assumed that this is due to a change in the effective deformation mechanisms. At the same time, the creep behavior at increased temperatures can change, which could be explained with a change in the activation energy of the dominant deformation mechanisms. Systematic experimental investigations are not yet available.

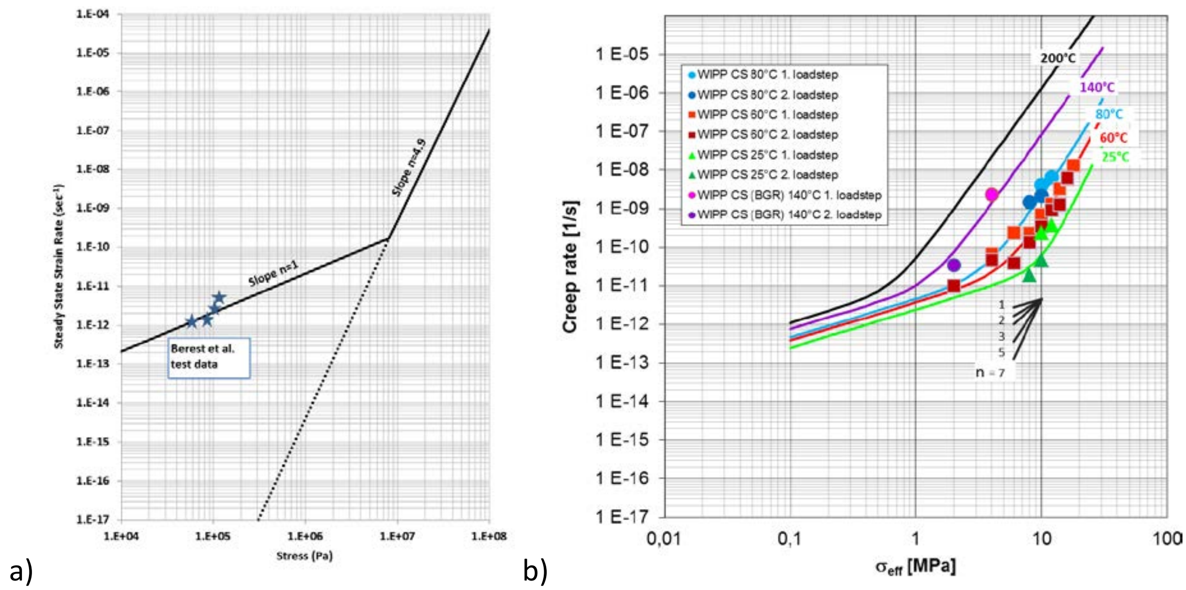

Figure 2.4, Creep of rock salt. a) Expansion of the classic Norton creep approach with n = 4.9 for the range with small deviatoric stresses (σ_{eff} < 8 MPa) with n = 1. b) Results of creep tests on WIPP rock salt at different temperatures (model curves according to the material approach by Günther Salzer) (Hansen and Popp 2015).

Requirements:

- Triaxial long-term creep tests at low differential stresses and different temperatures with accompanying microstructural investigations
- Adaptation and further development of constitutive laws for low deviatoric stresses
- Verification through calculations of *in situ* situations

2.4.1.2 Influence of temperature and stress state on damage recovery

It is generally assumed that long-term change in the stress boundary conditions, e.g., in the near field of sealing constructions due to drift convergence with pressure build-up caused by creep of the rock salt onto the backfill, leads to a recovery of damage and restoration of integrity due to crack closure with subsequent sealing and healing. However, systematic experimental and microstructural investigations for a further development and validation of existing calculation approaches for an correct assessment and prediction of the system behavior of sealing structures are not available.

- Systematic deformation tests regarding damage recovery using rock salt samples with defined pre-damage, with high-resolution measurement of dilatancy at different stress boundary conditions and temperatures

- Further development of the material laws based on the test results regarding the influence of temperature and stress state on the damage recovery of rock salt
- Verification through calculations of *in situ* situations

2.4.1.3 Deformation behavior under extension loads

The research work carried out so far focused primarily on the damage of rock salt in the compression direction. However, extension load can have a significant influence on the damage evolution at the contour of underground cavities and, thus, on the formation of an EDZ. Therefore, the modelling approaches to simulate tensile stresses implemented in the material laws need to be developed further. Specific experimental studies have to be carried out to determine the temperature-dependent tensile strength of undamaged material, followed by tensile tests to investigate the influence of existing damage on further deformation behavior. Defined pre-damage can be induced in a laboratory test by exceeding the dilatancy boundary in a triaxial strength test. Additionally, the influence of increased temperature and of permanently acting tensile stress must be measured. To improve the modelling approaches, the following investigations should be carried out:

- Tensile strength of intact rock salt – modified direct tension tests
- Temperature influence
- Tests with material with defined pre-damage
- Further uniaxial tension tests under constant loading
- Further development of the material laws for the description of damage, dilatancy, and strength of rock salt impacted by loads in extensile direction
- Verification through calculations of real *in situ* situations

2.4.1.4 Influence of inhomogeneities (layer boundaries, interfaces) in rock salt on deformation

Despite being lithologically largely homogeneous, natural rock salt (domal and especially bedded salt formations) comprises bedding planes or mechanical discontinuities that could become mechanically/hydraulically weak. Underground observations and simulation calculations of SNL regarding WIPP (Rath and Argüello 2012) show, for example, that sliding of rock salt along contact surfaces to anhydrite or clay layers can significantly influence the convergence behavior of underground cavities. However, these properties are minimally described by the existing THM calculations. In this context, the development of fundamental methods for a generally applicable description of interfaces based on the following experimental investigations is required:

- Experimental laboratory investigations for a process understanding of the behavior of interfaces (including direct shear tests with different normal loads and deformation rates on samples with bedding planes and joint faces)
- Identification and further development of methods to thermomechanically describe interfaces and anisotropies in rock salt
- Verification through calculations of *in situ* experiments, such as conducted at WIPP

2.4.1.5 Comparative analysis of the constitutive laws applied in the Joint Project

A number of different constitutive laws are applied in the joint research project; however, in the past, the results for identical calculations sometimes differed significantly in their predictions of the behavior in the laboratory and in the field. What is still missing is a comparison of the advantages and disadvantages of the individual models and of their effectiveness for the long-term prediction of the rock mechanical evolution of repositories. The results of such an investigation would allow an assessment of the suitability of the individual constitutive laws for their intended use.

2.4.1.6 Assessment of the suitability of the existing constitutive laws by back-calculating failures that have occurred

In the past, rock falls occurred both in potash mines and in rock salt mines when the pillar dimensioning was not adequate (Minkley et al. 2010). Furthermore, in rock salt mining, damage to the geologic barriers caused by mining processes led to brine intrusion or even mine inundation. Some of these incidents are well documented. A computer analysis of the incident scenarios in addition to a suitability assessment of the models and constitutive laws applied lead to an advanced understanding of the barrier integrity of salt formations (Minkley and Knauth 2014). In potash and rock salt mining, incidents leading to a loss of integrity and tightness of the geologic barriers occurred in the first one hundred years after excavation. These "industrial" analogues have to be included in the assessment of the barrier integrity of repositories.

The back-calculation of incidents leading to failure and inundation of potash and rock salt mines by applying coupled mechanical-hydraulic models can serve to validate the model and is a prerequisite for a reliable prediction to assess barrier integrity when disposing of radioactive waste in a salt formation. Only when the failure mechanisms along discrete pathways are well understood and can be reproduced in geomechanical models by applying suitable constitutive laws are the models qualified to reliably describe future evolutions of the integrity behavior of repository mines in rock salt.

2.4.1.7 Model development taking into account processes from discontinuum mechanics

Primarily, rock salt has a grain matrix with intergranular pore space (grain-boundary moisture). Secondarily, depending on the mechanical stress state, cross-linked fluid migration paths can form and close due to crack formation and closure. This causes changes in the hydraulic properties. In the joint research project, only approaches from continuum mechanics using the finite element method (ADINA, ANSYS) or the finite difference method (e.g., FLAC, FLAC3D) are applied, which do not model the physical process of crack formation directly. With the further development of computer technology in recent years, new approaches to describe hydro-mechanical processes using discontinuum approaches have been developed (Minkley et al. 2013). The advantage is that in addition to a direct hydraulic coupling of crack formation/fluid migration, it is also possible to model the directional dependence in accordance with the existing stress field. For an application to rock salt formations, a corresponding verification and validation are necessary.

- Comparison of continuum- and discontinuum-based modelling approaches
- Further development of these particular modelling approaches, especially application to rock salt formations, e.g., derivation of parameters for contact zones, description of intrusion/migration processes, and hydromechanical coupling in networks of cracks

2.4.2 Actions

The Joint Project intends to investigate and further develop the material laws and modelling of the open issues described above. Then, the scale of experiments should be expanded by simulating a particular repository situation (domal and bedded salt formations) to assess the suitability of the respective modelling approach for an integrity analysis. Verifications can also be carried out by back-calculating incidents that led to failure and inundation using large-scale *in situ* incidents.

2.4.3 Priority

High, because of the importance of the integrity analysis for the long-term safety analysis. At the same time, this would demonstrate that the constitutive laws and modelling procedures considered in the joint research project are suitable for salt formations.

2.4.4 US/German cooperation

Sandia National Laboratories already is an associated partner in the joint research project on the comparison of existing material laws for rock salt and is interested in continuing this cooperation in a follow-up joint R&D project on the further development of the material laws and modelling methods. In view of a future repository for heat-generating radioactive waste in rock salt, all partners have to qualify the methods used for integrity assessment. One focus of the joint work could be the modelling – integrity analysis of the salt barrier – of a generic repository in salt (domal and bedded salt formations).

2.5 Status/Outlook

As a result of the discussions of participants of the US/German workshop and the joint follow-up work, three possible R&D topics have been identified: (1) Consequence analysis when the minimum stress criterion is violated, (2) description of the hydraulic and mechanical properties of compacted crushed salt, and (3) mechanical behavior of rock salt/development of constitutive laws. In addition to recommendations with specific measures for their implementation, proposals for a prioritisation of the topics and opportunities for a US/German cooperation were given.

The topics proposed correspond explicitly with the funding concept of BMWi "Forschung zur Entsorgung radioaktiver Abfälle" (*Research on disposal of radioactive waste*) that has just been revised for the period 2015 – 2018. One central research focus of this concept is the development of tools for a safety demonstration; however, the work to be carried out has not yet been described in detail. This summary provides a qualified technical basis for future R&D projects in the sub-section "Geomechanical Integrity Analysis."

In the meantime, implementation of some of the research work outlined in this paper has started. Furthermore, the discussions held in this working group have been taken up by other bodies and discussion platforms.

Specific projects for which draft proposals already exist include

- Continuation of the existing research association "Stoffgesetze für Steinsalz" (C*onstitutive Laws for Rock Salt*) with the same partners
- Integrity analyses by Federal Institute for Geosciences and Natural Resources (BGR) and IfG within the scope of the concept development for a repository for heat-generating radioactive waste in bedded salt structures in Germany and studies on the applicability of the safety and demonstration concepts developed for a repository in domal salt
- Further development of the numerical tools for simulating the THM processes taking place in a repository in salt; research proposal of TUC together with other partners, including Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) GmbH
- and Lawrence Berkeley National Laboratory

The summarised key aspects of this position paper were presented in a short lecture by Ms Fahland (BGR) at the 4th Salt Club Meeting (February 25, 2015). It was suggested that the current status of research on the geomechanical integrity analysis of the geological barrier in salt be compiled in a NEA report (among others based on the results of VSG and other R&D projects that have been carried out since the beginning of the 1990s). The report is coordinated by BGR (Ms Fahland) and IfG (Mr Popp); the report is to be completed by the end of 2016.

Prof. Stahlmann, Technische Universität Braunschweig (TUBS), suggested that a research association with several partners be formed on the topic "Validierung der Kriterien zur Bewertung der Integrität" (*Validation of the Criteria to Assess Integrity*); detailed plans have yet to be made.

2.6 References

BMU. 2010. Federal Ministry for the Environment. Nature Conservation and Nuclear Safety (BMU, now BMUB): *Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste*. Bonn, state: September 30, 2010.

Berest, P., P. A. Blum, J. P. Charpentier, H. Gharbi, and F. Vales. 2005. *Very Slow Creep Tests on Rock Samples*. International Journal of Rock Mechanics & Minerals Society 42.

Beuth, T., G. Bracke, D. Buhmann, C. Dresbach, S. Keller, J. Krone, A. Lommerzheim, J. Mönig, S. Mrugalla, A. Rübel, and J. Wolf. 2012. *Szenarienentwicklung: Methodik und Anwendung*, Vorläufige Sicherheitsanalyse für den Standort Gorleben. GRS-284, ISBN978-3-939355-60-1. GRS mbH, Köln, Germany.

Czaikowski, O., K. Wieczorek, and U. Hertes. 2015. *Sealing Capacity of a Seal System in Rock Salt – Hydraulic Impact of the EDZ Long-Term Evolution*. Proceedings of the 49th US Rock Mechanics/Geomechanics Symposium. San Francisco, CA.

Eickemeier, R., S. Heusermann, M. Knauth, W. Minkley, H.-K. Nipp, and T. Popp. 2013. *Preliminary Safety Analysis of the Gorleben Site: Thermo-mechanical Analysis of the Integrity of the Geological Barrier in the Gorleben Salt Formation*. Waste Management 2013 Conference. Phoenix, AZ.

ESK. 2013. *STELLUNGNAHME für den Langzeitsicherheitsnachweis für das Endlager für Radioaktive Abfälle Morsleben (ERAM).*
http://www.entsorgungskommission.de/downloads/sneram31012013.pdf.

Hampel, A., J. G. Argüello, F. D. Hansen, R.-M. Günther, K. Salzer, W. Minkley, K.-H. Lux, K. Herchen, U. Düsterloh, A. Pudewills, S. Yildirim, K. Staudtmeister, R. Rokahr, D. Zapf, A. Gährken, C. Missal, and J. Stahlmann. 2013. *Benchmark Calculations of the Thermo-Mechanical Behavior of Rock Salt - Results from a US-German Joint Project.* Proceedings of the 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA.

Hampel, A., R.-M. Günther, K. Salzer, W. Minkley, A. Pudewills, S. Yildirim, R. Rokahr, A. Gährken, C. Missal, J. Stahlmann, K. Herchen, and K.-H. Lux. 2015. *Joint Project III on the Comparison of Constitutive Models for the Thermo-Mechanical Behavior of Rock Salt - I. Overview and results from model calculations of healing of rock salt.* In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

Hansen, F. D. and T. Popp. 2015. *Geomechanics Issues Regarding Heat-Generating Waste Disposal in Salt*. Proceedings of the 49th US Rock Mechanics/Geomechanics Symposium. San Francisco, CA. SAND2015-1234C. Sandia National Laboratories, Albuquerque, NM.

Hansen, F. D., T. Popp, K. Wieczorek, and D. Stührenberg. 2014. *Salt Reconsolidation Principles and Applications*. Nuclear Energy Agency Report. SAND2014-4502P. Sandia National Laboratories, Albuquerque, NM.

Joint Project I. 2004-2006. *The Modeling of the Mechanical Behavior of Rock Salt: Comparison of Current Constitutive Models and Modeling Procedures.* FKZ 02C1004 to 1054. Joint Project II. 2007-2010. *Comparison of Current Constitutive Models and Modeling Procedures Based on 3-D Model Calculations for Long-Term Mechanical Behavior of Real Underground Structures in Rock Salt*. FKZ 02C1577 to 1617. Joint Project III. 2010-2016. *Comparison of Current Constitutive Models and Modeling Procedures Based on Model Calculations for the Thermo-Mechanical Behavior and the Healing of Rock Salt. FKZ 02E10810 to 10860.*

Kock, I., R. Eickemeier, G. Frieling, S. Heusermann, M. Knauth, W. Minkley, M. Navarro, H.-K. Nipp, and P. Vogel. 2012. *Integritätsanalyse der Geologischen Barriere, Bericht zum Arbeitspaket 9.1, Vorläufige Sicherheitsanalyse für den Standort Gorleben*. GRS-286.

Kröhn, K.-P., D. Stührenberg, M. Herklotz, U. Heemann, C. Lerch, and M. Xie. 2009. *Restporosität und -Permeabilität von Kompaktierendem Salzgrus-Versatz; Projekt REPOPERM - Phase 1*. Abschlussbericht, FKZ 02 E 10477 (BMWi), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) GmbH. GRS-254. Köln.

Kröhn, K.-P., C.-L. Zhang, O. Czaikowski, D. Stührenberg, and U. Heemann. 2015. *The Compaction Behavior of Salt Backfill as a THM-Process*. FKZ 02 E 10740 (BMWi). In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

Minkley, W., U. Wüste, T. Popp, D. Naumann, M. Wiedemann, J. Bobinsky, and J. Tejchman. 2010. *Beweissicherungsprogramm zum Geomechanischen Verhalten von Salinarbarrieren nach Starker Dynamischer Beanspruchung und Entwicklung einer Dimensionierungsrichtlinie zum Dauerhaften Einschluss*. 214 Seiten, BMBF-Projekt FKZ 02C1264. Institut für Gebirgsmechanik (IFG). Leipzig, Germany.

Minkley, W. and M. Knauth. 2014. *Integrity of Rock Salt Formation under Static and Dynamic Impact.*. Salt Club Workshop Proceedings: Natural Analogues for Safety Cases of Repositories in Rock Salt. Braunschweig, Germany. http://www.oecd-nea.org/rwm/docs/2013/rwm-r2013-10.pdf .

Minkley, W., M. Knauth, and D. Brückner. 2013. *Discontinuum-Mechanical Behaviour of Salt Rocks and the Practical Relevance for the Integrity of Salinar Barriers*. Proceedings of the 47th US Rock Mechanics/Geomechanics Symposium. San Francisco, CA.

Müller-Hoeppe, N., M. Breustedt, O. Czaikowski, K. Wieczorek, and J. Wolf. 2012. *Integrität Geotechnischer Barrieren –Teil 2*: *Vertiefte Nachweisführung.* Vorläufige Sicherheitsanalyse für den Standort Gorleben. GRS-288, ISBN 978-3-939355-64-9. Gesellschaft für Anlagen- und Reaktorsicherheit, Köln, Germany.

Neubert, N. 2014. *Standsicherheit von Geotechnischen Barrieren unter Erdbebeneinwirkung, Diplomarbeit TUBAF*.

Popp, T., K. Salzer, O. Schulze, and D. Stührenberg. 2012. *Hydromechanische Eigenschaften von Salzgrusversatz - Synoptisches Prozessverständnis und Datenbasis*. Memorandum, Institut für Gebirgsmechanik (IFG), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). Leipzig, Germany.

Rath, J. S. and J. G. Argüello. 2012. *Revisiting Historic Numerical Analyses of the Waste Isolation Pilot Plant (WIPP) Room B and D in situ Experiments Regarding Thermal and Structural Response*. SAND2012-7525.

Thomauske, B., and F. Charlier. 2013. *Forschungs- und Entwicklungsbedarf auf Basis der Erkenntnisse aus der VSG sowie Empfehlungen.* Vorläufige Sicherheitsanalyse für den Standort Gorleben. GRS-304, ISBN 978-3-939355-83-0. GRS GmbH, Köln, Germany.

Warren, J. K. 2005. *Evaporites: Sediments, Resources and Hydrocarbons*. Springer.

3 GEOMECHANICS ISSUES/JOINT PROJECT

3.1 Introduction

This section provides an overview of the collaboration between German partners and SNL within Joint Project III on the comparison of constitutive models for the thermo-mechanical behavior of rock salt. This project began on October 1, 2010, and will end on March 31, 2016, followed by the preparation of a common synthesis report by September 30, 2016. The six German partners are Dr. Andreas Hampel, Mainz, IfG, Leipzig, Karlsruher Institut für Technologie (KIT), Leibniz Universität Hannover, TUBS, and TUC.

The general purpose of the whole Joint Project series is to document, check, and compare modeling tools for the evaluation and proof of the safe disposal of all types of radioactive waste including heat-generating high-level/high-activity (radioactive) waste (HLW, HAW) in deep geological salt formations. These tools comprise constitutive models as well as procedures for the determination of characteristic, salt type-specific parameter values, the generation of rock mechanical models and the performance of numerical calculations.

The huge progress in computer technology in the last 30 years with a much faster and dramatically more powerful hardware and essentially further developed numerical software systems have enabled experts to calculate much larger and more detailed computer models of repositories in geological formations (Rath & Argüello 2012, Argüello & Holland 2015). However, the big advances in calculation capabilities are only beneficial when the used constitutive models and modeling procedures also meet very high demands. These demands result from the fact that the evaluation of the long-term integrity of the geological barrier requires an extrapolation of a highly nonlinear deformation behavior to up to 1 million years, while the underlying experimental investigations in the laboratory or *in situ* have a duration of only days, weeks or at most some years.

3.2 History

For several decades, different institutions have gained a broad understanding and knowledge of the thermo-mechanical behavior of rock salt with many experimental investigations in the laboratory and in the underground. On this basis, several constitutive models for the physical description of this behavior and its dependences on relevant boundary conditions were developed and continuously improved. The models are used for numerical calculations in all phases from the planning and construction of an underground repository through the stability analysis in the operational period up to the closure of the underground openings and the evaluation and proof of the long-term integrity of the geological barrier.

In the past, constitutive models and procedures were developed by several groups in parallel and mostly independently. Shortly after the year 2000, Udo Hunsche and Otto Schulze at BGR Hannover proposed a common project with other model developers for the documentation, discussion, and comparison of their models and modeling procedures (Hampel et al. 2007).

In April 2004, the first Joint Project was started with six German partners: BGR Hannover, Dr. Hampel, Mainz, IfG Leipzig, KIT Karlsruhe, LU Hannover, and TUC. The main objective was to investigate and compare with benchmark calculations the ability of the models to describe the basic and most important deformation phenomena in rock salt, i.e. transient and steady-state creep, the evolution of damage and dilatancy, creep failure and short-term strength, post-failure behavior and residual strength. For this purpose, numerous back-calculations of specific laboratory deformation tests and simulations of typical *in situ* situations were performed by each participant with his constitutive model and his typically used numerical calculation program (Schulze et al. 2007, Hou et al. 2007, Hampel et al. 2007, 2010b).

In Joint Project II (2007–2010), the study was continued with commonly defined benchmark calculations of a 3-D section of the Angersdorf salt mine in Northern Germany. This work included extrapolations of the calculated mechanical behavior of the surrounding rock salt for at least 100 years into the future, and estimations of the permeability in the damaged rock zone (DRZ) based on the calculated dilatancy (Hampel et al. 2010 a; b, Salzer et al. 2012, Hampel et al. 2012).

3.3 Current Joint Project III

In the current Joint Project III, selected benchmark calculations have been performed in order to document, check, and compare the abilities of the involved models to describe correctly

I. the temperature influence on the deformation of rock salt, and

II. the damage and dilatancy reduction and healing of rock salt.

After the disposal of heat-generating radioactive waste, the temperature of the surrounding rock salt increases to higher values, maximum values depend on the disposal concept. This heating has a dramatic influence on the salt ductility, because on the microscale the creep of rock salt is a thermally activated deformation process. Therefore, an increase of temperature results in much higher convergence rates, a quicker closure of residual gaps, and a faster convergence of the surrounding rock salt against backfill materials and geotechnical barrier systems. This leads to the reduction of the differential stress and an increase of the confining stress (minimum principal stress). Therefore, cracks and other open pathways in the DRZ close and eventually heal. An important consequence is the decrease of permeability in the DRZ to immeasurably small values of the original intact salt. The correct and reliable modeling of these effects and consequences is therefore essential to the correct evaluation of the time-dependent restoration of integrity of the geological barrier in the post-operational phase of an underground repository.

This Joint Project III is carried out following the same stepwise procedure that was developed in the previous projects. It consists of the performance of systematic series of specific laboratory tests by the partners IfG and TUC, back-calculations by each partner of the lab tests in order to check and verify the correct modeling of the considered phenomena, and simulations of typical *in situ* situations for the demonstration of the applicability of the tools.

3.3.1 Experimental investigations

The modeling of the temperature influence is investigated for both domal salt of type “Speisesalz” from the Asse II salt mine in Northern Germany and for bedded salt of types “clean salt” and “argillaceous salt” from WIPP in New Mexico, USA (Hampel et al. 2013, Düsterloh et al. 2015, Salzer et al. 2015). The lab tests comprise creep tests and strength tests. The creep tests were performed at different temperatures (299, 333, 363 K), with various stress differences between 10 and 22 MPa and a constant confining stress of 20 MPa to ensure a stress condition below the dilatancy boundary, i.e. damage-free creep. The strain-rate-controlled strength tests were performed at different temperatures (300, 333, 373 K) with different confining stresses (0.2 … 20 MPa) and applied strain rates of 1E-5 1/s (Asse salt) and additionally 1E-4 and 1E-6 1/s (WIPP salt). In these tests, the dilatancy boundary is exceeded at an early stage, thus the focus here is on the damage and dilatancy evolution in the pre- and post-failure phases.

The modeling of the damage and dilatancy reduction was studied with additional healing tests so far only for the Asse salt. The experimental determination is difficult because it requires a stable and leakage-free measurement of extremely small volume changes over hundred days or more. Therefore, the testing machinery at the TUC lab had to be developed further, and in the remaining project time only two reliable tests could be performed at 323 and 333 K. In these tests, the dilatancy boundary was exceeded for a limited time period to introduce a certain amount of damage, followed by a period of about 150 days with a decrease of the stress difference to measure the dilatancy reduction, i.e. the volume decrease due to the closure of the previously induced microcracks (Hampel 2015). The investigation of this behavior in WIPP salt is planned to be a subject in another Joint Project after the current one. (See below.)

3.3.2 Back-calculations of lab tests

The lab tests are back-calculated by every partner for two reasons: The first and main objective is to check if the constitutive models are appropriate to correctly describe the investigated behavior and its dependences on *in situ* relevant boundary conditions. In the laboratory, the behavior can be investigated under well-defined and controlled conditions. In contrast, in the vicinity of drifts and rooms in the underground there is a complex superposition of different deformation phenomena under continually changing conditions through the convergence of the openings and resulting stress redistributions.

A second purpose of the adjustments of the constitutive models to lab test curves is to determine a unique set of constant salt type-specific parameter values and, thus, to thoroughly characterize the specific behavior of the investigated salt type. See an example in Figure 3.1 (Hampel et al. 2013, Hampel 2015).

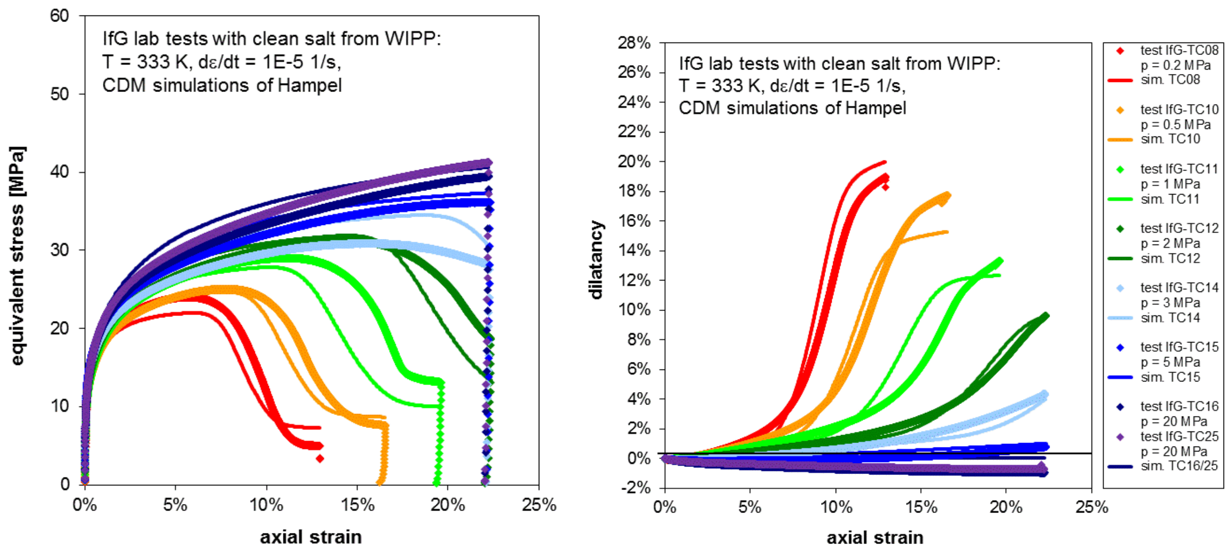

Figure 3.1. Example for the adjustment of a constitutive model (here: CDM of Hampel) to IfG strength tests with "clean salt" from WIPP at an elevated temperature with different confining stresses p = 0.2 … 20 MPa. The evolution of damage and dilatancy increases and the failure strength (maximum equivalent stress) decreases with decreasing confining stress.

The work within the Joint Projects has shown that a further improved agreement between the results of benchmark simulations and *in situ* measurements can be achieved, when after the general determination of parameter values some (mostly not more than one or two) values are modified with a subsequent adjustment of the model to data from an *in situ* measurement. See Figure 3.2 on the left. This is beneficial because in the laboratory the number of specimens and test conditions are necessarily limited. With an additional "*in situ* adjustment," specific features of the particular underground situation and modeling simplifications can be taken into account.

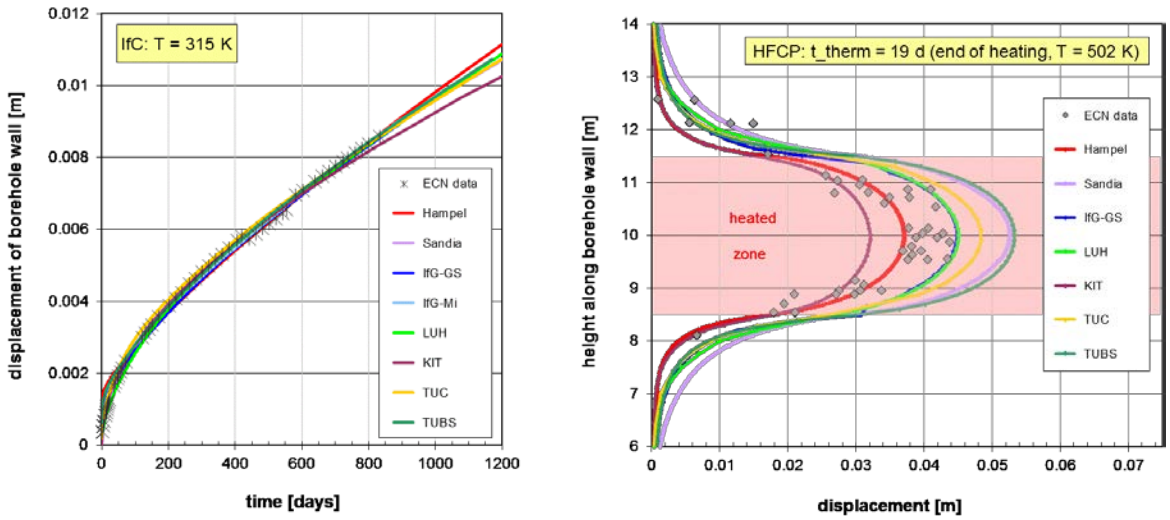

Figure 3.2. Left: The constitutive models were adjusted to the ECN measurement of the IFC of the unheated deep borehole in the Asse II salt mine for a fine-tuning of one or two parameter values as a basis for the HFCP simulation. Right: Comparison of the calculated temperature-dependent increase of displacements along the borehole wall in the heated section.

3.3.3 Simulations of heated *in situ* structures

The *in situ* example for the temperature influence on the deformation of domal rock salt consists of a deep, 300 m long, vertical borehole in the Asse II salt mine (Hampel et al. 2013). It was dry-drilled in December 1979 from a chamber at the 750 m level down to a depth of 1050 m below ground. Three days after the deepest point of drilling was reached, the Netherlands Energy Foundation (ECN) started isothermal free convergence (IFC) measurements in the unconstrained and unheated borehole at a borehole depth of 292 m (1042 m below ground); the measurements were continued for 830 days (Doeven et al 1983, Vons 1984). See Figure 3.3 on the right.

In July 1983, i.e. 1304 days after the end of drilling, three heaters with a total height of 3 m and their center at a depth of 231 m below the chamber (981 m below ground) were switched on in the Asse borehole for Heated Free Convergence Probe (HFCP) measurements (Lowe & Knowles 1989). After a period of 19 days with a free convergence of the borehole, the heaters were turned off because the probe was about to come in contact with the borehole wall. ECN continued the free convergence measurements in the subsequent cool-down phase for another 3 days, i.e. the experiment ended 22 days after the start of heating. Despite some uncertainties and simplifications, the calculated temporal evolution of the borehole wall displacements in the center of the heated zone during the heating period are in good agreement with the convergence histories measured by ECN. See Figure 3.3 on the right (Hampel et al. 2013).

As an *in situ* example for the temperature influence in bedded salt, simulations of the isothermal Room D and the heated Room B at WIPP were performed by each partner with his constitutive model and the parameter values from the lab test adjustments to both clean salt and argillaceous salt. In late 1979 and in the 1980s, SNL had equipped the two rooms at approximately 655 m below ground surface with a large instrumentation array and performed many *in situ* measurements. The Mining Development Test at Room D and the Overtest for Simulated Defense High-Level Waste at Room B were part of the Thermal/Structural Interactions Program (Munson et al. 1988, Munson et al. 1990).

Both rooms are equal in size and geometry with a length of 93.3 m and a square cross section of 5.5 m x 5.5 m. (See Figure 3.3.) While Room D remained at natural rock temperature of 300 K, Room B was heated with an array of heaters placed in boreholes 2.21 to 4.80 m below the floor. During the tests, the rooms were thermally isolated at both ends from the ventilation drifts. Because of the symmetry, only one half of a vertical cut through the center of the rooms was calculated in the benchmark simulations with plane strain conditions. The heating of Room B started 354 days after the excavation and reached at the end a temperature of about 400 K. See Figure 3.4 for an example from Composite Dilatancy Model (CDM) calculations of Hampel, more results from these benchmark simulations are shown in his presentation in Appendix F in this volume.

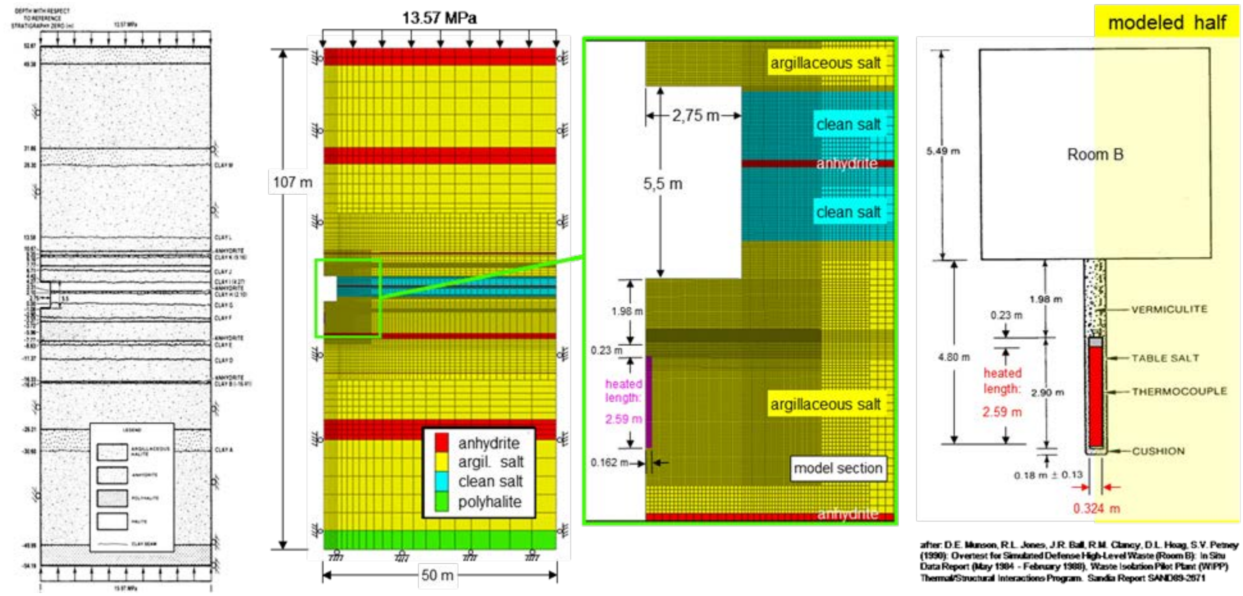

Figure 3.3. Left: Local stratigraphy at WIPP. Center: Total FLAC3D calculation model and enlarged section close to Room D / B (clay layers were considered). Right: Sketch of a vertical cut through Room B and a heater located in a borehole below the floor.

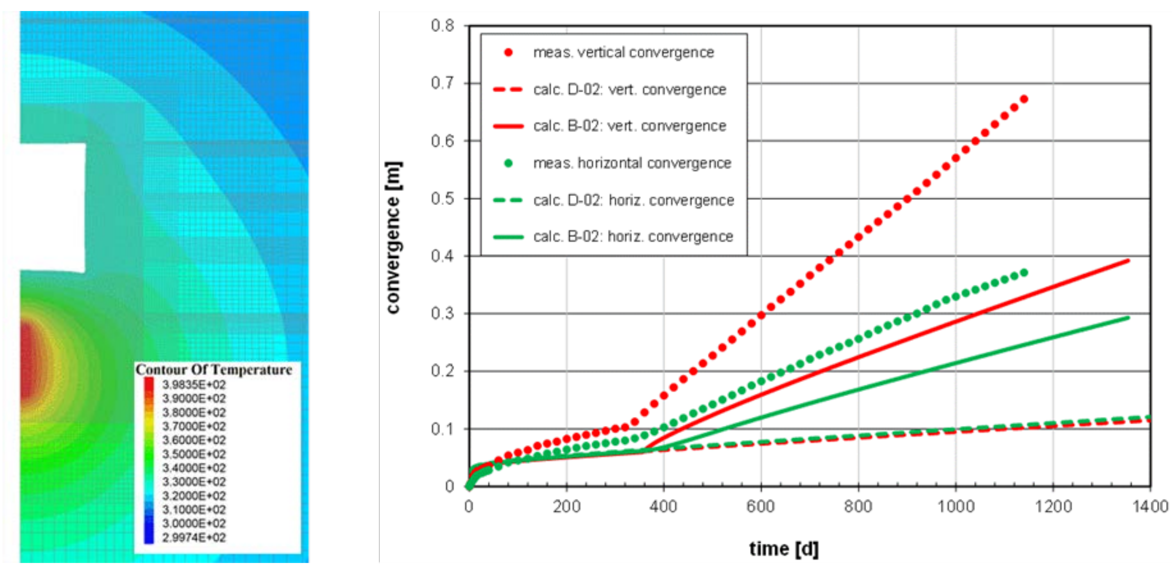

Figure 3.4. Left: Calculated temperature distribution around WIPP Room B at end of simulation (t = 1354 d), i.e. 1000 days after start of heating. Right: Comparison of calculated vertical and horizontal convergences of the unheated Room D and heated Room B with measurements of Sandia in Room B.

Figure 3.4 shows on the right a comparison of calculated and measured room convergences. The deviation of the results especially for Room B is explained with an insufficient knowledge because of insufficient experimental findings on 1) the magnitude of creep rates at small differential stresses, 2) the behavior of layer boundaries like the sliding on clay seams leading to an enhanced horizontal convergence, and 3) the formation and opening of tensile cracks above the room leading to a slab separation and, therefore, an enhanced vertical convergence. These subjects shall be investigated in another Joint Project after the current one.

3.3.4 Simulation of damage reduction around a bulkhead

As a real *in situ* example for the damage and dilatancy reduction in rock salt, the partners have selected an old bulkhead structure in the Asse II salt mine. The corresponding drift was excavated in 1911 on the 700 m level of the mine. Three years later, a 25 m long section of the drift was lined with a cast steel tube. The residual gap between the tube and the salt contour was filled with concrete. Figure 3.5 shows the numerical calculation model of one half of a vertical cut through the drift with bulkhead. The simulation ended 85 years after the bulkhead installation, i.e. 88 years after the excavation of the drift (Hampel et al. 2015).

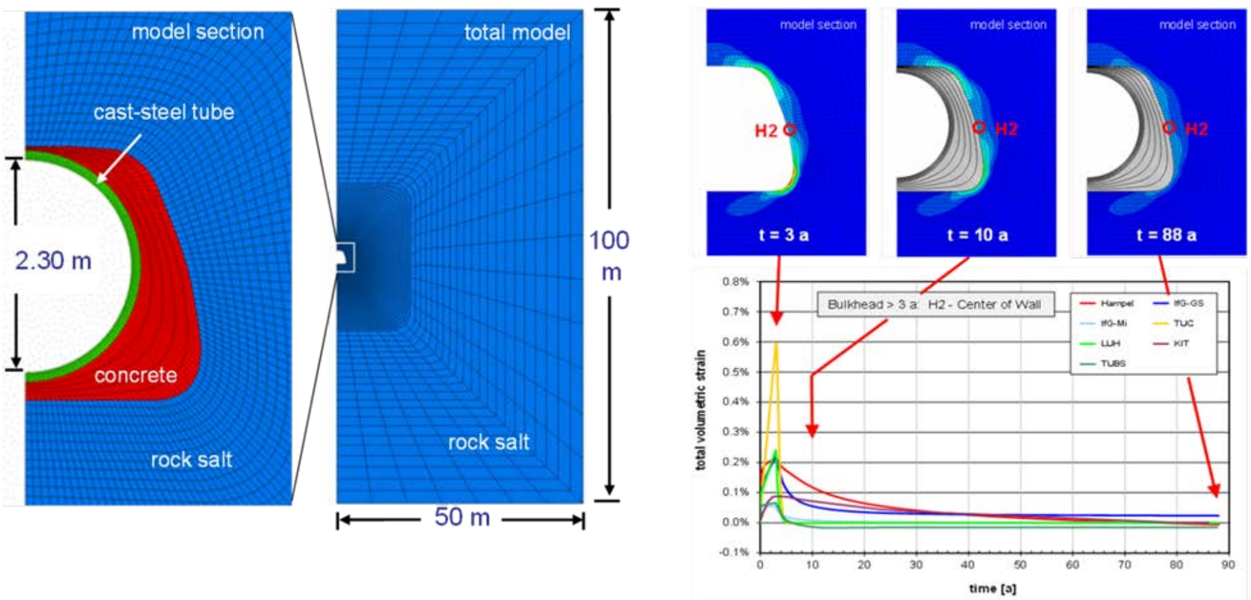

Figure 3.5. Left: FLAC3D model of one half of a vertical cut through a drift with bulkhead and the surrounding rock salt in the Asse II salt mine. Right: In the first 3 years with open drift, a DRZ evolves at the drift contour. After 3 years, the bulkhead is installed and the salt begins to creep against the bulkhead. Therefore, the stress differences are reduced and damage and dilatancy in the DRZ decrease.

In Figure 3.5 on the right, the calculated upper contour plots show different stages of the simulation. In the first 3 years before the installation of the bulkhead, a DRZ evolves around the open drift. After the installation, the simulation shows the reduction of damage and dilatancy in the DRZ. The temporal evolution of this decrease is shown in the lower right diagram of Figure 3.5. Here, differences among the reduction rates calculated by the partners are visible. The main reason for these differences is the very small number of reliable laboratory healing tests. More systematic and well-controlled high-precision lab tests are needed for a better understanding and an improved modeling of the dependence of damage reduction on temperature and stress state.

3.4 Conclusions and outlook

The back-calculations and the simulations of the selected underground structures were performed successfully and demonstrate the applicability of the involved constitutive models. The advanced models cover many phenomena of the thermo-mechanical behavior and their dependences on *in situ* relevant boundary conditions in a wide range. The results show that the partners do have appropriate tools for model calculations of the thermo-mechanical behavior of rock salt around underground repositories for a final disposal of radioactive waste including heat-generating HLW.

Generally, the results of the partners agree well with each other and with experimental results from the laboratory and from *in situ* measurements. The remaining bandwidth of results can be explained with differences in the physical principles of the constitutive models and in the determination of unique salt-type-specific parameter values. Although for all models the same experimental data were provided for the determinations, the data are used in different ways due to the different formulations and physical principles of the models.

A few larger differences occurred during the simulations of *in situ* structures. They can be attributed to still existing insufficient knowledge of the corresponding deformation phenomena, mainly because of a still insufficient number of related experimental investigations. Therefore, the performance and results of the simulations have helped to identify necessary specific experiments and revealed hints for the improvement and further development of the models.

The most important subjects for the further development of the models and modeling procedures based on new systematic experimental investigations have been identified as follows:

- Deformation behavior at small deviatoric stresses
- Influence of temperature and stress state on the damage reduction
- Deformation behavior resulting from tensile stresses
- Influence of inhomogeneities (layer boundaries, interfaces) on deformation

These subjects shall be explored experimentally and theoretically in a planned new Joint Project of the partners Dr. Hampel, IfG Leipzig, LU Hannover, TUBS, TUC, and SNL. The working title is “Joint project: Further development and qualification of the rock mechanical modeling for a HLW disposal in rock salt.” The project is being planned to begin soon after the current one, run for three years, and the German partners be funded by the BMWi and managed by the PTKA.

According to the current funding regulations (BMWi & PTKA 2015), the focus of the new project will be on bedded salt. Therefore, the experiments shall be performed again with “clean salt” from WIPP, new core material for testing is planned to be delivered by Sandia to IfG Leipzig and TUC. The theoretical work on the four identified subjects will comprise the analysis, discussion, physical description of the phenomena with the further developed constitutive models and modeling procedures, and their implementation into numerical calculation codes. This will be accompanied by numerical simulations of exemplary detail models of typical underground situations in bedded salt, e.g. Rooms D and B at WIPP.

Finally, the gained progress will be checked and verified with a complex 3-D demonstration model (“virtual demonstrator”) consisting of a drift with seal system in a generic repository in bedded salt similar to the geological situation at WIPP. Therefore, the new Joint Project will offer the chance to strengthen and deepen the US-German collaboration on the disposal of radioactive waste including HLW in rock salt.

3.5 References

Argüello, J. G. and J. Holland. 2015. *Two Problems to Benchmark Numerical Codes for Use in Potential HLW Salt Repositories*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

BMWi & PTKA. 2015. *Forschung zur Entsorgung radioaktiver Abfälle – Förderkonzept des BMWi (2015-2018)*. Bundesministerium für Wirtschaft und Energie (BMWI), Referat IIA5 "Reaktorsicherheits- und Endlagerforschung, Uranbergbausanierung" und Projektträger Karlsruhe – Wassertechnologie und Entsorgung (PTKA-WTE), Karlsruher Institut für Technologie.

Doeven, I., P. P. Soullié, and L. H. Vons. 1983. *Convergence Measurements in the Dry-Drilled 300 m Borehole in the Asse II Saltmine*. European Appl. Res. Rept. Nucl. Sci. Technol. 5(2).

Düsterloh, U., K. Herchen, K.-H. Lux, K. Salzer, R.-M. Günther, W. Minkley, A. Hampel, J. G. Argüello, and F. D. Hansen. 2015. *Joint Project III on the Comparison of Constitutive Models for the Thermo-Mechanical Behavior of Rock Salt - III. Extensive Laboratory Test Program with Argillaceous Salt from WIPP and Comparison of Test Results*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

Hampel, A. 2015. *Description of Damage Reduction and Healing with the CDM Constitutive Model for the Termo-Mechanical Behavior of Rock Salt*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

Hampel, A., J. G. Argüello, F. D. Hansen, R.-M. Günther, K. Salzer, W. Minkley, K.-H. Lux, K. Herchen, U. Düsterloh, A. Pudewills, S. Yildirim, K. Staudtmeister, R. Rokahr, D. Zapf, A. Gährken, C. Missal, and J. Stahlmann. 2013. *Benchmark Calculations of the Thermo-Mechanical Behavior of Rock Salt - Results from a US-German Joint Project*. In L. J. Pyrak-Nolte, A. Chan, W. Dershowitz, J. Morris & J. Rostami (eds.): Proceedings of the 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA. ARMA 13-456. American Rock Mechanics Association (ARMA).

Hampel, A., R.-M. Günther, K. Salzer, W. Minkley, A. Pudewills, B. Leuger, D. Zapf, R. Rokahr, K. Herchen, R. Wolters, and U. Düsterloh. 2010a. *Vergleich aktueller Stoffgesetze und Vorgehensweisen anhand von 3D-Modellberechnungen zum mechanischen Langzeitverhalten eines realen Untertagebauwerks im Steinsalz. – Abschlussbericht zum BMBF-Verbundprojekt (FKZ 02C1577-1617)*, Final Report of Joint Project II (in German), Projektträger Karlsruhe - Wassertechnologie und Entsorgung (PTKA-WTE), Karlsruher Institut für Technologie (KIT).

Hampel, A., R.-M. Günther, K. Salzer, W. Minkley, W. Pudewills, B. Leuger, D. Zapf, K. Staudtmeister, P. Rokahr, K. Herchen, R. Wolters, K.-H. Lux, O. Schulze, U. Heemann, and U. Hunsche. 2010b. *Benchmarking of Geomechanical Constitutive Models for Rock Salt*. Proceedings of the 44th US Rock Mechanics/Geomechanics Symposium, Salt Lake City, UT. ARMA10-287. American Rock Mechanics Association (ARMA).

Hampel, A., R.-M. Günther, K. Salzer, W. Minkley, A. Pudewills, S. Yildirim, R. Rokahr, A. Gährken, C. Missal, J. Stahlmann, K. Herchen, and K.-H. Lux. 2015. *Joint Project III on the Comparison of Constitutive Models for the Thermo-Mechanical Behavior of Rock Salt - I. Overview and results from model calculations of healing of rock salt*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

Hampel, A., K. Salzer, R. –M. Günther, W. Minkley, A. Pudewills, B. Leuger, D. Zapf, K. Staudtmeister, R. Rokahr, K. Herchen, R. Wolters, and K.-H Lux. 2012. *Joint Projects on the Comparison of Constitutive Models for the Mechanical Behavior of Rock Salt - II. Overview of the Models and Results of 3-D Benchmark Calculations*. In P. Bérest, M. Ghoreychi, F. Hadj-Hassen & M. Tijani (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VII. Paris. London: Taylor & Francis Group (Balkema).

Hampel, A., O. Schulze, U. Heemann, F. Zetsche, R.-M. Günther, K. Salzer, W. Minkley, Z. Hou, R. Wolters, U. Düsterloh, D. Zapf, R. Rokahr, and A. Pudewills. 2007. *Die Modellierung des mechanischen Verhaltens von Steinsalz: Vergleich aktueller Stoffgesetze und Vorgehensweisen*. – Abschlussbericht zum BMBF-Verbundprojekt (FKZ 02C1004-1054), Final Report of Joint Project I (in German), Projektträger Karlsruhe - Wassertechnologie und Entsorgung (PTKA-WTE), Karlsruher Institut für Technologie (KIT).

Hou, Z., R. Wolters, U. Düsterloh, R. Rokahr, D. Zapf, K. Salzer, R.-M. Günther, W. Minkley, A. Pudewills, U. Heemann, O. Schulze, F. Zetsche, and A. Hampel. 2007. *Comparison of Advanced Constitutive Models for the Mechanical Behavior of Rock Salt - Results from a Joint Research Project - II. Numerical Modeling of Two in situ Case Studies and Comparison*. In K.-H. Lux, W. Minkley, M. Wallner, and H.R. Hardy, Jr. (eds.): Basic and Applied Salt Mechanics; Proceedings of the Mechanical Behaviour of Salt VI. Hannover. London: Taylor & Francis (Balkema).

Lowe, M. J. S. and N. N. Knowles. 1989. COSA II: *Further Benchmark Exercises to Compare Geomechanical Computer Codes for Salt*. Final report No. EUR 12135 EN. ISBN 92-825-9943-4. Luxembourg: Office for Official Publications of the European Communities.

Munson, D.E., R. L. Jones, J. R. Ball, R. M. Clancy, D. L. Hoag, and S. V. Petney. 1990. *Overtest for Simulated Defense High-Level Waste (Room B): In Situ Data Report (May 1984 - February 1988).* Waste Isolation Pilot Plant (WIPP), Thermal/Structural Interactions Program. SAND89-2671. Sandia National Laboratories, Albuquerque, NM.

Munson, D. E., R. L. Jones, D. L. Hoag, and J. R. Ball. 1988. *Mining Development Test (Room D): In Situ Data Report (March 1984 - May 1988).* Waste Isolation Pilot Plant (WIPP), Thermal/Structural Interactions Program. SAND88-1460. Sandia National Laboratories, Albuquerque, NM.

Rath, J. S. and J. G. Argüello. 2012. *Revisiting Historic Numerical Analyses of the Waste Isolation Pilot Plant (WIPP) Room B and D in situ Experiments Regarding Thermal and Structural Response*. SAND2012-7525. Sandia National Laboratories, Albuquerque, NM.

Salzer, K., R.-M. Günther, W. Minkley, T. Popp, M. Wiedemann, A. Hampel, A. Pudewills, B. Leuger, D. Zapf, K. Staudtmeister, R. Rokahr, K. Herchen, R. Wolters, and K.-H. Lux. 2012. *Joint Projects on the Comparison of Constitutive Models for the Mechanical Behavior of Rock Salt - I. Overview of the Projects, Reference Mine for 3-D Benchmark Calculations, in situ Measurements and Laboratory Tests*. In P. Bérest, M. Ghoreychi, F. Hadj-Hassen & M. Tijani (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VII. Paris. London: Taylor & Francis Group (Balkema).

Salzer, K., R.-M. Günther, W. Minkley, D. Naumann, T. Popp, A. Hampel, K.-H. Lux, K. Herchen, U. Düsterloh, J. G. Argüello, and F. D. Hansen. 2015. *Joint Project III on the Comparison of Constitutive Models for the Thermo-Mechanical Behavior of Rock Salt - II. Extensive Laboratory Test Program with Clean Salt from WIPP*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

Schulze, O., U. Heemann, F. Zetsche, A. Hampel, A. Pudewills, R.-M. Günther, W. Minkley, K. Salzer, Z. Hou, R. Wolters, R. Rokahr, and D. Zapf. 2007. *Comparison of Advanced Constitutive Models for the Mechanical Behavior of Rock Salt – Results from a Joint Research Project - I. Modeling of Deformation Processes and Benchmark Calculations*. In K.-H. Lux, W. Minkley, M. Wallner, and H.R. Hardy, Jr. (eds.): Basic and Applied Salt Mechanics; Proceedings of the Mechanical Behaviour of Salt VI. Hannover. London: Taylor & Francis (Balkema).

Vons, L. H. 1984. *Measurements in the 300 m deep dry-drilled borehole and feasibility study on the dry-drilling of a 600 m deep borehole in the Asse II Saltmine*. Progress report covering the period 1-1-1984–31-12-1984. Petten: Netherlands Energy Research Foundation ECN.

4 DRIFT SEALS MADE OF CONCRETE – STATE OF THE ART IN GERMANY

When closing a final repository for radioactive waste in rock salt in Germany, drift seals are part of the sealing system. In connection with the closure of the Morsleben repository as well as the precautionary measures of the emergency concept for the Asse repository, drift seals made of salt concrete were planned or are under construction in order to contribute to long-term safety. Depending on the binding agent of the salt concretes – cement or MgO – they are named salt concrete (cement) or sorel concrete (MgO). During the last decade, several full-scale pilot seals were installed and have been investigated. The status of the investigations and their results are summarized below. The *in situ* investigations of drift seals have been supplemented by *in situ* tests of functional components within the scope of R&D projects.

4.1 Drift seals made of salt concrete (cement)

Two pilot drift seals made of salt concrete have been investigated, the Asse Seal and the ERAM *in situ* Test Seal, which is still going on.

The Asse Seal is situated in the Asse repository (Gläß et al. 2005). It was made of salt concrete (Type Asse). It was concreted in sections (block by block) in 1990. The remaining gap in the roof was closed manually by tamping salt concrete into it. In the meantime, the seal has been abandoned and is no longer accessible. The Asse Seal was investigated by permeability, stress, and ultrasonic measurements that mainly focused on the contact zone. Except in the roof (former gap), the permeability measurements showed permeability values (gas) in the range of 6.0E-19 m² to 4E-24m² (Mauke et al. 2006). The results were confirmed by investigations of core samples from the sealing body as well as the contact zone. These investigations have been performed by two different laboratories, independently (IBeWA 2007, Czaikowski et al. 2015). Within the framework of an R&D project, a geostatistical approach was applied for the permeability values measured *in situ* at several individual points in order to assess the integral permeability of a spatially extended structure and to investigate the influence of local inhomogeneities causing high permeability values. The integral permeability of the structure was calculated to be < 1E-23 m². Additionally, it turned out that local inhomogeneities can be neglected if they remain unconnected and neither penetrate the whole drift nor form fracture networks (Röhlig 2014).

The ERAM *in situ* Test Seal is being performed in the Bartensleben mine of the (Mauke 2013). The drift seal was made of salt concrete called M2. In 2010, it was concreted following an alternative approach to accept joints between dam and contact zone to the rock salt due to autogenous shrinkage and thermal contraction (BfS 2007, Mauke and Herbert 2013). Cracks should be localized by partition plates oriented in a cross-sectional direction, thus not reducing the effective length of the drift seal, and at the former drift contour due to its reduced strength. Afterwards, grouting measures were carried out to achieve sufficient tightness of the drift contour. Near-surface cracks at the edges of the outer cross-section were also predicted numerically; however, beyond that, a horizontal crack of some extent formed and is still under investigation.

In addition to temperature, deformation, stress, and permeability measurements, this *in situ* test seal was furnished with a pressure chamber that was filled with NaCl-brine in mid-2012. Subsequently, the pressure was raised slowly. Recalculation of the structure (August 2012) led to an integral permeability in the range of 2E-16 m² to 6E-18 m² (Mauke 2013). Only a few months later (April 2013), the integral permeability had decreased and showed a significantly smaller range of 8E-18 m² to 3E-18 m² (Mauke and Herbert 2013). The experiment is still going on, and the flow rate has been decreased further (currently lower than 50 ml/d). Although cracks like the unexpected horizontal crack have to be avoided, the results of recalculating the integral permeability showed that cracks do not form a fracture network that penetrates the seal completely, as an integral permeability in the range of 8E-18 m² to 3E-18 m² cannot be reached if cracks visible to the naked eye exist. Thus, the theoretical results of the geostatistical approach gained from the Asse Seal have been confirmed experimentally.

4.2 Drift seals made of sorel concrete (MgO)

A number of pilot drift seals and components made of sorel concrete were investigated, e.g., two pilot seals (PSB A2 and PSB A1) situated in the Asse repository, two tests of functional components (GV1 and GV2) in the CARLA R&D Project performed in the Teutschenthal mine, and a pilot seal that was installed at an anhydrite location in the Bleicherode mine. As recently demonstrated, sorel-building materials are chemically stable also in NaCl-dominated solutions at minimum Mg2+-concentrations. For details, see Freyer et al. (2015).

The PSB A2 pilot seal (Kamlot et al. 2012) was erected in the Asse repository using sorel concrete (29.6 A2) in 2003. It was concreted in layers wet in wet, which mitigated construction jointing. In addition to temperature, deformation and stress measurements, the PSB A2 was also furnished with a pressure chamber. The pressure chamber was filled with $MgCl_2$-rich brine in 2004. The underground observations, the measuring results and the recalculation of the *in situ* experiment using inflow and outflow rates of the seal showed the importance of an accurate EDZ removal, the necessity to use a stiff sorel concrete as well as the importance of a high quality production of sealing structures. Despite improvements of the construction process and the sorel concrete mixture, the required permeability level of 1E-15 m² for the Asse repository was reached one year after brine pressure build-up and it was decreasing further. The integral permeability level was governed by the EDZ.

The PSB A1 pilot seal (Heydorn et al. 2015) was also constructed in the Asse repository in 2007 taking into account the lessons learnt from the PSB A2 pilot seal. The EDZ was removed carefully and sorel concrete A1, which exhibits an elevated stiffness, was used for construction. The concreting process was interrupted due to technical problems. Nevertheless, permeability measurements in boreholes showed integral permeability values from 7E-18 m² to 1.2E-18 m², with local variations in the range of 1.3E-16 m² to 1.5E-18 m² (first measurement). Half a year later a second measurement yielded 2.6E-17 m² to 1.9E-19 m². During that period of half a year, the surrounding rock pressure increased by 2 MPa (from ~5 MPa to ~7 MPa). The pressure chamber of the PSB A1 pilot seal has been filled with $MgCl_2$-rich brine at a pressure of 1 MPa for several years. Indicators for extended cracks forming a fracture network have not been detected so far, neither indirectly by measuring results nor directly by visual borehole investigations. Based on experimental results, cracks were adequately avoided, empirically.

The GV1 and GV2 *in situ* tests were performed within the CARLA R&D Project (Knoll et al. 2010) between 2004 and 2010. Tachhydrite-bearing carnalite seams at the drift contour limited the temperature rise due to hydration to 65 °C. To meet the temperature limit, very small concreting sections were realized using sorel concrete MB10 (GV1). As a result, the small concreting sections showed cracks, and at the drift interface high permeability values were measured. Tracer tests indicated that there were connected transport pathways of high permeability in the structure and in the adjacent drift contour. Thus, the integral permeability measured by pneumatic test shortly after implementation was determined to be 1E-12 m². Alternatively, MgO shotcrete was used in GV2. The pneumatic test after erection and grouting showed an integral permeability level of ~2E-16 m².

Finally, the results of the Bleicherode *in situ* test are outlined briefly (Mauke 2015). The pilot seal is located in an anhydrite formation. It was concreted within 34 hours without interruption in 2010 using Sorel concrete DBM2. An effective gas permeability in the range of 3E-14 m² to 1E-15 m² was estimated (state December 2013). The relatively high permeability was caused by the contact zone between sealing body and surrounding rock. Leakage detected by gas tracers occurred mainly in the floor. Unlike rock salt, anhydrite shows negligible creep, and its mechanical behavior is assumed to be purely elastic. Therefore, neither convergence-induced pressure build-up onto the seal body nor self-healing of the EDZ is expected, even in the long term.

4.3 Conclusions

The investigations of the pilot drift seals led to the conclusions that tight drift seals can be made of both, salt concrete and sorel concrete. The long-term chemical stability of sorel-building materials in contact with NaCl-dominated solutions has been demonstrated (Freyer et al. 2015).

The functionality of a sealing structure is influenced by the construction material, the EDZ of the surrounding rock, and the contact zone between dam and host rock. A careful EDZ removal, a stiff sealing body, and limited crack evolution as well as a good production quality are fundamental to guarantee their functionality. The complex interaction of the dam and the rock in terms of volume changes caused by thermal expansion and contraction due to hydration and pressure build-up as a consequence of rock´s deformation behavior is of major importance (Stahlmann et al. 2015). Therefore, special attention must be paid to the EDZ and the contact zone as well.

4.4 References

Czaikowski, O., K. Wieczorek, and U. Hertes. 2015. *Sealing Capacity of a Seal System in Rock Salt – Hydraulic Impact of the EDZ Long-Term Evolution*. Proceedings of the 49th US Rock Mechanics/Geomechanics Symposium. San Francisco, CA.

Gläß, F., R. Mauke, G. Eilers, J. Preuss, H. Schmidt, C. Lerch, and N. Müller-Hoeppe. 2005. *Investigation of a Salt Concrete Seal in the Asse Salt Mine*. Waste Management 2005 Conference. Tucson, AZ.

IBeWa. 2007. *Untersuchung des Kontaktbereichs am Asse-Vordamm, Bestimmung der hydraulischen Kennwerte.* Abschlussbericht.

BfS. 2007. *Stillegung ERAM –Verfüllen von Strecken mit hohen Anforderungen, Bauzustände für horizontale Strecken (Ergänzende Untersuchungen zum Nachweis der Rissbeschränkung im Salzbeton) und Nachweiskonzept für das südliche Wetterrollloch, Salzgitter.* http://www.bfs.de/SharedDocs/Downloads/BfS/DE/genehmigungsunterlagen/morsleben-pfv/lfdnr094-255-00-v01-p255.pdf .

Freyer, D., M. Gruner, and T. Popp, T. 2015. *Zusammenhang von Chemismus und mechanischen Eigenschaften des MgO-Baustoffs / Relationship between geochemical and geomechanical properties of magnesia building material.* FKZ 02E10880, Project duration: 01.12.2010 – 30.09.2014, Final Report, 150p.

Heydorn, M., L. Teichmann, J. Schneefuß, and T. Meyer. 2015. *Asse II – Anwendungsversuch Pilotströmungsbarriere PSB A1, Fachgespräch "Verschlusssysteme – In situ -Bauwerke aus Magnesiabinder und Dessen Chemisch Mechanische Eigenschaften im Hinblick auf ein HAW-Endlager.* Freiberg, Germany. Materialienband. PTKA-WTE.

Kamlot, P., D. Weise, G. Gärtner, and L. Teichmann. 2012. *Drift Sealing Elements in the Asse II Mine as a Component of the Emergency Concept – Assessment of Hydro-Mechanical Functionality*. In P. Bérest, M. Ghoreychi, F. Hadj-Hassen & M. Tijani (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VII. Paris. London: Taylor & Francis Group (Balkema).

Knoll, P., M. Finder, and W. Kudla. 2010. *Entwicklung eines Grundkonzeptes für Langzeitstabile Streckendämme im Leichtlöslichen Salzgestein (Carnallitit) für UTD/UTV, Teil 2: Erprobung von Funktionselementen, Zusammenfassender Abschlussbericht*. FKZ 02C1204. Teutschenthal.

Mauke, R. 2013. *In situ-Verification of a Drift Seal System in Rock Salt – Operating Experience and Preliminary Results*. Proceedings of the 4th US/German Workshop. Berlin, Germany.

Mauke, R. 2015. *Stillegung ERAM – In situ -Versuch für ein Abdichtbauwerk im Anhydrit im Bergwerk Bleicherode, Verschlusssysteme – In situ -Bauwerke aus Magnesiabinder und Dessen Chemisch Mechanische Eigenschaften im Hinblick auf ein HAW-Endlager*. Freiberg, Germany. Materialienband, PTKA-WTE.

Mauke, R. and H.-J. Herbert. 2013. *Large Scale in situ Experiments on Sealing Constructions in Underground Disposal Facilities for Radioactive Wastes – Examples of Recent BfS- and GRS-Activities.* EUROSAFE Forum 2013. Safe Disposal of Nuclear Waste. Köln, Germany. In Progress in Nuclear Energy 84 (2015).

Mauke, R., N. Müller-Hoeppe, and J. Wollrath. 2006. *Planning, Assessment, and Construction of a Drift Seal in a Salt Repository – Overview of Investigations*. Proceedings of Engineered Barrier Systems (EBS) in the Safety Case: Design Confirmation and Demonstration. Tokyo, Japan. OECD/NEA.

Röhlig, K., E. Plischke, and X. Li. 2014. *Probabilistische Methoden als Hilfsmittel zur Bemessung von Verschlussbauwerken im Salinar*. Technischer Bericht, Institut für Endlagerforschung TU Clausthal.

Stahlmann, J., C. Missal, and A. Gährken. 2015. *Interaction between Salt Concrete Sealing Structures and Rock Salt*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

5 A COMPARISON OF BEDDED AND DOMAL SALT

5.1 Introduction

A topic of great interest at the 6th US/German Workshop on Salt Repository Research Design and Operation was comparison of bedded and domal salt characteristics as they pertain to disposal of heat–generating nuclear waste (spent nuclear fuel and HAW). Motivation from the German perspective is explained by Bollingerfehr et al. in their abstract and presentation contained in the Appendices of these Proceedings.

German partners (BGR, DBE TEC, GRS, and IfG) are currently performing an R&D project called KOSINA (Development of a generic HLW repository concept in bedded salt including safety and safety demonstration concept), the objective of which is to develop both technical site-independent generic repository concepts for a bedded-salt repository for heat generating waste and a safety concept. In the past, bedded salt formations were never actually considered to host a repository for HLW even though bedded salt has been and still is used to host underground hazardous waste disposal facilities. Therefore, the KOSINA project was addressed in BMWi´s new research concept as an important issue to improve knowledge and perform investigations that clarify conceptual questions and to contribute to the technical-scientific basis for the safety oriented evaluation of potential repository systems in host rocks available in Germany.

Since 1987, nuclear waste disposal in the US has concentrated on bedded salt while similar efforts in Germany emphasized geologic domal salt. The US is once again considering possible repository choices and therefore has parallel interests in relevant differentiating characteristics of bedded and domal salt. In Germany and the US rock salt remains one of the potential host rock formations. Because of collaborations in workshops such as this one, salt repository researchers in Germany and the US continue to agree this coincidence provides an excellent opportunity for collaboration. Both countries have advanced salt repository science and engineering developed and applied over several decades for the specific purpose of providing the necessary expertise for developing a safety case for salt disposal. Therefore, it was deemed necessary to create a document that takes credit for this expertise.

A compendium of some description is foreseen that compares and contrasts differences and similarities of bedded and domal salt characteristics at different scales and explores repository implications. In addition to salt repository experience, each country has extensive history of mining and salt exploitation for industrial purposes, which enriches the collective understanding of basic salt physical, mechanical, chemical, petrological, hydrological, and thermal behavior. These assets provide a supporting basis for such a compendium and compelling reasons to undertake this task are evident. The greater question discussed in breakout session at the 6th US/German Workshop on Salt Repository Research, Design, and Operation is how to approach the undertaking. What should be contained in the document? How should it be structured? A consensus developed that such a comparison document holds the potential to be a major contribution to international salt repository R&D as sanctioned by the NEA Salt Club.

5.2 Breakout session suggestions

A breakout session was chaired by Bollingerfehr and Hansen and their associated abstracts and presentations are contained in Appendices E and F in these Proceedings. After animated discussion, a considerable amount of feedback was provided, which is summarized in this sub-section without ascription (anonymous). Principles of what the comparison anthology should try to accomplish, what it should contain, and how it should be created, used, and updated were offered.

5.2.1 Nature of the compendium

- It should be a high-level document without too much underlying detail, a summary of supporting documents. The scope should be decided by a small group.
- It should be globally available as a living document to be updated and revised ~5 years with new information/knowledge.
- It should be a helpful document with summary statements and references to supporting papers.
- It should be a single document.
- It should identify what knowledge is required, i.e. if there are missing pieces needed for safety case, they should be identified.
- It will not resolve whether bedded or domal salt is preferred or make any statements on suitability.

5.2.2 Content recommendations

- Abstract WIPP and Gorleben and treat them as generic sites (WIPP—bedded and Gorleben—domal). Start with the VSG (Mönig et al. 2012) report concerning the safety case plus relevant WIPP chapters from the US DOE Compliance Certification Application (http://www.wipp.energy.gov).
- Address in which way differences between bedded and domal salt affect the safety case and safety demonstration concept.
- Agree on driving paradigms. For example, VSG is based on the concept “containment-providing rock zone (CRZ = ewG einschlusswirksamer Gebirgsbereich)” and minor release from CRZ, while WIPP is based on limited release. The safety assessment process is governed by regulation, not salt formation.
- Assessment basis is vital: including constitutive models, boundary conditions, parameters used, and evidence supporting appropriate model relevance (such as natural analogues).
- Requirements such as barrier thickness, technical concept, amount of waste and data needed.
- Commonalities and differences with respect to repository design, including constraints/challenges in concepts, for example deep boreholes in salt domes may be feasible but not in bedded salt.

- Include chapters of all geomechanics, which discusses such technical issues as dilatancy above the repository and stand-off distances.

Other statements and comments regarding the compendium included specific issues pertaining to geology, hydrogeology, safety, and geomechanics. For example, bedded salt contains significantly more brine (water) than domal salt, salt domes have boundaries and can contain anhydrite and clay intrusions at several orientations, bedded salt contains horizontal discontinuities, and the Salado Formation (WIPP) is not similar to German or European salt formations. These features and others require a clear line of sight between the comprehensive FEPs database, differentiating characteristics, and common patterns.

Each safety case is predicated on three prerequisites for development of FEPs, namely: 1) characteristics of the waste to be disposed, 2) the medium into which the waste will be placed, and 3) the safety and technical disposal concept. In addition, a salt repository for heat-generating nuclear waste and attendant safety case would have to be conceived without governing regulations, which may present difficulty in determining which models and parameters need substantiation. The collaborators have had several discussions regarding this goal and recognize the positive international benefits to the Netherlands, Poland, Germany and the US, as members of the NEA Salt Club. Work toward this end should be undertaken by a small working group (not yet identified) and progress expeditiously to be successful.

5.3 KOSINA

Salt domes are distributed mainly in northwestern Germany; whereas Central Germany contains flat or bedded salt formations and parts of North-East Germany contain salt pillow structures. The latter geologic formations are generically called bedded salt and have extensive lateral dimensions. The KOSINA R&D project has been initiated for repository concept development and safety concept development of a generic repository for heat-generating waste in such flat-lying salt formations in Germany.

Bedded salt formations differ from domal salt structures in many ways, of which lateral extent and vertical thickness are two of the most obvious geometric considerations. Repository concepts for heat-generating radioactive waste and spent fuel in bedded salt have not been developed in Germany; however, these efforts may have considerations in common with the WIPP repository in the US. The WIPP site in New Mexico has been an operating repository for long-lived transuranic waste of military origin. The facility is situated at 650m depth in the massive, bedded Salado Formation.

Long-term safety records and operational issues also profit from extensive experience accumulated from storage of chemical and toxic waste in flat-lying salt formations in Germany. This experience does not include the influence of heat and therefore KOSINA is undertaken to specifically address heat-generating waste disposal in bedded salt.

Germany has advanced the VSG, which is the Preliminary Safety Analysis for the Gorleben salt dome. Disposal concepts considered included drift and borehole emplacement and direct disposal of transport and storage casks (called the Direct Disposal concept “DIREGT”). Among multiple considerations, design of geotechnical barriers (plugs and seals) was developed accompanied by assembly of substantial technical database that was applied to these analyses. Here again we acknowledge an existing salt repository database comprising noteworthy background knowledge that can be applied to a repository in flat-lying formations.

5.4 Historical comparisons in the United States

The positive attributes of salt that make it an effective medium for disposal and isolation of hazardous, toxic, and radioactive materials have been recognized for some 60 years (National Academy of Science 1957). In the US, a large number of potential salt sites were characterized for disposal purposes in the draft Environmental Impact Statement (EIS) (DOE 1984). The first distinction among the salt settings related to domes and bedded salt. Although both bedded and domal salt have salt as a host rock the EIS made the following statements regarding differences in properties of the two types of salt and the hydrologic framework. Bedded salt occurs as sedimentary layers of salt and inter-bed impurities and is typically bounded by aquifers above and below the salt units. Domes in the Gulf Coast of the US are piercements of overlying thick sedimentary clays, silts and sands. Domes are surrounded by aquifers at different depths. Thus, the geohydrology around domes is distinctly different from that of bedded salt.

The pathways and mechanisms by which radionuclides might reach the accessible environment are also quite different for bedded and dome salt because of their fundamental structural and stratigraphic differences. Salt domes originate from thick beds of deeply buried salt. When sediments were deposited on these salt beds, the salt migrated upward owing to buoyancy and tectonic evolution in some cases to form a dome structure. Salt within the dome experienced extreme deformation by virtue of plastically emerging over kilometer distances. Intrinsic brine from original deposition was squeezed out. Consequently, salt domes contain less water than salt beds, which retain remnants of formation brine in fluid inclusions.

The draft EIS (DOE 1984) goes on to state the following differences between the two types of salt rock:

- Because of its higher water content, bedded salt has a lower strength than dome salt
- Bedded salt has lower geothermal temperatures at equal depths of burial
- Bedded salt tends to have faster creep rate
- Bedded salt has a more variable chemical composition than domal salt
- Bedded salt has a simpler structure than domal salt.

Some of the most important of the above factors affecting containment of wastes at salt sites are related to the chemical composition and configuration of the host rock. Domal salt may contain dispersed hydrocarbons and can occasionally contain pockets of methane gas (NEA 2013). Inter-bedding in bedded salt can vary dramatically between different beds within a specific basin and between basins (Johnson and Gonzales 1978). Some of the salt beds in the bedded salt of western New York, Michigan and Saskatchewan exhibit little insoluble clay shale and anhydrite. All salt sites will rely primarily on the extremely low permeability of the salt to provide isolation from surrounding aquifers.

Generic observations may be applicable across the spectrum of salt formations; yet, some are site specific. Information transferability is an important consideration! Thus, results derived from disposal concept mock-up, confirmation testing, seal system construction and performance testing, and operational demonstrations are often transferable between or among salt sites. Transferability of experimental and analogue information forms a fundamental scientific tenet and has been used to establish peculiarities and similarities in salt repository programs for decades. Proposed research, development and demonstration can further add to the scientific basis for salt disposal, although some information will unavoidably be site specific.

As salt repository science moves forward and compares attributes of bedded and domal salt, an appreciation of generic and site-specific factors will be debated. Table 5.1 is a draft list of generic and site-specific issues, which hopefully will add to the dialogue.

Table 5.1. Potential Generic vs. Site Specific Issues

Generic factor	Site Specificity
Bedded and domal lithology	Various heterogeneities
Mechanical behavior/deformational micromechanics	Discontinua, bedding weakness, brittle material response
Brine	Quantity and accessibility
Disturbed rock zone creation and mitigation	Depth, size, shape and arrangement of openings Local stratigraphic controls noted for bedded salt
Seal system	Specialty concrete Mine-run salt placement with additives Other materials
Constitutive models	Thermomechanical flow-law parameters calibrated for specific site
Disposal concept	Mining dimensions with depth and lithology considerations
Geomechanics modeling—coupling	Local stratigraphic controls

5.5 References

Department of Energy. http://www2.epa.gov/radiation/certification-and-recertification.

Department of Energy. 1984. *Draft Environmental Impact Statement*. DOE-800401-B9.

Johnson, K., and S. Gonzales. 1978. *Salt Deposits in the United States and Regional Geologic Characteristics Important for Storage of Radioactive Waste*. Y/OWI/SUB—7414/1.

Mönig, J., D. Buhmann, A. Rübel, J. Wolf, B. Baltes, and K. Fischer-Appelt. 2012. *Sicherheits- und Nachweiskonzept*. Bericht zum Arbeitspaket 4. Vorläufige Sicherheitsanalyse für den Standort Gorleben (VSG) GRS-277.

National Academy of Science. 1957. *Disposal of Radioactive Waste on Land*. Publication 519.

NEA. 2013. *Natural Analogues for Safety Cases of Repositories in Rock Salt*. Salt Club Workshop Proceedings. Braunschweig Germany. NEA/RWM/R(2014)10.

6 MODULAR BUILD AND CLOSE SALT REPOSITORY CONCEPT

6.1 Introduction

Permanent isolation of waste depends upon the ability to construct geotechnical barriers that achieve nearly the same high-performance characteristics attributed to the native salt formation. Salt repository seal concepts often include elements of reconstituted granular salt. As a specific case in point, the WIPP recently received regulatory approval to change the disposal panel closure design from an engineered barrier constructed of a salt-based concrete to one that employs simple run-of-mine salt and temporary bulkheads for isolation from ventilation. The technical basis for geotechnical barrier performance has been strengthened by recent experimental findings and analogue comparisons. The panel closure change was accompanied by recognition that granular salt will return to a physical state similar to the halite surrounding it. Use of run-of-mine salt ensures physical and chemical compatibility with the repository environment and simplifies ongoing disposal operations. Current knowledge and expected outcome of research can be assimilated with lessons learned to put forward designs and operational concepts for the next generation of salt repositories. Mined salt repositories have the potential to isolate permanently vast inventories of radioactive and hazardous wastes.

This Chapter draws from recent developments and subsequent contributions to the 6th US/German Workshop on Salt Repository Research, Design, and Operation (Gadbury 2015; Hansen 2015). Together, these two contemporary publications establish a new baseline for drift seal systems in salt, along with an achievable research agenda that foretells design improvement and inherent operational safety. The first (Gadbury 2015) explains the approval of a change to drift closures at the WIPP. The second (Hansen 2015) describes the scientific basis for salt reconsolidation and achievement of low permeability, while strengthening these arguments with analogue examples. This cumulative information was compiled in a paper at Waste Management 2016 Conference (Gadbury and Hansen 2016) and this summary is extracted directly from that longer paper.

Salt reconsolidation has a licensing role in the performance assessment of WIPP by its function in the shaft seal system. Now that WIPP panel closures include run-of-mine salt components, reconsolidation of granular salt is an important consideration in horizontal configurations as well. International salt repository programs have exerted long-term research efforts to understand and quantify reconsolidation and attendant permeability characteristics. In addition to specific R&D efforts, industrial mining practice often involves backfilling, which provides practical experience appropriate for repository applications. Natural geologic and anthropogenic settings also provide relevant analogues for assessment of permeability reduction as a function of granular salt consolidation.

A strong motivation to revisit the panel closure requirement initiated work with the regulatory agencies to replace it with a constructible and equivalently protective design. Seal concepts for international salt repositories and salt industry applications almost always include elements of granular salt reconsolidation. Replacement of Option D with a 100-foot (30-m) reach of crushed salt, as illustrated in Figure 6.1, was put forward as a reasonable replacement design. Numerous technical exchanges with the US Environmental Protection Agency (EPA) provided a forum to demonstrate the concept through testing and modeling results. The basic geomechanics surrounding performance of run-of-mine backfill in a creeping underground setting are well understood. Creep closure of the surrounding salt will reconsolidate the granular material to porosity and permeability characteristics approaching those of the host salt formation.

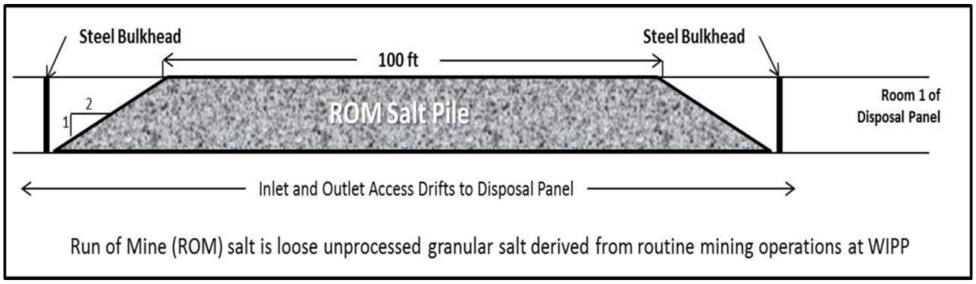

Figure 6.1. Redesigned panel closure of run-of-mine salt.

Long-term performance calculations (Gadbury and Hansen 2016) showed the new panel closure would not affect total-system safety standard compliance. The promise of enhanced closure capability presented by crushed salt, with or without additives, has important implications for the next-generation salt repositories.

Reconsolidation of granular salt is of high interest in the USA and Germany, countries actively collaborating in salt repository research, design, and operation (Hansen 2015). The realm of salt consolidation for nuclear waste disposal includes routine room backfill for structural stability, engineered systems to affect low-permeability seal capability relatively quickly, and in some cases higher-temperature environments near waste canisters. In almost all applications using crushed salt in the field, the most important characteristics are those that obtain at low porosity and attendant low permeability.

6.2 Modular build and close

Geotechnical barriers made of crushed salt have the potential to become impermeable during the operational period of a salt repository. There is persuasive evidence that reconsolidation can be furthered by improved construction techniques and enhanced by use of additives. These developments have significant implications for future salt repository operations and licensing. A concept styled *Modular Build and Close* for salt repositories may allow sequential sub-unit certification and closure in large salt repositories. It is feasible that a salt repository could accommodate nearly unlimited volumes of nuclear waste generated in the next 100 years, regardless of the nuclear industry future of the US. Such a repository would build on the enormous technical basis for salt disposal and rely essentially on salt reconsolidation performance to ensure operational safety and sequential closure. The *Modular Build and Close* concept would inherently minimize operational risk when unusual events occur, such as the fire and radioactive release at WIPP. Recent developments in terms of WIPP panel closure would seem to have moved positively toward a *Modular Build and Close* concept.

Recently, the EPA (the Federal regulatory authority for WIPP) approved DOE’s planned change request to implement a panel closure comprised mostly of run-of-mine salt. This change replaces a previous design without a crushed salt component. Based on its review and on the results of the performance assessment, the EPA concluded that the WIPP will continue to comply with the EPA’s disposal standard with the new panel closure design including a major element of 100 feet of run-of-mine salt. The EPA agreed with the use of a material that is physically and chemically compatible with the repository environment, and has relied on a body of data indicating that in time the salt panel closure will return to a physical state similar to the halite that surrounds it (EPA 2014).

Recognition by the EPA that the salt panel closure element will *return to a physical state similar to native salt* is important because the crushed salt element of seal systems can be engineered to achieve performance characteristics within an operational period of a salt repository. The EPA drew their conclusion from a modeling study that did not include advancement in the state-of-the art of salt reconsolidation applied to repository seals (Hansen et al. 2015). The revised panel closure will be consolidated by creep closure of the entry. Crushed salt is also proposed as one component of the shaft seal, and an assessment of the mechanical behavior of crushed salt is provided as part of the WIPP shaft sealing system design (DOE 1996). If salt reconsolidation is unimpeded, the material will eventually achieve extremely low permeabilities approaching those of the native Salado Formation. Further arguments from analogues provide actual measureable and testable properties, as contrasted to modeling predictions. Analogues support the idea that reconsolidation will occur expeditiously and experimental advances confirm that high performance reconsolidated drift seals can be constructed at high density and monitored during operations. These actualities, taken together, lead to a salt repository concept for complete isolation in a modular design.

The concept of *Modular Build and Close* is predicated on sequential disposal followed by licensing and permanent closure of the filled module. A notional layout of large repository is shown in Figure 6.2. Nominally, outer dimensions might measure some three kilometers by three kilometers. Production salt and potash mines are orders of magnitude larger than this hypothetical layout. Active mines exist today that have been in production for 100 years or more. A salt repository of such areal dimensions and longevity is achievable. The geometry of underground openings can be engineered for functional and operational purposes. Ground control challenges can be minimized by judicious selection of size, shape, extraction ratio, stratigraphic placement and sound mining practices. Of course, disposal modules would be excavated on a "just-in-time" basis giving due consideration to creep closure. Transport of mined salt can be minimized and optimized for real-time seal construction.

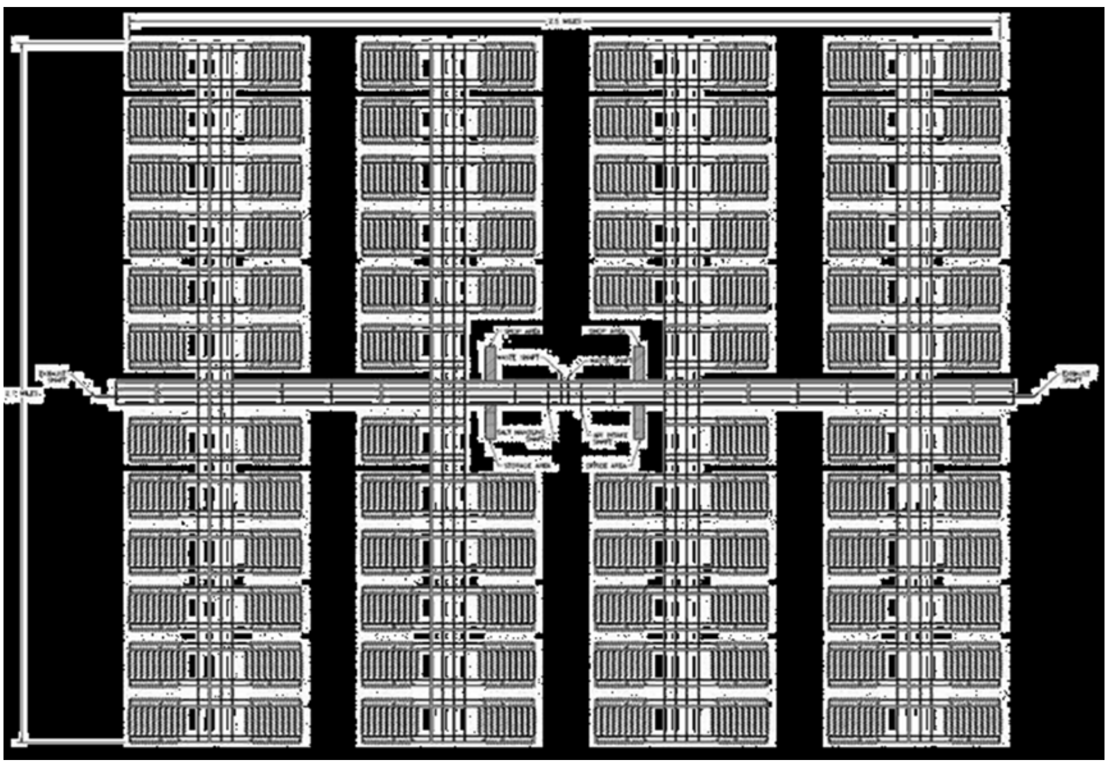

Figure 6.2. A 100-year salt repository.

Disposal would begin in a far corner and work progressively back toward the shafts. When a module of design dimension is filled, an advanced salt-based closure system would be emplaced. Design specifications for the closure systems can be based on current information as well as results of a research agenda presented by Gadbury and Hansen (2016). Closing and permanently sealing each module as disposal operations move forward creates a safety-by-design situation since exposure is progressively limited. Because disposal begins at the outer reach of the repository, underground manpower, equipment, and ventilation never breach the disposal module once it is filled, closed and licensed.

The state of knowledge regarding granular salt reconsolidation is well established. Crushed or run-of-mine salt makes an excellent backfill material for salt repositories because it reconsolidates readily under a wide range of conditions and will ultimately reestablish impermeability to brine flow and radionuclide transport. Laboratory testing, field-scale operational analogues, and natural geologic analogues attest to granular salt compressing and consolidating to assume properties of native formation salt. The science supporting the technical basis for properties of reconsolidating granular salt is objective and thorough. Remaining uncertainty within the safety case context can be reduced by focused research dedicated to achieving design specifications for drift seals as part of operational protocol.

6.3 References

Department of Energy (DOE). 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant*. DOE/CAO-1996-2184. Waste Isolation Pilot Plant, Carlsbad Area Office. Carlsbad, NM.

Environmental Protection Agency. 2014. *Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations; Panel Closure Redesign*. EPA-HQ-OAR-2013-0684.

Gadbury, C. 2015. *WIPP Panel Closure Using Run-of-Mine Salt*. 6th Proceedings of the US/German Workshop on Salt Repository Research, Design, and Operation. Dresden, Germany.

Gadbury, C., and F. D. Hansen. 2016. *Reconsolidated Salt as a Geotechnical Barrier*. Waste Management 2016 Conference. Phoenix, AZ. SAND2015-9936C. Sandia National Laboratories, Albuquerque, NM.

Hansen, F. D. 2015. *A Synthesis of Salt Reconsolidation Analogues*. ERMS 564594. Sandia National Laboratories, Carlsbad, NM.

Hansen, F. D., T. Popp, K. Wieczorek, and D. Stührenberg. 2015. *Salt Reconsolidation Applied to Repository Seals*. In L. Roberts, K. Mellegard & F. Hansen (eds.): Proceedings of the Conference on the Mechanical Behaviour of Salt VIII. South Dakota School of Mines & Technology, Rapid City, SD. London: Taylor & Francis Group (Balkema).

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7 UNDERGROUND RESEARCH LAB PRIORITIES

7.1 Introduction

Field testing at full-scale and large-scale plays an important role in salt repository licensing and performance assessment. Potential collaboration on field testing or demonstration projects has been a consistent theme at US/German workshops on salt repository research, as can be witnessed by review of yearly Workshop Proceedings located at http://energy.sandia.gov/energy/nuclear-energy/ne-workshops/usgerman-workshop-on-salt-repository-research-design-and-operation/. The group has continued to probe the utility of large-tests and demonstrations because the community is cognizant of planning requirements, logistical challenges, associated costs and anticipated return on investment. Collaboration and international agreement on relevance of underground research facility (URF) activities provide significant inducement for prioritizing and undertaking field activities. At the 6th US/German Workshop on Salt Repository Research, Design, and Operation, the collaborators once again evaluated merit of various possible field activities. Christi Leigh unveiled a series of potential activities for a salt URF that had been compiled by a small group of Sandia employees and asked for evaluation by participants. This chapter summarizes the open discussion and feedback received.

There is no operating URF for salt repository research in the US or in Germany. Further, there is no identified technical shortcoming that requires extensive field testing before developing a safety case for a HLW repository in salt. These circumstances provide a quiescent period and an opportunity for dispassionate reflection upon possible field activities outside of political and fiscal pressure to consider what priorities might be ***if*** a salt URF were to come on line. No matter what agreements are reached today, any commitment for large-scale testing would be obliged to be integrated and be prioritized with other pursuits of a multicomponent science program. This theme was expounded upon in Chapter 5 of the 5th Proceedings on Salt Repository Research, Design, and Operation (which can be accessed from our workshop website or available from an external publication (Hansen 2015)). The collaborators have recognized that a salt URF could potentially host a wide assortment of tests to confirm our collective (international) knowledge on the technical basis for salt disposal. Field tests that were planned and not conducted during WIPP site characterization and some more recent concepts have been described in previous publications (Hansen 2013). Sandia has revisited possibilities for URF utilization and used the 6th Workshop environment to ask for critical review by international peers.

Sandia National Laboratories has for many years sought to influence the uses to which underground research activities in salt are put. Our belief is that underground research space is expensive to create and maintain, and, as such, that space is precious and needs to be put to the best uses possible. Given the existence of WIPP, the safety case is solid via the licensing process for disposal of transuranic waste in salt. The next frontier for the use of salt (either bedded or domal) as a disposal medium of radioactive waste is to advance the safety case for the disposal of heat-generating waste. Therefore, the most appropriate work to be done in a salt URF would be to reduce uncertainties that are perceived to remain in long-term repository performance assessment, demonstrate operational feasibility, and be consistent with identified international priorities. Sandia, as the Science Advisor for WIPP since its inception, has maintained vigilance regarding the state of salt repository science and engineering. In March 2015, SNL revisited the topic of URF activities by calling upon a small group of in-house subject matter experts (SMEs). At the end of the internal review, a list of nine research initiatives was developed. The proposed activities do not represent unanimous consent, but are believed to offer material advancement to the safety case for disposal of heat-generating radioactive waste in salt.

What follows is the description of the activities Sandia SMEs recommended for consideration should a salt URF become available.

7.2 Proposed activities

To varying degrees, proposed URF activities describe research issues and include objectives and methodologies to be applied. A draft document summarizing the proposed field testing was circulated to participants at the 6th Workshop; however the draft is not in a referenceable form at the time of this writing. An abbreviated version of the URF activities is listed below. This list does not imply priority or sequencing with the exception of Test #1, which would require instrumentation in advance of excavation.

1. **Characterizing early behavior of excavations** in salt is a well identified information gap essential to geomechanical constitutive model development. Capturing transient development of the geotechnical setting is essential for many reasons, for example model validation and test boundary conditions. A Test Plan has been put forward with an advanced degree of attention to this underground activity (Hansen et al. 2015).

2. **Large-scale *in situ* consolidation** pertains to most concepts of salt disposal. Reconsolidation of granular salt to low porosity and low permeability at field-scale application is prerequisite to affecting sealing functions. Disposal of heat-generating nuclear waste in salt is safeguarded by characteristics of the geologic formation and geotechnical barriers. Reconsolidation to a low porosity state exhibiting characteristics of undisturbed natural salt has been demonstrated in laboratory testing and can be inferred from analogues. At the scale of meters, which is the applicable scale for salt geotechnical barriers, there are no existing controlled experiments in which granular salt has been reconsolidated to low porosity. The proposed *in situ* tests provide a straightforward approach with conceivable variations to evaluate first-order consolidation parameters, such as moisture, temperature and additives.

3. **Drift-scale seal demonstrations** are vital because geotechnical barriers are the most important barrier to radionuclide transport after the geologic formation itself. A drift-scale seal demonstration involves several essential elements. The first involves capturing early evolution changes induced in the salt formation by the act of excavation, as described above. Successful measurement of transient displacement, strain and permeability of the EDZ created by mining the opening sets the stage for remaining elements of a drift-scale seal demonstration. Placement of a rigid seal system (the construction itself) constitutes a demonstration of ability to form, mix and place high-performance salt-based concrete in an underground salt environment, i.e., constructability. Subsequent interactions between the rigid seal and the creeping salt formation address performance. Placement of a rigid volume would initiate reversal of the deviatoric stress state that gave rise to EDZ in the first place. Further elements of the drift-scale demonstration would reduce and eliminate the enhanced permeability zone comprising the EDZ and the seal/salt interface.

4. **Borehole seal demonstration** in a salt URF provides opportunity to place, test and forensically examine borehole plugs. Requirements for sealing abandoned drill holes will be important for siting, characterizing and licensing a salt repository. Performance testing of borehole plugging in salt repository applications has been rare, but has been accomplished without a URF (Christensen and Peterson 1979). However, access to a salt URF would allow direct evaluation of borehole sealing techniques via lateral re-entry to the sealed section for forensic studies.

5. **A single-heater test** provides a flexible opportunity to predict and measure salt response and establish test protocol. If salt repository researchers had an opportunity to conduct field tests in an underground facility, a single-heater test would be in the mix as a high priority activity. Many small and large-scale heater tests conducted over the last 50 years have witnessed expected and unexpected formation reactions to heat. Therefore, a single heater test would provide confidence for field-testing procedures and allow demonstration and verification of repository design concepts.

6. **Salt decrepitation** has been observed but its effects on porosity, permeability, and strength of the salt have not been quantified. Bedded salt contains isolated brine inclusions, which are liberated when heated to the decrepitation temperature. With renewed interest in high-level radioactive waste disposal in salt, it is increasingly important to understand the impact decrepitation has on salt properties, and characterize when and how it happens at the borehole scale under variable conditions.

7. **Diffusion tests** to characterize diffusion model parameters will provide key support for the safety case. In low-permeability systems, diffusion of solute concentrations is likely to be the dominant transport process in long-term performance assessment calculations. Therefore, experimental measurements to characterize diffusion model parameters will be a key aspect of the safety case. *In situ* diffusion tests at a larger scale, conducted in a URF, build confidence in the transport models and may provide up-scaled diffusion coefficients that are more appropriate for long-term repository performance.

8. **Brine availability borehole heater tests** involving a small, standardized borehole heater fielded in a range of vertical and horizontal orientations will address generic open issues from previous tests and provide fundamental data for the local salt system. Because of the low permeability of geologic salt, the total amount of brine available to flow into an excavation is a crucial input for long-term performance of a salt repository. Both bedded and domal salt can produce significant quantities of brine during periods of rapid temperature change (both heating and cooling).

9. **An underground salt creep laboratory** is proposed to investigate low-strain-rates. One application is to understand the potential for large, heavy waste packages to sink over time periods of 10^4 years or longer. In Chapter 3 of these Proceedings the salt repository research agenda has identified the issue of salt creep under low deviatoric stress as a key uncertainty. In addition to waste package movement, low deviatoric stress conditions and low strain rates are relevant to large-scale analysis because they occur in much of the formation rock around a disposal room or experimental set up. Additional testing is needed to extend constitutive models to better represent deformation at these conditions.

7.3 Discussion and feedback

As noted previously, there was not unanimous agreement by SNL personnel on merits of proposed activities. Some efforts are more clearly defined and directly relevant than others. The level of complexity varies significantly and overall usefulness may be a matter of opinion. Therefore, independent review by qualified international experts can be deeply informative. Moving forward, consensus from peers as well as nontechnical stakeholders will play an important discriminating role.

The intent of this summary is to describe useful science that can be achieved in a salt URF. Potential underground activities were identified in a two-day workshop by Sandia SMEs and therefore embody national and international context of salt R&D programs. The workshop output comprises descriptions of focused activities that are presumed to be highly relevant to salt science and can be advantageously approached by underground testing and demonstration. Relationship to the safety case or other justification for URF activities would remain open issues until final decisions are made. Nonetheless, the nine activities listed and described here have merit and support at some level.

In September 2015, this list of proposed URF activities was shared with international colleagues while conducting the 6th US/German Workshop on Salt Repository Research, Design, and Operation in Dresden, Germany. In reaching out to peers who are equally vested in salt repository science and engineering, international perceptions were ascertained. Input from our international colleagues will be essential when proposals are made for *in situ* nuclear waste disposal research to potential governmental sponsors. To introduce the proposed field activities, a synopsis of URF activities was given at the 6th US/German Workshop. A presentation *Salt Underground Research Facility Activities* (Leigh 2016) outlined the current collective thinking captured by the nine activities identified above at SNL regarding the need for and use of a URF in salt.

Workshop attendees were provided a table for eliciting feedback on this list of activities. Five participants responded, and one could assume they represent SMEs in their respective organizations. The feedback was illuminating, illustrative, and consistent—revealing the type of reactions one could expect in other forums. Guidance for the elicitation asked three questions:

1. If you had 1 million dollars to spend, where would you invest it and why?
2. If you had 10 million dollars to spend where would you invest it and why?
3. If you had 100 million dollars to spend where would you invest it and why?

The three questions were posed to see how committed the salt researchers were to particular investment areas. The researchers were asked to provide written information and their identities remain confidential for purposes of this document.

Large-scale *in situ* consolidation (Test Proposal #2) was strongly supported. Comments included:

1. *With 1M available I would concentrate on in situ consolidation because in my opinion this is the critical question.*
2. *Crushed salt consolidation is of fundamental importance to the safety concept and not easy to model. A test here is absolutely necessary.*
3. *Priority 1 for us but additional laboratory measurements are necessary.*

Drift-scale seal demonstrations (Test Proposal #3) also received high marks:

1. *Tests 2,3,4 address the most crucial aspects in the safety assessment demonstration concept in Germany*
2. *With 10M you can do in situ consolidation and in addition a drift seal test which is also very important.*
3. *I think it is necessary to collect available information on existing large-scale in situ tests*
4. *…a drift seal test is also very important*
5. *One researcher suggested a (drift-scale field) test called "Behavior of sealing plugs, backfill material, and salt, under thermal load." The test would support research into the thermal behavior of the host rock (salt), the EDZ, the contact zone and the concrete. In general, it promotes an understanding of the thermal behavior of the materials (concrete, salt, etc.). If it is performed in the in situ situation it can also serve as a monitoring program.*

A third priority was Test Proposal #9: **An underground salt creep laboratory** to investigate low-strain-rate waste package buoyancy effects. Agreement mostly rested on *the need for long-term creep tests under in situ boundary conditions…*and …*Creep and relaxation tests at low strain rates/stress…even if the waste package buoyancy effect is small because at the salt top low differential stresses are decisive for seal function*.

Guiding considerations for potential URF events may be shaped by licensing requirements, including nontechnical aspects such as public acceptance. Weighting factors of importance include perceptions of stakeholder interest, uncertainty reduction, construction demonstrations, model validation, and confirmation among others. There is not a unique test in a salt URF that must be conducted to address an unknown science or engineering issue that stands between current knowledge and a license application. If a decision is made to dispose of heat-generating nuclear waste in salt, and that decision includes a site, a concept for disposal and waste inventory, then these three additional factors may help refine the recommendations made here and lead to demonstrations of operational features and similar specific activities that might be a variant of our current list.

Priority for URF activities determined from workshop feedback embraces large-scale consolidation testing of crushed salt and drift seal testing for international collaboration. It is recognized here and elsewhere that testing at low deviatoric stresses remains pertinent and enigmatic.

7.4 References

Christensen, C., and E. Peterson. 1979. *Field-Test Program of Borehole Plugs in Southeastern New Mexico.* SAND79-1634C. Sandia National Laboratories. Albuquerque, NM.

Hansen, F. D. 2013. *Underground Salt Research Laboratory at the Waste Isolation Pilot Plant*. SAND2013-0356C. International High Level Radioactive Waste Management Symposium. Sandia National Laboratories, Albuquerque, NM.

Hansen, F. D., K. Kuhlman, C. Howard and J. Holland. 2015. *Capturing Early Evolution of Salt Openings.* Proceedings of the 49th US Rock Mechanics / Geomechanics Symposium. SAND2015-1570C. Sandia National Laboratories, Albuquerque, NM.

Hansen, F. D. 2015. *An Underground Laboratory in the Context of Salt Disposal Research*. Waste Management 2015 Conference. SAND SAND2014-18368C. Sandia National Laboratories, Albuquerque, NM.

Leigh, C. D. 2016. *Salt Underground Research Facility Activities*. 6th Proceedings of the US/German Workshop on Salt Repository Research, Design, and Operation. Dresden, Germany.
http://energy.sandia.gov/energy/nuclear-energy/ne-workshops/usgerman-workshop-on-salt-repository-research-design-and-operation/

8 CONCLUDING REMARKS

The US/German workshops on salt repository research, design, and operation continue an unabated mandate to provide, justify, and document the scientific and engineering bases for salt disposal of heat-generating nuclear waste.

These Proceedings summarize the 6th US/German Workshop on Salt Repository Research, Design, and Operation. Coordinators and attendees recognized that a successful continuation would be best facilitated by focus on a few topics, advancing those to a mature status and reporting—such as accomplished in the area of Natural Analogues and Granular Salt Reconsolidation (Please see the NEA website for these reports.) Publication provides documentation and knowledge preservation, two of our essential goals. Among upcoming activities and collaboration are the comprehensive FEPs database for repositories in domal and flat-lying salt formations and collaboration on a compendium elaborating relevant characteristics of these salt formations. Collaborators will combine the technical basis for salt disposal in either geologic setting as national site selection programs move forward. Evaluation of the FEPs for the safety case would undoubtedly draw references from the compendium.

Research, development, and demonstration such as reported in these Proceedings help extend budgets of all involved parties and ensure scientific rectitude. These workshops continue to provide enormous benefit to both Germany and the US; however, the US/German moniker may have to be updated owing to intensified interest shown by the Netherlands and Poland.

The next workshop is planned for September 7-9, 2016. The venue is Embassy Suites in Washington, DC. This decision was reached by the workshop organizers for three reasons: 1) Specific requests by several participants, 2) A Washington, DC venue could make attendance easier for DOE, Nuclear Regulatory Commission, and EPA representatives located in the area, and 3) The NEA Salt Club has the option to plan its workshop dates to occur in DC during the same week, thereby streamlining travel by common participants. The Washington venue for the seventh workshop was agreed upon while conducting the sixth workshop in Dresden. The dates for the seventh workshop are not negotiable because of other competing events in Europe and a fixed schedule allows the NEA Salt Club to coordinate their workshop dates accordingly.

APPENDIX A: AGENDA

6th US/German Workshop on Salt Repository Research, Design, and Operation

Hotel Pullman Dresden Newa

September 7 – 9, 2015

PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology
Sandia National Laboratories
DBE TEC DBE TECHNOLOGY GmbH

U.S. Department of Energy
NNSA
Federal Ministry for Economic Affairs and Energy

TECHNICAL AGENDA

September 7— Monday

Day 1

08:00-08:30	Registration	
08:30-08:50	Welcome by the organizers	T. Lautsch, DBE F. Hansen, SNL W. Steininger, PTKA
08:50-09:15	Welcome by BMWi	U. Borak, BMWi
09:15-09:30	Welcome by USDOE	N. Buschman, US DOE
09:30-10:00	NEA Salt Club	J. Mönig, GRS
	SAFETY CASE ISSUES	
10:00-10:30	WIPP recovery	F. Hansen, SNL
10:30-11:00	***Coffee break and photo event***	
11:00-11:30	Then and now – Assessing updates to 1998 WIPP Modeling	K. Economy, US EPA
11:30-12:00	PFLOTRAN: Coupled THC simulations	D. Sevougian, SNL
12:00-12:30	RepoTrend: A program system for safety analysis	J. Wolf, T. Reiche, GRS
12:30-13:30	***Lunch***	
13:30-14:00	Extended storage approach of COVRA	E. Neeft, COVRA
14:00-14:20	Joint US – D activities on the FEP catalogue /scenario development	J. Wolf, GRS G. Freeze SNL
14:20-14:40	Uncertainty management	D. Becker, GRS
14:40-15:15	***Coffee break***	
	OPERATIONAL PHASE ISSUES	
15:15-15:45	Probabilistic and deterministic safety assessment approach for shaft hoisting systems	R. Gasull, DBETEC
15:45-16:15	Balancing operational phase and post-operational phase safety	J. Wolf, GRS
16:15-16:45	Monitoring of repositories (EC-Projects Modern and Modern2020)	M. Jobmann, DBETEC

No evening activity planned.

TECHNICAL AGENDA

September 8 —Tuesday

Day 2

GEOMECHANICAL ISSUES

09:00-09:30	Joint Project on constitutive models: Benchmark calculations of WIPP rooms B and C	A. Hampel Hampel Consulting
09:30-10:00	Topics for future R&D activities focusing on integrity analysis	T. Popp, IfG
10:00-10:30	Integrity of saliferous barriers for heat generating radioactive waste – natural analogues and geomechanical requirements	W. Minkley, IfG
10:30-11:00	***Coffee break***	
11:00-11:20	Content and distribution of fluids in domal and bedded salt: influence on the geomechanical behavior of rocks	M. Pusch, J. Hammer, I. Plischke, BGR
11:20-11:40	Comparison of confined constant strain rate strength tests performed on WIPP clean salt	S. Buchholz, RESPEC
11:40-12:00	Compilation of salt dilatation test data for assessment of variability	L. Roberts, SDSM&T
12:00-12:20	Rock salt dilatancy load path effects (not presented)	J. M. Hertzsch, BGR
12:20-13:30	***Lunch***	
13:30-13:50	The concept of SN fuel and HLW disposal in salt rock in Poland	L. Lankof, MEERI
13:50-14:10	Comparison of rock salt in stratiform and diapiric deposits in Poland – hints for selection and safety of repositories	S. Burliga, UWR
14:10-14:30	Shear strength and deformation of discontinuities in salt	S. Sobolik, SNL
14:30-14:50	Priority testing in a salt URL	C. Leigh, SNL
14:50-15:20	***Coffee break***	
15:20-15:40	Modelling of crushed salt compaction: Recent findings	O. Czaikowski, GRS

BREAKOUT SESSIONS

15:40-17:00	Safety and demonstration concept for bedded salt (KOSINA project)	W. Bollingerfehr DBETEC
	Comparison of bedded and domal salt for repository application	F. Hansen, SNL
15:40-17:00	FEPs catalogue development	G. Freeze, SNL J. Wolf, GRS
15:40-17:00	Arising issues (to be identified at the workshop)	

19:00 CONFERENCE DINNER

TECHNICAL AGENDA

September 9—Wednesday

Day 3

PLUGGING & SEALING

09:00-09:30	In situ verification of a drift seal system in rock salt – preliminary results	R. Mauke, BfS
09:30-10:00	Permanent panel closures at WIPP using run-of-mine salt	C. Gadbury, DOE/ Presented by F. Hansen, SNL
10:00-10:30	Plugging & Sealing projects ELSA and DOPAS	U. Glaubach, TU BAF O. Czaikowski, GRS
10:30-11:00	***Coffee break***	
11:00-11:30	Special topics on sealing materials behavior	H. Mischo, TU BAF
11:30-12:00	Sorel building materials in salt formations (MgO)	D. Freyer, TU BAF
12:00-13:00	***Lunch***	

SPECIAL TOPICS

13:00-13:30	Update on the ABC-Workshop and Pitzer-database	C. Leigh, SNL V. Metz, KIT/INE
13:30-14:00	BAM-SNL cooperation on container behavior / influence on prolonged interim storage periods	H. Völzke, BAM K. Sorenson, SNL
14:00-14:15	Evaluation of current knowledge for building the Dutch Safety Case	D. Becker, GRS J. Hart, NRG
14:15-14:45	IAEA Safety Standards and the Safety Case	A. Orrell, IAEA
14:45-15:00	***Coffee break***	
15:00-15:30	Far-field hydrologic modeling around a salt repository	A. Schneider, GRS K. Kuhlmann, SNL
15:30-16:00	Deep borehole disposal: pros & cons of such a concept	G. Freeze, SNL W. Bollingerfehr, DBETEC
	Wrap-up, conclusions and outlook	Organizers

Technical Tour 1

TU Bergakademie Freiberg
Thursday, Sept. 10th, 2015

Transportation by bus (free of charge)

Departure: Hotel Pullmann Dresden Newa at 8:30 am, ride to Freiberg (about 1hr)
Arrival: Hotel Pullmann Dresden Newa at 6:00 pm

Program

1. *Lecture "250th anniversary of Bergakademie Freiberg" (http://tu-freiberg.de/en)*
2. *Visit of the research mine Reiche Zeche (briefing, underground tour, installations for underground experiments, miner's lunch, …); duration: 3 - 4 hours*
3. *Terra Mineralia, exhibition of minerals in the Freiberg Castle (http://www.terra-mineralia.de/english/startpage) (please by a ticket by yourself)*
4. *Guided city tour Freiberg (cathedral with the famous Silberman organ)*
5. *Visit of laboratories at the Institute of Mining and Special Civil Engineering*

Technical Tour 2

Glückauf Mine Sondershausen
Friday, Sept. 11th, 2015

Transportation by bus (free of charge)

Departure: Hotel Pullmann Dresden Newa at 7:00am, ride to Sondershausen (about 3 hrs)
Arrival: Hotel Pullmann Dresden Newa at 6:00 pm (departure from Sondershausen: 2:30pm)

GSES / EBBG
Glückauf Sondershausen Entwicklungs- und Sicherungsgesellschaft mbH (www.gses.de)
Erlebnisbergwerk-Betreibergesellschaft mbH (www.erlebnisbergwerk.com)
Schachtstraße 20 – 22, 99706 Sondershausen

GSES Business Areas
The main business of GSES GmbH is backfilling mine workings with suitably prepared mineral industrial wastes. Various backfilling methods are used for the different types of waste. The excellent geological and hydrogeological conditions in the Glückauf Mine enabled a class IV underground disposal facility to be created, which has been in operation since 2006. Another field of business is stacking uncontaminated mineral wastes on the mine tailings dump. The dump is being covered with these waste materials to stabilize it hydrologically, and prepare it for recultivation. The mining of rock salt is the last major field of business which is currently being expanded.

Program

Geotechnical underground tour in the Glückauf Mine Sondershausen: 10:30 – 14:30

Local guides: Dr. A. Stäubert (K-UTEC Salttechnologies), Dr. T. Popp (IfG)
Co-Sponsor: IfG GmbH, Leipzig (Underground tour)

APPENDIX B: WELCOME ADDRESSES:

Mrs. Borak – Welcome Address

Ladies and gentlemen,

On behalf of the Federal Ministry for Economic Affairs and Energy, I would like to extend a warm welcome to you to the sixth US-German workshop on Salt Repository Research, Design, and Operation organised by Sandia National Laboratories, DBE Technology, and the Project Management Agency Karlsruhe.

I am delighted that more than 70 participants from Germany and from abroad have made their way to the beautiful city of Dresden, the capital of Saxony. Dresden, which is situated on the river Elbe, is famous for its impressive Baroque and Mediterranean architecture. Therefore, it is also known as "Florence on the Elbe."

The fact that there are so many colleagues participating in this workshop from both Germany and especially from abroad - from the United States, the Netherlands and Poland - underlines the particular importance of the workshop.

Ladies and gentlemen,

I am particularly pleased that Ms Nancy Bushman, the representative of the US DOE, has made the long journey to Dresden to attend this year's workshop. It shows that both the US DOE and the German Federal Ministry for Economic Affairs and Energy greatly value this cooperation which was officially institutionalised in 2011, when the agreement between the Federal Economic Affairs Ministry and the two Offices of the US Department of Energy – Environmental Management and Nuclear Energy – was signed. I would like to express my thanks to the US DOE for its support and for its active commitment to our cooperation.

The workshop brings together 'salt experts' from the US, the Netherlands, Germany, and, for the first time, from Poland, providing them with the opportunity to exchange information, analyse the current status of research, discuss what has happened so far, and in doing so, draw conclusions for future joint research activities.

This workshop, which takes place every year, has become well-established and is a showcase for US-German cooperation. In fact it also contributed to the initiation of the Salt Club, an OECD/NEA expert working group, in 2012.

Dr Mönig, the chairman of the Salt Club, will later report on its activities and successes.

Ladies and gentlemen,

As participants of the workshop, you may be interested in knowing how the situation in Germany has developed since we last met and how this impacts on the topics of our workshop.

Let me start by giving you a brief overview of the political and legal framework.

The legal framework is provided at European level by the Radioactive Waste and Spent Fuel Management Directive, which was adopted in 2011, and at national level by the Site Selection Act, which entered into force in 2013, and the Atomic Energy Act, which is currently being revised. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety has the lead responsibility for the two German Acts.

Pursuant to the **Site Selection Act**, investigative work to identify a final disposal site and/or an alternative disposal method for highly radioactive, heat-generating waste is being undertaken. The Act prescribes an unbiased as to the results site-selection process, starting from a so called 'white map'. This means that potential rock salt sites have to compete with sites in alternative rock formations. The implementation of the Site Selection Act thus means that, in addition to consideration of alternative means of disposal and rock formations, further work has to be done on research and technology regarding the suitability of rock salt for the disposal of radioactive waste. Here, we particularly need to draw on international networks and experience.

The "Commission Storage of High-Level Radioactive Waste Material," the **Repository Commission**, which was established in the context of the implementation of the Site Selection Act, started its work more than one year ago. I am delighted that Prof. Dr Kudla, a member of the Commission, has taken the time to attend this workshop. The Commission's task is to address fundamental aspects of the disposal of highly radioactive waste and to review, substantiate and further develop the existing requirements of the Site Selection Act.

The Repository Commission has since used the opinion several expert institutions and specialists, including some at international level. For instance expertise on deep borehole disposal of nuclear waste was provided by Andrew Orrell.

The Commission will present its results to the German Bundestag in a report that sets out recommendations by mid-2016. This report will be the basis for the long-term strategy for the disposal of highly radioactive waste in Germany.

It is also strategically important that Germany, like all other EU Member States, had been called upon to draw up and submit a National Nuclear Waste Disposal Programme for all radioactive waste by August 2015 in accordance with the Radioactive Waste and Spent Fuel Management Directive.

According to the Programme, Germany will install **two final repositories**, one for low and medium-level radioactive waste that generates negligible amounts of heat, and one for particularly high-level radioactive waste.

The **Konrad** mine is the planned final repository for low and medium-level radioactive waste. The work on converting the Konrad mine into a final repository has been under way since 2007. The work is currently scheduled to be completed in 2022. The Konrad repository is crucial for the disposal of low and medium-level radioactive waste resulting from the decommissioning of Germany's nuclear power plants. Pursuant to the nuclear phase-out decision, the last nuclear power plant will be switched off in 2022. The Konrad repository needs to be completed swiftly and without any further delay in order to provide planning certainty to nuclear power plant operators and the institutions involved.

Apart from dealing with the tasks relating to the search for a high-level waste repository, and the completion of the Konrad final repository, the National Nuclear Waste Disposal Programme also addresses the low and medium-level radioactive waste that is already stored in the **Asse** II mine. There is the firm political will to retrieve this waste and store it in a suitable final repository.

Finally, I want to mention the **Gorleben** final repository project. The underground work at the Gorleben site was discontinued in November 2012 in line with the Site Selection Act. Pursuant to the Act, the Gorleben salt dome must be included in the selection procedure and treated the same as any other potential site in line with the rules and criteria set out in the Act. This means that operations at the Gorleben mine are to be brought down to an 'absolute minimum'.

Ladies and gentlemen,

The Federal Ministry for Economic Affairs and Energy has the lead responsibility for project funding for research on the disposal of radioactive waste that does not focus on a particular site and is supported by the Project Management Agency Karlsruhe to determine the strategic and technical direction of the research activities.

Against the background of the new approach regarding the search for a final repository for highly radioactive waste and the work of the Repository Commission, it is clear that comprehensive support from science is needed for the disposal of highly radioactive waste. The Federal Ministry for Economic Affairs and Energy has thus implemented the new political framework by introducing the funding concept entitled 'Research on the Disposal of Radioactive Waste', which was published in February 2015.

The funding concept defines the following major **objectives of the research activities**:

1. creating the scientific and technical basis for building a final repository especially for heat-generating radioactive waste;

2. developing methods and techniques necessary for specific measures to prepare final disposal, and methods and techniques for the planning, construction, operation and decommissioning of final repositories, while continually further developing the state of the art in science and technology; and

3. providing expertise and thus making a major contribution to the creation, further development and maintenance of scientific and technological knowledge and skills and to fostering young talent in the field of the disposal of nuclear waste in Germany.

During the current phase of the project funding for the next four years, the **Federal Ministry for Economic Affairs and Energy** plans to clarify conceptual issues concerning the final disposal in bedded rock salt. In this context, the continuation of our cooperation with the United States is particularly valuable.

Germany plans to continue to meet the identified need for R&D on final disposal in salt domes.

At the same time, research on the final disposal in clay and crystalline rock will be consistently expanded.

In order to implement this strategy, international cooperation will be intensified. This includes participation in underground research laboratories and in various bodies.

The major **changes compared with the Ministry's previous project funding** include

- doing more research in different types of host rock,
- considering prolonged interim storage periods,
- considering alternative disposal methods than the final disposal in mined repositories, and
- taking greater account of socio-technical aspects in future R&D work.

It is particularly important for the Federal Ministry for Economic Affairs and Energy to undertake broad-based research and to find a responsible and honest solution that is fair for all parties concerned. This means that we should not stipulate any specific ways of disposal or any specific host rocks at the beginning of the process. All potential and promising disposal options must be examined and evaluated. The task now is to make use of the technological and innovative capabilities of Germany and its partners. Assuming that it will take 100 to 150 years before a final repository for high-level radioactive waste in Germany is closed, we not only need to think about an appropriate site, but we also need to make use of global technological progress.

Ladies and gentlemen,

This workshop also aims to foster technological progress. I would now like to go into the individual topics in greater depth:

Let me point out how important the political situation in our countries has always been with regard to the development of our cooperation in the field of final disposal in **salt** rock. This is also reflected in the motto of this year's workshop 'Salt Repository Research, Design, and Operation' as well as in the special topics.

In the context of the Ministry's research funding, R&D projects have since been launched in the new fields of interest. These include the **KOSINA Project**, which deals with bedded salt. This project is also one of the topics of the workshop. Here, the international contributions, especially the experience gained in the WIPP, are very important and helpful.

The issues that continue to be significant for **final disposal in rock salt** also include of course those pertaining to geomechanics, which will be dealt with on the second day of our meeting. These issues have played a key role in the previous workshops and will continue to do so into the future. Let me also mention issues such as the safety case, operational safety and the closure and sealing of the final repository. Some of these matters are also relevant for final repositories in other host rocks, and thus are also of interest from these perspectives.

I would like to point out that current matters that are of great interest for Germany - not least in view of the discussions in the Repository Commission - will be addressed in particular in the meeting on Wednesday, which will focus on special topics. These include the disposal approach of the Netherlands, the issue of prolonged interim storage periods, very deep borehole disposal, and final disposal in bedded salt formations.

Ladies and gentlemen,

We are convinced that the research work that is being done as part of our US-German cooperation is important for us to **gain further insights into the qualities of rock salt as a host rock** and to bring older findings in line with the current state of the art of science and technology in accordance with our Ministry's funding concept.

We are taking account of the experience that has been gathered in similar geological conditions, namely domal and bedded salt, by our direct neighbours **Poland** and the **Netherlands**. The geological data and the excellent expertise gained will make a major contribution to the success of the research activities.

The **United States** continues to be our **most important international research partner** on **salt** as a host rock. As we tackle the challenges which lie ahead of us, Germany will be feeding in its many years of 'salt expertise'. We are glad that the **Netherlands** and **Poland** are contributing to these efforts. Our cooperation with the United States makes it possible for the partners to create synergies in their work and thus advance their programmes. We can reap scientific and economic benefit and continue our joint research based on what we have already achieved. This can certainly be regarded as added value - not least for the Salt Club and its member countries as well.

Ladies and gentlemen,

I would like to take this opportunity to stress that Germany will continue to view **salt** as a viable option for the **disposal of radioactive waste into the future**. We also **need more research** to be conducted on this.

I therefore hope that the fruitful cooperation between our countries will be continued with the same degree of intensity.

In this spirit, I wish us a successful event.

Dr. Lautsch – Welcome Address

Dear Ladies and Gentlemen,

I warmly welcome you to Dresden, the capital of Saxony.

Dresden is a very famous place for research and development of nuclear technology.

Today the Helmholtz Center Dresden-Rossendorf – founded in 1956 on the site of the former "Zentralinstitut für Kernphysik" employs more than 1100 people, 500 of them scientists, most of them working in different challenging areas of nuclear sciences.

Dresden is a very famous place for mining as well.

The silver ore mining district in the "Erzgebirge" is the first mining district in the world, which was exploited in an industrial scale as early as in the 14th century.

This mining activity laid the foundation for the wealth, both financial and cultural, of Dresden.

Mining engineers from the "Erzgebirge" joined the Spanish ships and helped setting up the mining industry in the Americas being amongst the first to globalize our industry.

And also the mining traditions have been largely influenced by Saxonian mines.

These traditions are also lived in Silesia, where I personally had the pleasure to enjoy living amongst the Polish mining community.

To summarize mining always was closely connected and the mining community exchanged their ideas at all times.

I wish this workshop continues that tradition.

I would like to shortly introduce you to DBE.

DBE is operating three facilities:

The Gorleben mine, which is an exploratory mine in a salt dome in Northern Germany, was selected in 1977 as a site for exploring the suitability of a salt dome to host in particular heat generating waste (high level waste and spent fuel).

Today following the decision as of summer 2013 to set up a new siting process and to stop all exploration activities at the Gorleben site we are going to transfer the mine into a position that it is still accessible for a future use.

We will carefully transfer the mine into an adequate position in close cooperation with our customer and the involved experts from the authorities.

Second DBE operates the Konrad mine.

Konrad mine is more in the center of Germany close to Salzgitter and is a former iron-ore-mine which is in the process of being converted into a repository for disposal of low radioactive waste.

DBE is currently employing together with contractors more than 500 people on a daily basis to erect the surface facilities and to retrofit the two shafts of Konrad mine and also to upgrade the underground openings and to develop disposal chambers.

Last but not least the third facility which is operated by DBE is the Morsleben mine.

Morsleben mine is close to Magdeburg in the state of Saxony-Anhalt which is neighboring to Saxony where we are currently sitting.

The Morsleben mine closes the cycle of nuclear facilities in the former GDR.

It was operated to accept low active waste in the years from 1982 until 1996.

During this operating time roughly 40.000 m^3 of radioactive waste has been stored underground. Currently the legal status of this facility still is an operational nuclear disposal facility but in agreement with the decision makers of the public entities, the politics and of the state of Saxony-Anhalt it was decided to stop disposing material underground.

Morsleben is under preparation for being sealed up, a process which will start in the 2020ies.

At that time DBE will have not only the first operational deep underground nuclear disposal in Germany but also it will have the first sealed off repository in Germany

So what I can tell you is that DBE is highly knowledgeable and an expert in disposal of nuclear waste in Germany.

It is the only organization in Germany which is experienced in operating such a facility and we are proud and we are also pleased that we are able – with our subsidiary DBE TEC – to deliver this knowledge and these capabilities to the world market and I warmly welcome you again to this event here in Dresden.

Glück auf!!!

APPENDIX C: LIST OF PARTICIPANTS AND OBSERVERS FROM 6TH WORKSHOP

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APPENDIX D: BIOS

Dirk-Alexander Becker

After finishing his studies of mathematical physics at the Technical University of Braunschweig, Germany, Dr. Becker joined the Institute for Deep Geological Disposal in Braunschweig, which was later overtaken by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) GmbH. He has 22 years' experience in repository research, especially in modelling contaminant dissemination in salt and clay. For more than ten years he has been investigating probabilistic methods for uncertainty and sensitivity analysis.

Sebastian Becker

Stephan Bödecker

Frank Bok

Vinzenz Brendler

Wilhelm Bollingerfehr

Diplom-Bauingenieur (M.Sc.eq) –civil engineer

Prokurist

Head of Research and Development Department

DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine

After finishing the Technical University of Hannover in Germany as a civil engineer in 1985 he gained extensive experience in the field of repository design and development of engineered barriers. As project engineer and project manager he developed concepts for technical barriers for repositories in salt and managed the construction of prototype barriers. In addition he was responsible for developing transport and emplacement systems and components for heat generating radioactive waste, industrial demonstration test included. Nowadays, as Prokurist and head of the Research and Development (R&D) department he is responsible for a staff of some 10 scientists and engineers all of them working in RD&D projects in the field of safe disposal of heat generating waste (reprocessing waste and spent fuel). His recent work was focusing on the development of a repository design and closure measures for a high-level radioactive waste (HLW) repository in salt formations in the context of a preliminary safety case. One new challenge he is faced with is an analysis of possibilities to retrieve emplaced waste packages and to develop technical solutions for retrieval processes for HLW-repositories in salt and clay formations.

Since autumn 2012 he has the honour to give lectures on Repository Techniques at the University of Braunschweig at the Institut für Grundbau und Bodenmechanik (Institute of Geotechnics) lead by Prof. Stahlmann.

Stuart A. Buchholz

Mr. Buchholz is the manager of the Materials Testing Laboratory for RESPEC Consulting and Services in Rapid City, SD. He holds B.S. and M.S. degrees in Geological and Mechanical Engineering from the South Dakota School of Mines and Technology. Mr. Buchholz started his professional career at Halliburton Energy Services where he worked as a wireline logging engineer in the Gulf of Mexico for 7 years. Mr. Buchholz has been a geomechanical consultant for RESPEC for the last 10 years and has extensive experience in analyzing salt caverns that are used for hydrocarbon and waste storage, dry mine excavations in bedded and domal salt formations, and dry- and solution-mined potash excavations.

Stanislaw Burliga

Dr. Stanislaw Burliga works as an assistant professor at the Univeristy of Wroclaw in Poland in the Institute of Geological Sciences. His primary research interests are salt tectonics and Zechstein stratigraphy. His studies focused on rock salt deformation, gas and fluid migration in salt and occurrence of natural threats in salt mines.

Nancy Buschman, PE, PMP

Nancy is a chemical engineer who worked as a process and project engineer in private industry before joining the Department of Energy (DOE) in 1991. She has overseen programs within the National Nuclear Security Administration, Office of Nuclear Energy, and Office of Environmental Management, particularly in the areas of technology development and nuclear materials and spent nuclear fuel (SNF) management. Nancy's education includes a BS degree in chemical engineering from the University of Maryland and an MS in Technical Management from the Johns Hopkins University. She is a licensed professional engineer, certified project management professional, and federal project director.

Andrea Cherkouk

Oliver Czaikowski

Dr.-Ing. Oliver Czaikowski is working at the GRS in Braunschweig, a technical safety organization for nuclear safety and repository issues in Germany. Oliver made his PhD in the field of nuclear waste disposal at the Technical University Clausthal. As a member of the Repository Research Division at GRS, he is now dealing with experimental investigations in lab and *in situ* and its corresponding THM-coupled modelling activities.

Uwe Düsterloh

Degree: PD Dr.- Ing. habil.
Institution: Clausthal University of Technology
Chair: chair for waste disposal technologies and geomechanics

1982- 1988 field of study: mining engineer
1989- 1993 PhD work – geomechanical investigations on the stability of salt caverns for waste disposal
2009 Habilitation - proof of stability and integrity of underground excavations in saliniferous formations with special regard to lab tests
1989 - 2012 chief engineer at Clausthal University of Technology

Kathleen Economy

Ms. Economy has been working on nuclear waste repository issues since 1992. She has held various roles in the preparation of performance assessments for both the Waste Isolation Pilot Plant (WIPP) and the Yucca Mountain Project. In 2010 she began her role as a WIPP regulator for the United States Environmental Protection Agency. She has a master's degree in Hydrology from New Mexico Institute of Mining and Technology.

Sandra Fahland

Civil engineer degree (Dipl.-Ing.) in 1997 at the Technical University of Braunschweig, Germany and Ph.D. degree (Dr.-Ing.) in 2004 at the Technical University of Clausthal, Germany. Joined the Federal Institute for Geoscience and Natural Resources (BGR), Department 3 ―Underground Space for Storage and Economic Use, in 2005 as a scientist of the Sub-Department ―Geological-geotechnical Safety.‖ Scientific background: Rock mechanics - especially salt mechanics, thermomechanical numerical analysis of underground structures, radioactive waste disposal, field measurements.

Wolfgang Filbert

Bettina Franke

Geoff Freeze

Geoff Freeze is an Engineer/Hydrogeologist at Sandia National Laboratories in Albuquerque, New Mexico. Mr. Freeze has 30 years of professional experience in radioactive waste disposal, probabilistic risk and safety analyses, groundwater modeling, and site characterization. He has supported radioactive waste disposal programs in the United States (US) (at both Yucca Mountain and the Waste Isolation Pilot Plant) and internationally, including 4 years as the Yucca Mountain Project Lead for Features, Events, and Processes (FEP). He is currently the Project Integration Manager for the Deep Borehole Field Test.

His radioactive waste performance assessment modeling experience ranges from the development and application of complex, highly coupled, site-specific, probabilistic system models in a legal/regulatory environment to simplified, generic, deterministic system models supporting FEP screening and scoping studies. His flow and transport modeling experience includes single- and multi-phase, saturated and unsaturated, dual-porosity and discrete fracture implementations, as well as evaluations of alternative remediation techniques.

Mr. Freeze has authored over 40 journal articles and project reports, taught short courses in computer solutions to groundwater problems, and written chapters on “Decision Making” and “Solute Transport Modeling” for the McGraw-Hill Environmental Handbook. He holds an M.S. degree in Agricultural Engineering from Texas A&M University and a B.A.Sc. degree in Civil Engineering from the University of British Columbia.

Mr. Freeze presented at the 3rd US/German Workshop on the topic of Safety Case for Salt Disposal of HLW/SNF and at the 4th and 5th US/German Workshops on the topic of FEPs.

Daniela Freyer

Daniela Freyer is scientific assistant at the Institute of Inorganic Chemistry at the Bergakademie Freiberg (Germany). Her research field focused on salt and mineral chemistry since over 20 years with experiences in determination of solubility equilibria in the oceanic salt system up to 200°C (solution analysis; solid phase characterization: XRD, Raman, thermal analysis, Scanning Electron Microscope, chemical analysis; modelling). Special research activities are in the range of construction materials consisting of salt binder phases, such as calcium sulfate phases against the background of gypsum building material applications. A specific research field is focused on Sorel phases formation concerning geochemical and geomechanical properties of the magnesia building material.

André Gaßner

Casey Gadbury

Ramon Gasull

Ramon Gasull is an electronic and industrial engineer (Polytechnic University of Catalonia) with five years of experience in nuclear technology. He was involved in deterministic and probabilistic safety assessments of nuclear facilities, as well as in qualification processes related to I&C equipment for a new build project of a nuclear power plant. Since joining the International Cooperation Department of DBE TECHNOLOGY GmbH in 2012, he has been involved in industrial and R&D projects related to the design and operational safety of near surface and geological radioactive waste repositories in various countries.

Uwe Glaubach

Since 2004, Uwe Glaubach works as a scientist at the Technical University Bergakademie Freiberg. His work is focused on the development of bituminous and asphaltic sealing elements in underground engineered barrier systems, the optimization of sealing materials based on crushed salt, materials characterization and development, and planning, managing and execution of field and laboratory tests. Uwe Glaubach holds a degree as graduate geotechnical engineer at the faculty of Geoscience, Geotechnique and Mining at Technical University Bergakademie Freiberg. He will present at the sixth US/German workshop on the topic of the progress of the shaft sealing project (ELSA).

Jacques Grupa

Matthias Gruner

Jörg Hammer

Andreas Hampel

Dr. Hampel is a physicist. After his PhD work at the TU Braunschweig about deformation micro-processes in metals and alloys, he started in 1993 at the BGR Hannover his investigation of the thermo-mechanical behavior of rock salt and the development of the Composite Dilatancy Model. In 1998 he began to work as an independent scientific consultant, since 2004 he has been the coordinator of a Joint Project series on the comparison of constitutive models for rock salt.

Frank Hansen

Dr. Hansen has over 40 years of experience in repository sciences and has contributed significant original research in rock mechanics, seal systems, materials, design, and analysis. He is a Senior Scientist at Sandia National Laboratories, a registered professional engineer and an American Society of Civil Engineers Fellow.

Jaap Hart

Dr. Jaap Hart, PhD in Process Engineering, is Senior Consultant in the Department of Radiation and Environment at NRG, with more than twenty years of experience within ECN/NRG in the fields of thermalhydraulics and severe accident analysis of nuclear power plants, and performance assessments for geological radioactive waste repositories. Jaap Hart has been involved in a variety of EU Framework projects, e.g., such as BENIPA, RED-IMPACT, ESDRED, PAMINA, SITEX, and MoDeRn. Recent activities include the long-term analysis of the nuclear fuel cycle, and the participation in the IAEA Coordinated Research Projects ASAM, PRISM, and PRISMA. Within the Dutch research program OPERA Jaap Hart is involved in several research projects on Safety Case development, waste characterization, and safety assessment.

Jan-Martin Hertzsch

Michael Hofmann

Michael Jobmann

Diplom Geophysiker (M. Sc. Eq.), Deputy Head of Research & Development Department, DBE TECHNOLOGY GmbH. After finishing his studies at Technical University of Clausthal as Diplom Geophysiker in 1986, he gained experience in the field of geothermal energy exploration. As a project scientist, he was involved in the theoretical development of borehole logging tools, analysis methods and laboratory measurement methods for drill core sample investigations regarding hydro-thermal rock properties. From 1994-2001, he was manager of different research projects at DBE in Germany that dealt predominantly with the development of fibre optic monitoring systems. Since 2001, he is a member of DBE TECHNOLOGY GmbH as project manager and deputy head of the Research & Development department. His current work focuses on the monitoring of high-level waste repositories and the development of a safety and safety demonstration concept for a HLW repository in clay in Germany.

Jürgen Krone

Wolfram Kudla

Kris Kuhlman

Kristopher Kuhlman is technical staff at Sandia National Laboratories. His research interests include ultra low-permeability rocks and geologic disposal of radioactive waste in mined repositories and boreholes. Kris worked for Sandia at the Waste Isolation Pilot Plant in Carlsbad before his current focus on deep borehole disposal. Kris got a BS in Geological Engineering from Colorado School of Mines and a PhD in Hydrology from University of Arizona.

Leszek Lankof

Mr Leszek Lankof is a research fellow in Polish Academy of Sciences. He holds M.S and PhD degrees in Geology and Earth Sciences of Jagiellonian and Silesian Universities. He was involved in many projects commissioned by National Atomic Energy Agency and Ministry of Economy on site selection for SN fuel and HLW underground repository. He also has an experience in prospecting for potash deposits in Poland as well as in evaluation of domal and bedded salt formation for hydrocarbon storage in underground caverns. Nowadays he is involved in works on site selection of new surface repository for low and intermediate radioactive waste in Poland.

Thomas Lautsch

Dr. Thomas Lautsch studied at the RWTH in Aachen from 1979 to 1985 and completed his PHD in 2004. He also holds a master degree in business administration from Waynesburg College.

Dr. Thomas Lautsch is manager in the mining industry with 30 years of experience. He has a strong background in operating deep mines; 13 years being mine manager at Westerholt coal mine, 6 years of being technical director of RAG's international operations in the US and Australia and being COO of PG Silesia in Poland for the last two years. He also carried out large scale mining projects such as recommissioning the Reichwalde strip mine in Lusatia and conducted the pre-feasibility-study for the Spremberg copper mine in the same area. Since 2015 Dr. Thomas Lautsch is managing director of DBE in Peine (Germany), responsible for the technical areas of the company and for the construction of final geological disposal sites for radioactive waste materials.

Christi Leigh

In October of 2007 Christi began the management of Sandia's Repository Investigations Department where she is still today. While in this assignment, Christi has assumed leadership for the science programs supporting certification of the Waste Isolation Pilot Plant. She is currently leading the salt R&D program funded by the US DOE Office of Fuel Cycle Technologies in the Used Fuel Disposition Campaign. Prior work at SNL focused on performance assessment, probabilistic risk assessment, and decision making for environmental problems in regulatory environments. She has been at SNL for thirty-one years. Beginning in 1989, Christi's emphasis has been in developing the technical basis for radioactive waste disposal, low-level, transuranic and high-level waste. Her technical contributions in the areas of geochemical, hydrological, and contaminant transport issues have supported performance assessments for both Yucca Mountain and the Waste Isolation Pilot Plant. She has also offered her expertise to the DOE on a number of surface soil remediation problems throughout the US.

Christi holds a Bachelors, Masters and PhD in Chemical Engineering from Arizona State University, Stanford University and the University of New Mexico, respectively.

Bastian Leuger

Karl-Heinz Lux

Ralf Mauke

Ralf Mauke holds a degree as graduate geotechnical engineer at the faculty of Geoscience, Geotechnique and Mining at Technical University “Bergakademie Freiberg.” He has worked on repository sciences since 1995 and also other rock mechanic related repository and tunnelling projects (e. g. “Schacht Konrad” and “Stuttgart 21”). For the BfS he led the design and analysis work for the Morsleben drift seal systems over 15 years, oversee backfilling measures, and is responsible for different research items related to the closure concept of the Morsleben repository including the large scale testings of the sealing measures.

Volker Metz

Since 2000 Dr. Metz works at the Research Center Karlsruhe (FZK) now Karlsruhe Institute of Technology, Institute for Nuclear Waste Disposal (KIT-INE) currently being the head of the “Safety of Nuclear Waste Disposal“ division. He obtained a M.Sc. degree in mineralogy from the Leibniz University Hannover (Germany) and a Ph.D. degree in geochemistry from the Ben-Gurion University of the Negev (Israel). His field of research comprises experimental and modelling studies on radiolysis induced dissolution of UO2 / SNF, behavior of radionuclides during alteration of radioactive waste products under conditions of a repository in rock salt, geochemistry of Ra-226 in highly saline systems and clay mineral dissolution kinetics.

Wolfgang Minkley

Helmut Mischo

Helmut Mischo, Prof. Dr.-Ing., Pr. Eng. (ECN), born in Püttlingen/Saar in 1969. Prof. Mischo graduated from Aachen Technical University as Diplomingenieur Mining Engineering. He then worked in different positions in the hard coal as well quarry stone industry before changing to Clausthal Technical University as a research fellow in . There he was appointed chief engineer at the Department of Mining in 1998 and was awarded his PhD in 2002. He continued working as assistant professor and 2004, when he changed to the Knauf group. As of 2007, as Professor for Mining Engineering and Director of the Civil and Mining Engineering Department at the Polytechnic of Namibia/Namibia University of Science and Technology, Helmut Mischo set up the first Namibian mining engineering university degree course and institute as well as the Namibian GeoCentre. He served as a member on the board of the Engineering Council of Namibia and is still working as an advisor to the Namibian Chamber of Mines and the Uranium Institute today. In 2011 he took up the chair of Underground Mining Methods at Freiberg Technical University and, in 2012, additionally the post of Scientific Director of the Research and Educational Mine FLB "Reiche Zeche."

Christian Missal

Christian Missal has been working as scientific staff at the Institute for Soil Mechanics and Foundation Engineering at the Technische Universität Braunschweig since October 2008. He studied civil engineering and has worked on salt mechanics, underground disposal and the development of a constitutive model for rock salt.

Matthias Mohlfeld

Jörg Mönig

Nina Müller-Hoeppe

Erika Neeft

Dr. Neeft is the technical coordinator of the Dutch research programme into geological disposal of radioactive waste at the waste management organisation COVRA. She holds a MSc degree in Earth Sciences from Utrecht University and a PhD in reactor physics (transmutation of nuclear waste) from Delft University of Technology.

Gerald-Hans Nieder-Westermann

Mr. Nieder-Westermann has over twenty years of experience in nuclear waste management issues. He currently works for DBE TEC located in Peine Germany in their International Cooperation Department. He is primarily involved in projects in Eastern Europe, specifically in Bulgaria and Ukraine. Related to Bulgaria he supports the State Enterprise for Radioactive Waste in the development of detailed technical specifications for the construction of a short-lived low and intermediate level radioactive waste repository. Specific to the Ukraine he is involved as an expert providing support to the Ministries of Ukraine in their effort to redesign and modernizing that country's national waste management organization in-line with best international practices. Prior to moving to Europe Mr. Nieder-Westermann worked on the Yucca Mountain Project in the US as a lead technical manager in work leading to the license application. Specific to the license application he acted as a key technical lead for Bechtel SAIC LLC in review and approval of the post-closure performance assessment of the Yucca Mountain Safety Analysis Report. Related to his years of experience in post-closure assessment he also developed extensive experience in scenario development and evaluation of features, events, and processes. Post license submittal Mr. Nieder-Westermann provided key technical support to the DOE's legal team in preparation for the Atomic Safety and Licensing Board hearings.

Andrew Orrell

Mr. Andrew Orrell is the IAEA Section Head for Waste and Environmental Safety, in the Division of Radiation, Transport and Waste Safety responsible for the development and promulgation of internationally accepted safety standards, requirements and guides for the management of radioactive waste and spent fuel, decommissioning, remediation and environmental monitoring. In addition, Mr. Orrell oversees the planning and execution of support to the IAEA Member States for the implementation of the IAEA Safety Standards and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Prior to joining the IAEA, Mr. Orrell was the Director of Nuclear Energy Programs for Sandia National Laboratories, providing leadership for program development initiatives involving all facets of the nuclear fuel cycle. He was responsible for Sandia's Lead Laboratory for Repository Systems program and led Sandia's completion of the post-closure performance assessment portions of the Yucca Mountain License Application. Prior to working on the Yucca Mountain Program, he was a manager for the Waste Isolation Pilot Plant and the National Transuranic Waste Management program. His professional experience spans technical and managerial roles for the US and international programs, including repository development and licensing, national policy development, regulatory framework development, site characterization studies, safety assessments and safety case development, and public confidence.

H.-Chr. Pape

Thomas Pick

Ingo Plischke

Till Popp

Dr. Till Popp is a mineralogist working since 1986 in the field of hydro-mechanical rock investigations at a lab or field scale. Since 2003 he is appointed at the IfG, Leipzig as project manager, mostly responsible for research projects aiming on disposal of radioactive and toxic waste in salt and argillaceous clay formations.

Maximilian Pusch

Mr. Pusch is geologist at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover. He studied geology (2004-2009) at the Lehrstuhl für Ingenieurgeologie & Fachgebiet Tektonik und Gefügekunde at Technische Universität München (TUM) and holds an Dipl.-Geol. (Univ.) degree (M.Sc.eq.). Within the realms of the joint research project "Dynamik abgesoffener oder gefluteter Salzbergwerke und ihres Deckgebirgsstockwerks (*Staßfurt II*)" Mr. Pusch went in summer 2008 for his diplom thesis to BGR Hannover. After university graduation Mr. Pusch was employed in the Staßfurt -project until fall 2010 by BGR. From fall 2010 to the end of December 2013 in the realms of the further exploration of Gorleben salt diapir by BGR he analyzed together with other BGR-experts the concentration and distribution of hydrocarbons within the main rock salt of Gorleben exploration mine and is still employed at BGR for further geological investigations of rock salt.

Benjamin Redlunn

Dr. Benjamin Reedlunn is a Senior Member of the Technical Staff at Sandia National Laboratories. His primary focus is computational solid mechanics, but he also has a strong background in experimental solid mechanics and materials science. Dr. Reedlunn's research interests include shape memory alloys, ductile failure modeling, additively manufactured alloys, and, more recently, the mechanics of salt.

Tatiana Reiche

Tatiana Reiche studied physics at the Technical University of Tashkent (Uzbekistan) and computer science at the Technical University of Braunschweig (Germany). In 2009 she joined GRS GmbH (Final Repository Safety Research Division) as a scientific employee. She is engaged mainly in development of the mathematical and numerical models of the processes in a final repository for radioactive waste in different types of geological formations as well as in software design and development of the program code.

Andreas Reichert

Lance Roberts

Lance A. Roberts, Ph.D., P.E. is a Professor and Department Head of the Mining Engineering and Management Department at the South Dakota School of Mines and Technology (SDSMT). Prior to joining SDSMT, Dr. Roberts was the Senior Vice President of the Mining & Energy Division at RESPEC, Rapid City. Over his career, Dr. Roberts has published over 40 technical papers in both national and international journals and conference proceedings and has presented his research results at numerous forums. His current research interests include time-dependent behavior of geological materials, underground mined storage and waste disposal, and reliability-based design for underground caverns and general rock mechanics problems.

Klaus-Jürgen Röhlig

Anke Schneider

David Sevougian

Dr. David Sevougian is a principal member of the technical staff at Sandia National Laboratories, with over 30 years of experience in earth sciences, including geologic repository science, hydrogeology, geophysics, decision analysis, and petroleum engineering. He has an AB degree from Cornell University and a PhD from The University of Texas at Austin. He is a member of the American Nuclear Society, the American Geophysical Union, and the Society of Petroleum Engineers. Recently he has been working on the safety case and performance assessment methodology for a generic repository for high-level nuclear waste, as well as on characterization and design activities for the US DOE's Deep Borehole Field Test.

Jaroslaw Ślizowski

Steven Sobolik

Steven Sobolik is a Principal Member of the Technical Staff at Sandia National Laboratories in Albuquerque, New Mexico. He is a mechanical engineer by degree, obtaining his Bachelor’s and Master’s degrees from Texas A&M University. He began his career performing high-velocity impact tests at the Sandia rocket sled track. For the past twenty years he has specialized in computational and experimental geomechanics, applied to radioactive waste repository projects such as the Yucca Mountain Project; underground oil storage caverns in salt formations for the US Strategic Petroleum Reserve; CO_2 sequestration, wellbore integrity, and other underground storage and geomechanical projects.

Joachim Stahlmann

Joachim Stahlmann has been working as head of the Institute for Soil Mechanics and Foundation Engineering at the Technische Universität Braunschweig since October 2002. Since the early 1990s he has been active in the field of salt mechanics and underground disposal. He has worked on the construction of the shafts at the Gorleben exploration site and has developed the decommissioning concept and sealing structures in the radioactive waste repository Morsleben, in particular the stability and integrity as well as the functionality of flow barriers and shaft seals. He was a member of the Consulting Group Asse for the Asse mine until 2007.

Walter Steininger

Walter Steininger is a physicist (University of Stuttgart). He made his doctoral thesis at the Max-Planck-Institute for Material Research, Material Science, and worked as a project scientist at the Staatliche Materialprüfungsanstalt, University of Stuttgart, in the field of radiation embrittlement of RPV steels. Since 1991 he is working as a program manager at the Project Management Agency Karlsruhe, Water Technology and Waste Management at the Karlsruhe Institute of Technology, managing, supervising and administrating, on behalf of ministries and on the basis of Federal Programs, RD&D projects related to radwaste disposal.

Thorsten Stumpf

Holger Völzke

Dr. Völzke is a mechanical engineer and has 24 years of experience in the area of spent fuel and radioactive waste management with the Federal Institute für Materials Research and Testing (BAM). There he is head of Division 3.4 “Safety of Storage Containers” and responsible for safety evaluation, experimental and numerical design testing, research projects, and advising authorities, industry and the public. Dr. Völzke is member of the German Nuclear Waste Management Commission - Committee on Waste Conditioning, Transport and Interim Storage (ESK-AZ), consultant for the IAEA and managing collaboration with several international partners.

Thilo von Berlepsch

Erik Webb

Erik manages the Geoscience Research & Applications Group, the core of Sandia’s geoscience capability with five departments centered around Geotechnology and Engineering, Geophysics and Atmospheric Sciences, Geomechanics, Geochemistry, and Geothermal Research. These departments engage across atmospheric monitoring and modeling, climate programs, fossil energy, geoengineering, nuclear repository programs, detection of underground structures, basic science of geological materials, geothermal energy, and geological elements of treaty verification and nuclear weapons programs for multiple federal agencies, foreign governments and in partnership with universities and commercial companies.

Klaus Wieczorek

Degree in geophysics at the university of Münster 1984, since 1985 in repository research, since 1995 with GRS Repository Safety Research Division in Braunschweig. Various projects on rock salt, clay, and crystalline rock, head of geotechnical section.

Max Wippich

Holger Wirth

Jens Wolf

Jens Wolf is a scientist at GRS GmbH. He holds a Diploma in Geology/Hydrogeology and a Ph.D. in Civil Engineering (Hydraulic and Environmental Systems). For nine years he has been engaged at GRS in several projects concerning long-term safety analyses for repository systems in salt, clay and crystalline host rocks.

Ralf Wolters

APPENDIX E: ABSTRACTS

Then and now—Assessing updates to 1998 WIPP modeling assumptions

Kathleen Economy

6th US/German Workshop on
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Abstract

In 1998 the United States Environmental Protection Agency (US EPA) approved the US Department of Energy's (DOE's) Compliance Certification Application for the Waste Isolation Pilot Plant (WIPP) to receive defense transuranic waste; the final review process was initiated in 1996. EPA's approval included features, events, and processes analyses and assessment, a subset of which addressed the transient properties of a salt repository over the 10,000 year regulatory period. DOE's features, events, and processes calculations used 'bounding' assumptions which, coupled with the limited 1990s computational capabilities, translated in adopting conservative parameter values. Some of these bounding assumptions were intended to capture parameter uncertainty for the non-waste area and DRZ porosity over the 10,000 year regulatory period. EPA accepted these to capture the long-term uncertainties of repository behavior. Since the initial 1998 certification DOE has demonstrated WIPP is compliant with these bounding assumptions.

Now, approximately 20 years later, EPA is re-evaluating the bounding assumptions submitted during the certification adopted to support the non-waste area and DRZ parameters against the current knowledge of salt repositories. The evaluation was precipitated, in part, by DOE's recent modification to the repository panel closure design from that of a concrete monolith to one consisting of run-of-mine salt. Several issues motivate this reassessment. First, the recertification is an opportunity to re-evaluate the repository model(s) and incorporate new information as appropriate. An update of bounding assumptions can provide confidence to both the scientific community and the public that appropriate evaluations have been performed and the disposal system is robust. Secondly, what is being done for the WIPP repository—in essence a living laboratory as well as a repository—can be used as a stepping stone to provide knowledge and understanding in designing the next generation of potential salt repositories systems for high- level waste and spent nuclear fuel.

This presentation will briefly review some modeling assumptions adopted during the 1998 WIPP certification and subsequent recertifications related to the DRZ and non-waste areas and compare this to current understanding of the behavior of a salt excavation. Given this comparison, possible model updates will be presented.

The US EPA sets radiation protection standards for low-level and transuranic radioactive waste repositories and oversees and approves the DOE's long-term Performance Assessment for WIPP.

PFLOTRAN: Coupled THC simulations

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Abstract

The United States (US) Department of Energy Office of Nuclear Energy Office of Used Nuclear Fuel Disposition is conducting scientific research to enable disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in a variety of geologic media and generic repository concepts, including mined disposal in salt, clay/shale, and granite formations, and deep borehole disposal in granite formations. An important goal of this research is the development of an enhanced performance assessment (PA) modeling capability that utilizes high-performance computing (HPC) environments to simulate important multi-physics phenomena and couplings associated with the potential behavior of the geologic repository. The application of an HPC-capable modeling/simulation framework for repository performance assessment is a significant advancement because it allows the important multi-physics couplings to be represented directly, rather than through simplified abstractions. It also allows for complex representations of the source term, e.g., the explicit representation of many individual waste packages.

This work describes the application of the HPC-based PA modeling capability to a hypothetical repository for SNF/HLW in a generic bedded salt formation. The salt PA model includes representations of important thermal-hydrologic-chemical (THC) processes and couplings in the various engineered and natural features, including

- Radionuclide Source Term – Waste form degradation and radionuclide mobilization processes associated with the THC environment in the waste form and waste package
- Near Field – Fluid flow and radionuclide transport processes (advection, dispersion, diffusion, sorption, radionuclide decay and ingrowth) in and through the engineered components (backfill and seals) and adjacent disturbed rock zone (i.e., host rock affected by thermal-mechanical-chemical processes associated with repository excavation and waste decay heat)
- Far Field – Fluid flow and radionuclide transport processes (advection, dispersion, diffusion, sorption, radionuclide decay and ingrowth) in and through the undisturbed host rock and an overlying aquifer to a receptor location in the biosphere
- Thermal Effects – Effects of radionuclide decay heat on source term processes and flow and transport processes in the near field

The new PA modeling framework currently utilizes two main software components that are optimized for parallel computations in an HPC environment: DAKOTA for uncertainty quantification and propagation and PFLOTRAN for multi-physics domain simulation. The capabilities of the PA framework were demonstrated for the generic salt repository by performing both deterministic and probabilistic simulations applicable to SNF waste with a burn- up of 60 GWd/MTHM (a burn-up that is expected to be "bounding" for the US inventory in a "no replacement" nuclear generation scenario, wherein all reactors are shut down by 2055). The deterministic simulations were run using "best estimate" generic parameter values for waste degradation and groundwater flow and radionuclide transport under undisturbed repository conditions (e.g., no human intrusions). For the probabilistic simulations, parameter (and potentially model) uncertainty was taken into account using probability distributions that were propagated through the system via a

Monte Carlo approach in DAKOTA. Classical sensitivity analysis (linear and rank regression, correlation study) was implemented to identify the most important parameters.

The results of these deterministic and probabilistic simulations provide insights into the important THC multi-physics processes and couplings controlling long-term repository system performance for a generic SNF/HLW repository in salt as well as into the necessary model fidelity (i.e., the model dimensionality and complexity of process representations). A comparison of these thermal simulation results with results from comparable isothermal simulations (i.e., no decay heat) identifies thermal influences and couplings that are important to system and subsystem behavior. These insights can be used to guide and prioritize future research.

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RepoTREND – A program system for safety analysis

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Abstract

RepoTREND is a new final repository simulator, developed in GRS since 2007. RepoTREND provides functionalities for simulating the release of contaminants in a repository and the transport of these contaminants through the near-field and far-field to the biosphere including the estimation of the radiological consequences for man and environment. This tool is applicable for different concepts of the final repository in different host formations. Main objectives in designing of RepoTREND are modularity and extensibility of the program code. In designing, the state-of-the-art object-oriented approach is used. This approach has the advantage of modelling a final repository system in a natural way, enables data-encapsulation, clear code structure, easy maintaining and unlimited extensibilities. Currently RepoTREND includes the universally applicable graphical user interface XENIA and the framework for statistical analysis RepoSTAR as well as the two near-field computational modules LOPOS and CLAYPOS (old Fortran-code for one-phase transport through a repository in a salt rock and through a saturated clay barrier), the biosphere module BioTREND and some modules (GeoTREND-family) for simulating the contaminant transport in a far-field: POSA (fully saturated porous media), FRAME (fully saturated fractured media), COFRAME (colloid facilitated transport in porous- fractured media). Currently the new near field computational module NaTREND is being developed, taking into account the two-phase contaminant transport. The main goal in the designing of NaTREND is to provide a high flexibility and extensibility while maintaining good performance and high accuracy. Some concept ideas for considering of different effects are presented as an example of how to achieve this objective.

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Microstructure stabilized crushed rock salt backfill material for HAW-repositories in underground saliniferous rock formations

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Abstract

The refill of openings in HAW-repositories (HAW = high-activity waste) is necessary to guarantee the long-term stability of the geological barrier by reduction of the geological movements as well as the reduction of possible flow path for fluids within the repository. Currently there are two main types of materials for backfilling in saliniferous rock formations. These are crushed rock salt and saliniferous composite backfill materials

Crushed rock salt is a bulk material with a defined grain-size distribution that is won by mining rock salt deposits. Crushed rock salt consists mainly out of the mineral halite as well as other naturally occurring mineralizations. Due to its origins, crushed rock salt is an adequate backfill material for HAW-repositories in saliniferous rock formations. Moreover, crushed rock salt is available in high quantity and it is a low cost material for backfilling. The disadvantages of crushed rock salt are the low permeability, the low refilling rate of openings, the tendency of settlements and the formation of roof clefts. A late stabilization of the surrounding rock is the consequence.

Saliniferous backfill materials consist out of a grain mixture that is imbedded in a matrix formed by a binding agent that fills out the pores within the grain mixture. The advantage of these backfill materials are a high refill ratio, a low permeability as well as a fast stabilization of the surrounding rock. The disadvantage of these materials is the high content of the binding agent that is needed to form the supporting matrix. Due to this high amount of a binding agent the material require abutments and casings to put it into place, which means complex technical installations. Moreover, with these materials, normally a high amount of water is applied into the saliniferous formation, a situation to be avoided under any circumstances.

The microstructure stabilized crushed rock salt backfill material is developed to realize a fast stabilization of the geological barrier, a reduction of the permeability within the repository as well as the fast backfill progress. This is reached by the addition of low binding agent content to a crushed rock salt. The emplacement of the backfill material can be done without abutments or drainages like a bulk material due to the low binding agent contents. The microstructure stabilization is realized by the formation of new long-term stable salt minerals that connect the rock salt grains with each other. Tests have shown that the formation of long-term stable minerals is occurring. The stabilization of the surrounding rock happens faster than compared with common rock salt.

Uncertainty management in performance assessment

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Abstract

Proper uncertainty management is necessary for any performance assessment to be- come meaningful and is therefore increasingly considered an important task in the Safety Case. Uncertainty management consists of two parts: in the first step it has to be made sure that the modelling setup, i.e. the investigated scenarios, the applied computer models and the assumed parameter uncertainties, correctly reflect the degree of knowledge or non-knowledge about the system. In the second step, mathematical uncertainty and sensitivity analysis has to be performed. For the first step, which can only be done via expert assessment, widely accepted, transparent and unique procedures do not yet exist. For the second step, a variety of mathematical methods exist and new ones are constantly being developed, but these methods have to be tested and qualified for repository models. Some work was done in projects like PAMINA and in national programs, but international harmonization is necessary. A Technical-scientific working group of the IGD-TP is addressing these topics.

Probabilistic and deterministic safety assessment approach for shaft hoisting systems

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Abstract

The main concern related to shaft hoisting of payloads associated with underground transport of radioactive waste for disposal is a failure in the hoisting system that could result in a fall of a waste package down the shaft and the associated potential for release of radioactive materials. For this reason and to ensure that all relevant operational safety requirements are met by the design of the facility, operational safety assessments for shaft hoisting systems have been carried out in Germany for more than twenty years.

In a similar way as it is done in nuclear power plants (NPPs), deterministic and probabilistic safety methods have been applied. Deterministic methods have been used to qualitatively analyze the sequence of operations, to identify potential safety relevant events and to quantify their consequences. These deterministic analyses have been complemented by probabilistic methods, which determined the probability of failure of the components and the frequency of occurrence of the undesired end-states. The starting point of the safety assessment for shaft hoisting systems is the identification of potential safety-relevant events that can lead the facility to an undesired end-state (i.e. events leading to potential radiation exposures). The undesired end-states can occur in the event of loss of waste package integrity (e.g., damage of the waste package) or when operating personnel are required to remain in the vicinity of a waste package for periods longer than required under normal operation conditions (e.g., to carry out repair work).

Currently, DBE TECHNOLOGY GmbH is analyzing the safety assessment methodology for shaft hoisting systems used in Germany, as well as the methodology currently used in German NPPs in order to determine the best methodology for assessing the operational safety of a shaft hoisting system. This work is carried out in the framework of the research and development project "Safety studies on the shaft transport of heavy loads up to 175 t *(Sicherheitstechnische Untersuchungen zum Schachttransport schwerer Lasten bis zu 175 t Nutzlast - SULa)*," which is funded by the Project Management Agency Karlsruhe of the Karlsruhe Institute of Technology.

Balancing operational phase and post-operational phase safety

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Abstract

The concept of a "safety case" for a deep geological repository for radioactive waste was introduced by the Organisation for Economic Co-operation and Development/Nuclear Energy Agency in the last decade of the last century and has been developed and applied within many national radioactive waste disposal programmes and also taken up in some national regulatory guides. A safety case pertains to the operational phase and the post- operational (post-closure) phase, and thus both operational safety and long-term safety should be addressed. In the past, the emphasis of research and development activities was clearly on the operation of the disposal facility and the assessment of the impact of the emplaced waste on the environment after repository closure. Operational safety was often addressed but not discussed in detail.

Now that some national programmes move towards licensing and practical realizations, operational safety becomes more and more a focus of public interest. Internationally, considerations on methodologies for hazards assessment for the operational phase are under development (e.g., the International Atomic Energy Agency GEOSAF projects or the Nuclear Energy Agency expert group on operational safety) and reveal strong interdependencies between operational safety and post-closure safety: on the one hand, design and operational constraints are set by post-closure safety requirements while on the other hand, the operation of a disposal facility determines the initial conditions for the post- closure phase and thus for the assessment of post-closure safety. For a safe operation the impacts of post-closure constraints on the design and implementation of the geological disposal facility must be identified. Moreover, it is important to realize more clearly the impact of operation, including construction, on post-closure safety. According to the basic ideas of the safety case the interdependencies between operational phase and post-operational phase must be documented thoroughly. Methods to illustrate these interdependencies have not been developed yet.

The challenge of balancing the requirements of both phases within a safety case is supposed to be a suitable field within the US/German cooperation. In this contribution first ideas will be presented how to analyze and document the interdependencies between the operational phase and the post-operational phase in order to be able to balance requirements of both phases within a safety case.

Monitoring of repositories for high-level radioactive waste (EC-Projects Modern and Modern2020)

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Abstract

The successful implementation of a repository program for radioactive waste relies on both the technical aspects of a sound safety strategy and scientific and engineering excellence as well as on social aspects such as stakeholder acceptance and confidence. Monitoring is considered key in serving both ends. Not only is it essential to underpin the technical safety strategy and quality of the technical implementation. It can also be an important tool for public communication, contributing to public understanding of and confidence in repository behavior. In the framework of an international project called MoDeRn (Monitoring Developments for safe Repository operation and staged closure) that is funded by the European Commission, a monitoring reference framework has been developed by 18 international partners. This reference framework describes the common understanding of how monitoring of a high-level radioactive waste repository can be done and at the same time gives an overview of the technological possibilities and limits of monitoring systems. During the MoDeRn project, several open questions have been identified, which focus on monitoring of engineered barrier systems, the use of monitoring results for decision making processes during the operational phase of a repository and probably after closure as well as on technical aspects regarding sensor technology, wireless data transmission, and power supply.

These open questions are tackled by the follow-up project of MoDeRn, which was launched in June 2015 and is called MODERN2020. This new project addresses the development of a monitoring program design basis, monitoring strategies and the role of monitoring in decision making by focusing on specific national programs. Stakeholders will be involved in each task of this work to explore how their early involvement should be addressed appropriately. It also addresses research and technical developments on monitoring technologies and intends to demonstrate the practical implementation of specific monitoring plans through several *in situ* demonstrations including the application of innovative monitoring techniques to further enhance the knowledge on the operational implementation of specific disposal monitoring. Finally, stakeholder engagement activity will be in direct relation to the research and development work developed in the work mentioned above and will be an issue throughout the project's lifetime.

The MODERN2020 project receives funding from the Euratom research and training program 2014-2018 under grant agreement n° 662177.

Joint Project on constitutive models for rock salt: Benchmark calculations of WIPP Rooms D and B

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Abstract

The current third Joint Project on the Comparison of Constitutive Models for the Thermo-mechanical Behavior of Rock Salt (2010-2016) is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and managed by the Project Management Agency Karlsruhe (PTKA). The project is a US-German collaboration of the following seven partners:

- Dr. Andreas Hampel (AH), Scientific Consultant, Mainz, Germany
- Institut für Gebirgsmechanik GmbH (IfG), Leipzig, Germany
- Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany
- Leibniz Universität Hannover (LUH), Hannover, Germany
- Sandia National Laboratories (SNL), Albuquerque and Carlsbad, NM, USA
- Technische Universität Braunschweig (TUBS), Braunschweig, Germany
- Technische Universität Clausthal (TUC), Clausthal-Zellerfeld, Germany

In this project, selected benchmark calculations are carried out in order to check the ability of the involved models to describe correctly 1) the temperature influence on deformation in a) domal salt from the Asse II mine and b) bedded salt from the Waste Isolation Pilot Plant, and 2) the damage and dilatancy reduction and healing of rock salt from the Asse II mine. This contribution focuses on part 1b.

At first, unique sets of model parameter values for the two salt types at the Waste Isolation Pilot Plant (WIPP), clean salt and argillaceous salt, were determined by each partner with back-calculations of extensive and systematic series of laboratory creep and strength tests that were performed by IfG and TUC. Then, several simulations of the unheated Room D and the heated Room B at WIPP were performed in order to examine and compare the modeling of the temperature influence on the horizontal and vertical room convergences.

For the simulations, each partner uses his constitutive model with the determined parameter values and a simplified plane strain model of a vertical cut through the center of a room. While the results are in the right order of magnitude a show the right dependences, remaining deviations from the *in situ* measured convergences can be explained with deformation phenomena that are not taken into account sufficiently yet and need more experimental and theoretical research and further development of the constitutive models. These phenomena shall be investigated in detail in another planned joint project (2016-2019).

Topics for future US/German research work focusing on integrity analyses – Repositories in salt

Till Popp, Wolfgang Minkley (IfG, Leipzig), Sandra Fahland, Jörg Hammer (BGR, Hannover), Andreas Hampel (Hampel Consulting, Mainz), Karl-Heinz Lux (TU Clausthal),Nina Müller-Hoeppe (DBE TEC, Peine), Joachim Stahlmann, Christian Missal (TU Braunschweig), Klaus Wieczorek (GRS Braunschweig), Frank Hansen (SNL)

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Abstract

The 5th US/German Workshop "Salt Repository Research, Design, and Operation" took place from 8 – 10 September 2010 in Santa Fe, New Mexico. In addition to the presentation of current results of ongoing research projects, one more task consisted in the identification of future common research foci, which was carried out in working groups formed for specific topics. In the following, the results of the discussions of participants from the above-mentioned institutions and the joint follow-up work are summarised.

According to the safety requirements issued by the Bundesministerium für Umwelt (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the main safety principle for the final disposal of radioactive waste is to contain the waste and its contents as quickly as possible and in a permanently safe way in a containment providing rock zone during the post-closure phase. In repository concepts in salt, safe containment has to be ensured by the properties of the rock salt in the containment providing rock zone combined with the properties of the geotechnical barrier system. The integrity of the geological barrier has to be verified by means of the dilatancy and minimum stress criteria. Taking into account the acting loads, the effectiveness of the drift and shaft seals has to be demonstrated for the period in which the crushed salt backfill has not yet developed its full sealing function.

As part of the system analysis, the corresponding integrity analyses of the geological barrier (1) and of the geotechnical barriers (2) in the reference period are a central element of every safety analysis for a repository and are thus also necessary for a comparative site assessment within the framework of a repository site selection process.

The required demonstrations of geological and geotechnical barrier integrity can only be carried out by means of numerical model calculations. Although it can be stated that the scientific level of system analysis (especially regarding integrity analysis) is high, improvement of uncertainties is necessary. Due to the complex boundary conditions (e.g., geologic environment), the resulting models should be three-dimensional where necessary. This requires a basic understanding of the safety-relevant impacts and processes as well as their description in a theoretic model including constitutive relations in the form of material laws that link impacts and consequences. Furthermore, the material parameters necessary for the application of the models have to be known, and suitable calculation programmes for implementing the model-based theoretical approaches must be available.

Taking this in mind, three possible research and development topics have been identified: (1) Consequence analysis when the minimum stress criterion is violated, (2) description of the hydraulic and mechanical properties of compacted crushed salt, and (3) mechanical behaviour of rock salt/development of constitutive laws. In addition to recommendations with specific measures for their implementation, proposals for a prioritisation of the topics and opportunities for US/German cooperation were given.

The detailed summary is available as a joint discussion paper.

Integrity of salinar barriers for heat-generating radioactive waste – Geomechanical requirements and natural analogues

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Abstract

Undisturbed salinar rocks are impermeable to fluids and gases. This is supported by natural analogues. For example, tertiary volcanism has left deposits of supercritical CO2 as large as 10^5 m3 contained in rock salt until today. In contrast, the overall volume (including containers) of heat-generating radioactive waste in Germany is 4*104 m3 for drift emplacement and is in a solid state.

Salt formations can lose their geomechanical integrity and leak tightness if the groundwater pressure or a gas pressure exceeds the minimal stress in the salt formation. The minimal stress may be lowered due to extensional strain conditions, either by subsidence or by thermo-mechanically induced lift-up of the rock mass above the mining horizon.

So far, saline barriers have lost their integrity only for relatively thin barriers (< 100 m) with low confining pressure, i.e. in salt mines in shallow depths. If the barrier is sufficiently thick, salt mines are safe from water inflow even under earthquake-like incidents, as can be seen from a dozen rock bursts in potash mines worldwide with magnitudes up to 5.6.

The conventional containment mechanism for HLW relies on the compaction of crushed salt backfill by the convergence of the host rock, with residual porosity over a long time. Novel experimental results show that immediate complete containment as well as retrievability of the waste can be achieved by using eutectic molten salts as backfill material, which are kept liquid by the waste-generated heat. Hence, the waste canisters at the borehole emplacement could be easily retrieved. Furthermore, water cannot reach the canisters because of the higher density of the molten salt. When the temperature reaches the freezing point (in the range of $100^{\circ} - 200^{\circ}$C) after hundreds of years, the molten salt solidifies and becomes an impermeable salt mass like the host rock. Since from the outset there would be no residual pore volume, a contamination scenario with transport of harmful material to the biosphere by fluids would be obsolete.

Laboratory investigations at the IfG have shown that recrystallised eutectic HITEC salt is impermeable to fluids similar to natural rock salt and loses its integrity only for fluid pressures above the minimal principal stress. A backfill concept with molten salt for repositories for heat-generating nuclear waste for drift or borehole emplacement in salt rocks has several distinct advantages:

- Immediate and complete containment of the waste containers in the molten salt
- No water or brine access to the containers due to the higher density of the backfill
- No porosity, no squeeze-out of contaminated solutions by creep convergence
- Only slight volume reduction upon recrystallisation
- Retrievability even for borehole emplacement
- Earthquake resistant
- Technologically simple complete filling of all cavities because of the low viscosity of molten salt

Content and distribution of fluids in domal and bedded salt: influence on the geomechanical behavior of rocks

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Abstract

Content and distribution of fluids (e.g., brines or saline solutions, hydrocarbons, CO_2 and other gases) as well as of anhydrite or clay minerals in domal and bedded salt are very important parameters influencing the geomechanical behavior of salt rocks.

New geomechanical testing data for bedded salt from the Waste Isolation Pilot Plant (WIPP) in combination with new microscopic studies on thin sections demonstrate the influence of water content and impurities (e.g., anhydrite and clay minerals) on strength and creeping of salt rocks. Unlike the nearly homogeneous Hauptsalz from Gorleben salt dome (with an anhydrite content of mostly less than 3 Vol.-%), the halitic rocks of WIPP are differentiated into the argillaceous (clay- and polyhalite-bearing) and the clean rock salt. Compared to the clean rock salt, the argillaceous rock salt of WIPP (excluded polyhalite enriched samples) shows a significant higher creeping rate. Testing results show that concentration and distribution of clay and other minerals, fluid inclusions and grain size distribution determine the creeping rate of WIPP salt.

Furthermore we have tested a new preparation method to quantify the water content in different rock salt types by Karl-Fischer-Titration. We used a halitic sample from WIPP-drilling SNLCV302 near MB139 (as example for bedded salt and increased water content) and a Hauptsalz sample from drilling station 3 in Gorleben exploration mine (as example for domal salt and decreased water content). To avoid loss of water during sample preparation (burst of grain boundaries and fluid inclusions placing on the boundaries) the samples have been milled with anhydrous acetone (with less than 70 ppm of water) in a hermetically sealed crushing mill with argon as protective gas in order to free up the water bound within the samples and ligated within the acetone without gathering water from hydrous mineral phases like e.g., polyhalite or carnallite. The first analyses revealed significant differences in the water content of rock salt from domal and bedded salt formations between WIPP clean rock salt (0.99 wt-%) and Gorleben (0,29 wt.-%) samples.

As requested by the US-German salt community three series of creep tests on halite have been investigated in the BGR laboratory at very low differential stress conditions. These samples from the ERA Morsleben are stratigraphically located in z2HS (Hauptsalz), z3LS (Liniensalz) and z3BK/BD (Bank-/Bändersalz). Differential stress was set to 6 MPa for z2HS, 5 MPa for z3LS and 3 MPa for z3BK/BD. The creep rates of z2HS (after 220 days) and z3LS (after 210 days) correlate with the values predicted by BGR for these stratigraphic units. The sample of halite from z3BK/BD has not reached stationary creep after 150 days.

Comparison of confined constant strain rate strength tests performed on WIPP clean salt

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6th US/German Workshop on
Salt Repository Research, Design, and Operations
Dresden, Saxony, Germany
September 7-9, 2015

Abstract

This project describes scientific procedures for completing confined, triaxial, constant strain rate strength tests of intact salt at temperatures ranging from about 25°C to about 100°C. Laboratory studies allow generic salt properties (mechanical, thermal, hydrological, and chemical) to be measured in a controlled environment. There is a large body of laboratory data that describes the phenomenology of salt across a broad range of temperatures expected in a heat-generating waste disposal system. Laboratory studies currently underway in Germany are being conducted using salt samples provided by Sandia National Laboratories that were obtained from the Waste Isolation Pilot Plant site and those test results will add substantively to that body of knowledge. When combined, the total database of laboratory results will be used to develop input parameters for models, to assess adequacy of existing models, and to predict material behavior. These laboratory studies are also consistent with the aims of international salt repository research programs.

The focus of the activity in this project is to complete a limited number of independent, adjunct laboratory tests in the United States to assist in validating the results being provided by the German facilities. Assuming the adjunct tests substantially agree with the German test results, the overall database of test results will be considered more robust and confidence in the databases for assessing adequacy of heat-generating waste disposal systems will be enhanced. This adjunct testing program will represent a subset of the extensive test matrix being completed in Germany and it will aid in reducing uncertainties that remain in the technical databases for a generic safety case for disposal of heat-generating waste in salt.

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy's National Nuclear Security Administration under contract DEAC04-94AL85000. SAND2015- 6923 A.

Compilation of salt dilation test data for assessment of variability

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Abstract

The dilation limit, often determined from a series of constant mean stress (CMS) tests conducted under laboratory conditions, is one criterion used to assess the performance of underground storage caverns and mines in salt. In the case of a cavern, the allowable operating conditions, such as the minimum gas pressure, are typically determined based on limiting stress levels within the salt to those that do not result in dilation. This produces a factor of safety with respect to dilation for all points of interest within the cavern. A significant amount of laboratory testing conducted over several years on both bedded and domal salt specimens at RESPEC Consulting and Services shows that the dilation limit can vary significantly within salt, even in specimens that are sampled at the same location. This presentation will highlight the magnitude of that variability. In addition, in lieu of assuming a conventional lower bound criterion for the dilation limit, it is possible to incorporate reliability-based design principles to assess the probability of dilation occurring within the cavern. An introduction to the assessment of dilation limit data using statistical analysis and the RESPEC Dilation (RD) criterion will be presented. The goal is to determine a "probability of exceedance" for dilation within a cavern rather than merely a factor of safety.

Dilatancy of rock salt – load path effects

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6th US/German Workshop on
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Abstract

If rock salt is used as a host rock for final repositories of radioactive waste, it will be subject to thermo-mechanical stress. Mechanical loads in the neighborhood of subterranean excavations and of high-activity waste containers may give rise to dilatancy, and thereby to damage by microcracks, reduction of the load-bearing ability, and increased porosity which causes pathways for transport.

Results of investigations are presented that were conducted on rock salt samples originating from the exploration mine Gorleben. Particular attention was given to the dilatant behavior of the material. For technical reasons, experiments could only be conducted in the compressive load path ($\sigma_1 > \sigma_2 = \sigma_3$). By transforming the invariant formulation of the results onto other stress states, such as the extensive load path ($\sigma_1 < \sigma_2 = \sigma_3$), it can be shown that the formulation which apply to the compressive load path would lead to implausibly high dilatant strengths.

In consequence, numerical simulations which are based e.g., upon the Composite Dilatancy Model (CDM) constitutive law and which apply the values for the dilatancy boundary derived from experiments in the compressive load path will produce satisfactory results for load-bearing structures such as narrow pillars. If, however, predictions are attempted for cases in which the extension load path applies, the dilatancy effects will be severely underpredicted. For such purposes it has been necessary to apply a version of CDM that allows a prediction of the onset and progress of dilatancy for arbitrary stress states.

Since few experimental data exist for other load paths than the compressive one, and consequently there is still considerable uncertainty about the dependency of the dilatancy boundary on the stress components, true triaxial tests on rock salt samples are planned and will be conducted by BGR.

The concept of the SNF and HLW disposal in salt rock in Poland

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6th US/German Workshop on
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Abstract

SNF and HLW disposal concept in salt rock in Poland was considered already in the 70s of the twentieth century in connection with the construction of the nuclear power plant Żarnowiec. Due to construction work stoppage research and development program for radioactive waste disposal was also suspended. Further studies were continued in XX century. As a result of carried out studies potential locations of repository were selected. On the basis of the developed criteria three primary location in rock salt domes: Damaslawek, Łanięta and south part of Kłodawa were chosen. As an additional location bedded salt formation in Łeba region was also considered. Geological exploration revealed that a significant part of the salt domes consist of the clayey salt of Z3 Leine cyclothem ("brown zuber formation") and Z4 Aller cyclothem ("red zuber formation"). In addition to halite, clayey salts consist of anhydrite, clay materials (mainly illite group), dolomite, and some other minerals as quartz, hematite, magnesite, sylvite or bischofite. Therefore laboratory testing carried out to date were focus both on rock salt and clayey salts. The scope of laboratory tests of zuber formations included geomechanical investigations (rheological and strength tests), evaluation of sorption ability and study of thermal expandability and mass losses during heating up. The results of laboratory tests indicate that the strength and rheological properties of clayey salts (especially red zuber) is lower than rock salt while sorption properties are much stronger. The conceptual models of SNF and HLW repository as well as a project of underground research laboratory were also developed.

Comparison of rock salt in stratiform and diapiric deposits in Poland – hints for selection and safety of repositories

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Abstract

Rock salt deposits targeted for storage of hydrocarbons and waste disposal in Poland are built of Zechstein (Upper Permian) salt that accumulated in the Polish Zechstein Basin. At present, the deposits are stratiform in marginal parts and diapiric in the centre of the former basin. This enabled comparison of petrographic and microstructural features and geomechanical properties of salt in various geological settings. The similarities and differences between salts are summarized in this paper. They are noticeable in macro-, meso- and micro-scales.

Studies carried out in stratiform deposits showed that salt series is internally deformed, being folded and zonally sheared in response to flow of salt induced by basement tectonics and load. Lithological heterogeneity of a salt series caused splitting of the salt complex into intensely and weakly deformed zones. This is shown among others by variability in microstructural attributes in halite, advancement in halite recrystallization, content of brine and occurrence of relic sedimentary structures. As a consequence of petrographic and textural variability, rock salt typically displays variable geomechanical properties throughout the salt complex. Fluid and gas migration pathways are determined by layering and mostly related to non-salt interlayers.

Salt diapirs are more heterolithic and the distribution of rock salt complexes largely depends on the shape and tectonic evolution of a diapir. Diapirs are built of different types of rock salt with varying content of anhydrite, clays and potash minerals. The flow of salt into a diapiric structure led to welding of originally separated rock salt beds due to dismembering of more brittle interlayers. Anhydrite, carbonate, clay and potash beds make up minor portion of the bulk diapir mass, their occurrence, however, significantly influenced rock salt behaviour during deformation. Semi-brittle deformation and fracturing of rock salt was documented in portions adjacent to potash layers, in clay-rich rock salts and near hydrocarbon-bearing zones. Rock salt displays multi-stage recrystallization of halite, therefore most diapiric rock salt is free of primary fluid inclusion in halite. Fluid and gas migration paths are determined by layering and tectonic structures. Higher porosity of salt and open conduits for fluids were documented in hydrocarbon-bearing zones, whereas gas-bearing zones contain mostly tight gas entrapped in and between halite crystals. Geomechanical properties of salts depend on rock salt petrography.

The studies showed that salt deposits targeted for disposal of wastes should be evaluated individually. The lithology of a rock salt complex is primarily influenced by environmental factors, specific for each sedimentary basin. The geological and geomechanical characteristics of buried rock salt are mostly functions of the depth of burial, lithological heterogeneity and tectonic evolution of a salt complex. Both in stratiform and diapiric deposits, there are portions of very weak deformation, documented by preservation of primary sedimentary structures. This indicates that salt complexes are compartmentalized and some compartments can be very weakly affected by deformation over millions of years. Fluid and gas migration paths mostly occur in heterolithic complexes, however, there may also exist conduits in rock salt – predominantly inherited from early diagenetic and ancient deformational stages of the salt structure development.

In situ measurements of shear strength and deformation along discontinuities in salt

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Abstract

The Third US-German Joint Project on Salt has identified four key subject areas in the understanding of the behavior of salt for radioactive waste repository operations. One of these subject areas includes the influence of nonhomogeneities in repository performance. Examples of these nonhomogeneities include bedding interfaces, boundary shear planes, joints, and seams of non-halite material such as anhydrite. One of the primary issues regarding these features is the effect of shear strain along their length, especially if that shear strain causes the formation of a permeable flow path along an interface, or results in premature salt failure due to exceeding the shear strength of the interface or joint. Currently there exists little *in situ* measurement data to characterize the shear strength of an interface in salt, and the resulting effects of shear on interface displacement and permeability.

This presentation describes a proposed pressurized slot test to measure the displacement and shear strength of an interface in salt. The idea for this *in situ* test comes from a pressurized slot test performed in volcanic tuff in Yucca Mountain, Nevada, during the characterization of that site as a potential radioactive waste repository. The Yucca Mountain test was designed to measure a rock mass modulus and to determine the extent of nonelastic, permanent deformation under high stress loading conditions. However, the test can be easily modified to provide a shear loading environment on two sides of an interface. Measurements of applied pressure and displacement will capture the evolution of shear-induced changes in the salt during the test. Changes in permeability may be obtained by measurement of the changes to the interface aperture. Pre- and post-test modeling of the experiment and comparison to experimental results will also be critical components to evaluate the effects of the shear loading on the interface. In addition to the *in situ* test design, options for similar laboratory-scale experiments will be presented.

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Salt underground research facilities

Christi Leigh

6th US/German Workshop on
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Abstract

Evaluating the basis of need for an underground research facility (URF) for salt science and engineering is imperative because of the significant commitment of time and money involved. Decades of salt repository studies, numerous experiments, and sophisticated modeling capabilities underpin the scientific database that supports safe disposal of nuclear waste in salt. The safety case for disposal of non-heat-generating waste such as transuranic waste interred at the Waste Isolation Pilot Plant is robust, with the only long-term releases to the environment projected to be by way of human intrusion. The scientific evidence also favors safe disposal of heat-generating waste. The goal for disposal research in salt is to provide sufficient technical information to license a repository. The necessity or utility of a salt URF is to be evaluated in the context of an overall research agenda that supports a license application.

It is widely believed that further salt testing in a URF is not required to address a perceived technical deficiency to be answered as a prerequisite to preparation of a safety case for salt disposal of heat-generating high-level waste. The technical basis for salt disposal provides strong and pervasive evidence that radionuclides in a salt repository will not migrate from the disposal horizon. Current knowledge of thermal effects supports viable concepts for disposal operations and underground evolution. The suitability of salt as a disposal medium has been recognized by national and international repository programs. Therefore, the scientific community must balance desire for field experiments with the recognition that a very strong scientific basis already exists for salt disposal of nuclear waste.

Discussions at the 6th US/German Workshop are intended to help prioritize field testing if research groups were to undertake a commitment to establish a URF. Currently there are no dedicated salt URFs in the world. Given the well-established scientific basis for salt disposal, considerations for testing underground must include scientific rigor and transparent evaluation, implemented with formality, to establish merit and priority. At this workshop paper we identify and URF activities perceived to advance the technical basis for salt disposal and encourage open discussion with technical peers.

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Modelling of crushed salt compaction: Recent findings

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Salt Repository Research, Design, and Operations
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Abstract

Rock salt is considered as a potential host rock for the disposal of high-level radioactive waste (HLW) in Germany. After emplacement of HLW canisters, the disposal boreholes, drifts and shafts must be backfilled and sealed with suitable materials to prevent a release of radionuclides into the biosphere. For this purpose crushed salt from the excavation is envisaged. The viscous deformability of salt allows a convergent deformation of the openings. This leads in turn to a gradual compaction of the crushed salt and concurrently to an impediment of the convergent movement of the host rock. While not directly shown yet it is expected that compaction will result in sufficiently low porosities and permeabilities in the backfill to isolate the waste permanently from the biosphere.

The barrier function of the sealing systems for shafts and drifts must be guaranteed for at least 1000 years (Fischer-Appelt et al. 2013). So groundwater or brine in the overburden aquifer may possibly reach the backfilled drifts and boreholes. However, before reaching the waste canisters the brine will accelerate the compaction of the backfill by the additional processes of fluid- assisted diffusion and possibly even by solution or precipitation of salt minerals in the pore space. For an evaluation of the long-term barrier function of the backfill it is thus essential to understand and describe the compaction process and the concurrent development of permeability of the backfill under repository conditions. Especially in case of wet conditions the complex THM-process regarding the relation between porosity, permeability, effective stress and compaction rate has to be fully understood.

These issues have been studied in the German national project REPOPERM, including laboratory investigation on the dry and wet compaction behaviour of crushed salt, theoretical analyses of the compaction mechanisms, and development and testing of constitutive models for the compaction behaviour. Additional measurements of hydraulic properties of the compacted backfill are performed to provide information about gas/brine two-phase flow parameters. Main results have been presented at SaltMech8 in Rapid City (Kröhn et al. 2015).

With respect to theoretical considerations the work presented here aims at the evaluation of numerical modelling capabilities for the long-term deformation behavior of granular salt backfill. Several constitutive models are available, and different aspects of material behaviour can be modelled separately. Up to now there is no evidence whether the implemented constitutive equations are valid for the experimental range especially the compaction behaviour at low porosities. The experimental data as well as theoretical considerations have shown that the predictability of crushed salt compaction still is imperfect.

Kröhn, K.-P., C.-L. Zhang, O. Czaikowski, D. Stührenberg, and U. Heemann. 2015. *The compaction behaviour of salt backfill as a THM-process*. Mechanical Behavioir of Salt VIII Conference (Salt Mech 8). Rapid City, SD, USA.

Safety and demonstration concept for a HLW-Repository in bedded salt (KOSINA project)

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6th US/German Workshop on
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Abstract

The German Parliament decided to restart the site selection process for a HLW repository and passed an appropriate law in summer 2013. The idea is to find that site that provides best safety for one million years. This approach implies a comparison of different alternative repository systems in different host rocks. From the very beginning in the early 1960ies rock salt was considered to be the best option because of the favorable salt features and more than 100 years of experience in salt mining. Thus, repository designs and safety as well as safety demonstration concepts were developed for salt domes accordingly. A prominent example was given with the preliminary safety analysis for the Gorleben site in spring 2013. However, since more than 15 years generic conceptual designs and safety investigations were performed for repositories in clay and crystalline rock in the course of research and deevelopment funded by the Federal Ministry for Economic Affairs and Energy (BMWi). Very recently BMWi decided to start safety investigations on repository systems in bedded salt in order to complete the set of repository systems in potential host rock formations in Germany. In this context an research and development project (acronym: KOSINA) was launched in July 2015.

The objective of the research and development project KOSINA is to develop a technical site independent concept for a repository for heat generating waste and spent fuel on basis of generic geologic models for bedded salt. This should include a safety and safety demonstration concept as well. The expected project results should provide a technical-scientific basis for the safety oriented evaluation of repository systems in different host rocks according to the site selection law.

To achieve these objectives the scientific and engineering competences of BGR, DBE TEC, GRS, and IfG were compiled and an adequate working programme was set up. It consists first of elaborating and compiling the basic data (type and amount of waste, design requirements, description of a generic but appropriate geological situation, review of existing safety and safety demonstration concepts). Next steps are the development of generic geologic models including derivation of model-parameter, development of a safety and safety demonstration concept and analysis of the geomechanical integrity. In parallel technical repository concepts will be developed which includes the consideration of four different variants (drift disposal of POLLUX®-casks, vertical and horizontal borehole disposal and direct disposal of CASTOR®-casks). The evaluation of radiological consequences on the long-term as well as investigations of safety in the operational phase will accomplish the work programme. Eventually a synthesis in English report will be written and published.

A comparison of bedded and domal salt regarding heat- generating nuclear waste disposal

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Abstract

A compendium is foreseen that compares and contrasts bedded and domal salt characteristics applicable to disposal of heat-generating nuclear waste. The content will be developed from extensive salt repository experience garnered by both the United States and Germany in their respective research and development programs. Both countries have advanced salt repository science and engineering over several decades for the specific purpose of developing a safety case for salt disposal. Largely, nuclear waste disposal in the United States has concentrated on bedded salt while similar efforts in Germany emphasized geologic domal salt. At this time, each nation is once again considering possible repository choices, which presents a need and an opportunity to compare repository-relevant differentiating characteristics of bedded and domal salt. Each country also has extensive salt exploitation experience for industrial purposes, which enriches the collective understanding of basic salt physical, mechanical, chemical, petrological, hydrological, and thermal behavior. Differences and similarities exist for bedded and domal salt and they manifest at different scales when applied to nuclear waste disposal. Therefore, the relevance of similarities and differences are discussed on the basis of scale from the large-scale (formation), to the mesoscale (meters), and to the microscopic scale. It is inherently necessary to bound the subject matter to those elements relevant to the safety case; otherwise, the work will be become large and unwieldy. At the formation scale structural geology, formation characteristics—layering, stratigraphy, petrography—flow paths, access ways, and therefore seal systems, concept of operations, performance assessment modeling, and boundary conditions come into play. At the mesoscale, the disposal concept, interbeds and fabric, near-field phenomenology, damage and healing, creep constitutive models, formation fluid accessibility, and corrosion potential may differ between bedded and domal salts. At the microscale, mineralogy, impurities, hydrous minerals, fluid content, deformation mechanisms, healing processes, and decrepitation may depend on differences between and among grains.

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Plugging & sealing project DOPAS

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Abstract

The DOPAS Full-Scale Demonstration of Plugs and Seals project consisting of 14 beneficiaries from 8 European countries brings forward important demonstration activities in plugging and sealing. These activities are also a part of each participants national long-term RD&D programmes and are therefore jointly funded by Euratom's Seventh Framework Programme and national funding organisations. The demonstration experiments which are partially or wholly implemented during the DOPAS project lifetime from 2012 to 2016 are a full-scale seal (FSS) implemented in Saint-Dizier in France, an experimental pressure sealing plug (EPSP) underground in the Josef Gallery in Czech Republic, a deposition tunnel dome plug (DOMPLU) in the Äspö Hard Rock Laboratory in Sweden, a deposition tunnel wedge plug (POPLU) in the underground rock characterisation facility ONKALO (future spent fuel repository) in Finland, and components of a shaft sealing system (ELSA) in Germany (Dopas 2012).1

ELSA is a programme of laboratory and *in situ* experiments that will be used to further develop the reference shaft seal for the German disposal concept for a repository in rock salt and to develop reference shaft seals for a repository in clay host rocks (Kudla et al. 2013)2.

On behalf of BMWi, the national funding organisation for research and development (R&D) work related to radioactive waste management, facing the ELSA project phase 3, GRS is investigating sealing and backfilling materials planned to be utilised in salt and clay formations. According to current R&D work on the salt option, the shaft and drift seal components considered in Germany comprise seal components consisting of MgO and cement based salt concrete (Mueller-Hoeppe et al. 2012).

The GRS programme aims at providing experimental data needed for the theoretical analysis of the long-term sealing capacity of concrete based sealing materials. In order to demonstrate hydro-mechanical material stability under representative load scenarios, a comprehensive laboratory testing programme is carried out. This comprises investigation of the sealing capacity of the combined seal system and impact of the EDZ as well as investigation of the hydro- chemical long-term stability of the seal in contact with different brines under diffusive and advective conditions.

Dopas. 2012. *DOPAS - full-scale demonstartion of plugs and seals, Annex 1: Description of work. Grant agreement no: 323273.* Seventh framework programme.

Kudla et al. 2013. *Schachtverschlüsse für Endlager für hochradioaktive Abfälle – ELSA Teil 1*. FKZ 02E10921 / 02E10931. TUBA Freiberg / DBE TEC.

Mueller-Hoeppe et al. 2012. *Integrität geotechnischer Barrieren. Teil 2: Vertiefte Nachweisführung. Bericht zum Arbeitspaket 9.2*. Vorläufige Sicherheitsanalyse für den Standort Gorleben. GRS – 288.

Sorel building material in salt formations

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Abstract

Long-term isolation of radioactive wastes from the biosphere imposes particular demands on potential building materials for engineered barrier systems (EBS). Due to its proposed long-term stability in salt formations MgO-based ("Sorel") mortar or concrete is the preferred material option for construction of dam or shaft seals. Fundamental investigations concerning geochemical and geomechanical properties of the Sorel-building material were performed. The investigation approach delivers a comprehensive understanding of the strongly interrelated aspects and processes, **a new state of the art for the magnesia building material**.

From long-term solubility equilibria result, that in presence of $MgCl_2$-bearing solutions the 3-1-8 binder phase represents the thermodynamically stable phase up to temperatures of 80°C. Above 80°C, the phase 3-1-8 [$3\,Mg(OH)_2 \cdot MgCl_2 \cdot 8\,H_2O = Mg_2(OH)_3Cl \cdot 4\,H_2O$] is replaced by the 9-1-4 phase [$9\,Mg(OH)_2 \cdot MgCl_2 \cdot 4\,H_2O$]. At NaCl saturation ("rock salt conditions") the corrosion resistance of the material increases even as the 3-1-8 phase is stable at very low Mg^{2+} solution concentrations (0.5 $MgCl_2$ molal). The 5-1-8 phase [$5\,Mg(OH)_2 \cdot MgCl_2 \cdot 8\,H_2O$] is not stable in saline solutions, i.e. depending on temperature the phase 5-1-8 transforms below 80°C into the 3-1-8 phase and above 80°C into the 9-1-4 phase or brucite, depending on $MgCl_2$- concentration of the contact-solution. Following, a long term stable magnesia building material should be consist of the 3-1-8 binder phase. However, long-term safety of a "5-1-8" material in case of a secondary solution access can be demonstrated due to the sealing effect: the primary building material structure is tied off by a "3-1-8-insulating coat," i.e., the material properties of the 5-1-8 phase remain unchanged (hydro-mechanical integrity).

The geomechanical properties (e.g., density, porosity, compaction behavior, strength, and relaxation properties) were determined for both formulation types. The strength differences, i.e. 5-1-8 formulations usually shows very high strengths (in the order of ultra-high-strength concrete: σ_1-uniaxial > 80 MPa) in contrast to relatively lower values of 3-1-8 formulations (30 - 38 MPa), are correlated with the individual (two-phase) microstructure formation. Accordingly, the compaction behavior of a 3-1-8 type is significantly higher and also the stress relaxation behavior is more pronounced, compared to a 5-1-8 type with low relaxation effects under high loading, act in sealing systems as "stiff" abutment, respectively the 3-1-8-type as "weak" inclusion. Importantly, both MgO-concrete types show very low permeability properties (generally lower than 10^{-19} m^2).

The results of the complete investigation program are published in: *Daniela Freyer, Matthias Gruner und Till Popp „Zusammenhang von Chemismus und mechanischen Eigenschaften des MgO-Baustoffs"/„Relationship between geochemical and geomechanical properties of Magnesia building material" Freiberger Forschungshefte E15 – Naturwissenschaften, Verlag der TU Bergakademie Freiberg 2015, ISBN 978-386012-516-8.*

Update on the ABC-Workshop and Pitzer-database

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6th US/German Workshop on
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Abstract

This presentations updates upon two activities related to radionuclide and brine chemistry relevant for assessing the long-term safety of nuclear waste repositories in rock salt. For further information on these activities please contact marcus.altmaier@kit.edu or dreed@lanl.gov.

The **4th ABC-Salt (Actinide Brine Chemistry in a Salt-Based Repository) Workshop**, was held on April 14-15, 2015, in Heidelberg, Germany, with 60 participants from 8 countries attending. The workshop addressed the scientific community working on aquatic systems at high ionic strength and experts involved in implementing salt-based repository projects. The workshop was part of the ABC-Salt Workshop series, established with the aim to present new scientific investigations and discuss advanced approaches to establish a better understanding of the aqueous geochemistry and radiochemistry required to predict the long- term safety of a salt-based nuclear waste repository. ABC-Salt Conferences serve as a platform for the exchange of new scientific results, a forum for the discussion of current topics in the field, the identification of needed future research activities and the promotion of the scientific exchange on actinide brine chemistry within the international community. ABC- SALT (IV) consisted of invited and contributed talks and a poster session for the presentation of additional topics and focus upon: (i) Overview talks on current repository projects, (ii) Actinide chemistry in brines, (iii) Brine chemistry and brine evolution, (iv) Microbial effects in brines, and (v) Thermodynamic databases and modeling studies. ABC-SALT (IV) was co- organised by KIT-INE and LANL-CO, sponsored in part by BMWi and DOE, and is integrated in Nuclear Energy Agency Salt Club activities. The book of abstracts for ABC-SALT (IV) is currently being prepared and will be available via KIT-INE. In view of the very positive feedback received on the ABC-Salt Workshop Series, the next ABC-Salt (V) conference has been announced for spring/summer 2017 in the US.

Within the scope of the Organisation for Economic Co-operation and Development Nuclear Energy Agency Thermochemical Database (TDB) Project, the preparation of a State of the Art Report (SOAR) to assess the modeling and experimental approaches used to describe high ionic-strength solutions has been started. This SOAR builds on past Nuclear Energy Agency-TDB documents and focuses on ionic strength where the Pitzer formulation rather that the SIT approach, is recommended and usually applied. The authors contributing to this project are from Germany (M. Altmaier, KIT-INE; H. Moog, GRS; W. Voigt, TU Freiberg) and the US (D.T. Reed, LANL; A. Felmy, (retired) PNNL; L. Brush, (retired) SNL; W. Runde, LANL), with support from the Nuclear Energy Agency-TDB coordinator M. Ragoussi. The focus of this SOAR update is on the nuclear waste disposal aspects that apply to repository concepts in bedded and domed rock salt formations although there is also relevance to other geologic disposal concepts where transient high ionic-strength aqueous conditions can exist. The Nuclear Energy Agency SOAR will provide an overview of existing Pitzer interaction parameters with emphasis on those that are relevant to nuclear waste disposal, will highlight the main achievements and challenges of the application of the Pitzer approach, and conclude with a critical assessment of the key data gaps and modeling limitations/concerns that are identified. The Kick-off meeting of the Nuclear Energy Agency SOAR project was held April 2015 in connection to the ABC-Salt (IV) Workshop.

BAM-SNL cooperation on container behavior / influence on prolonged interim storage periods

Holger Völzke, Bundesanstalt für Materialforschung und –prüfung (BAM), Berlin, Germany

Ken B. Sorenson, Sandia National Laboratories (SNL), Albuquerque, New Mexico, USA

6th US/German Workshop on
Salt Repository Research, Design, and Operations
Dresden, Saxony, Germany
September 7-9, 2015

Abstract

The Bundesanstalt für Materialforschung und –prüfung (BAM) and Sandia National Laboratories (SNL) entered into a Memorandum of Understanding (MOU) in September 2012 to foster technical collaborations in the areas associated with the backend of the commercial nuclear fuel cycle. Specifically, the focus is on packaging, transportation, and storage of commercial SNF. The MOU continuous long lasting collaboration between BAM and SNL in the area of package design testing. The institutes meet about twice each year, alternating between institutes. This provides the flexibility to more staff members from the host organization exposure to technical issues that are of concern internationally and to collaborate with technical experts working on similar problems.

Since 2012, the focus of the meetings has been on technical issues associated with extended dry storage and subsequent transportation of commercial spent fuel. Topics range from hydride effects on cladding integrity, spent fuel response during Normal Conditions of Transport (NCT), finite element analyses of fuel and cask response to accident conditions, bolt and seal behaviour over extended periods of time, and corrosion associated with bolts, metallic seals, and stainless steel canisters.

This MOU has provided an effective leverage for technical collaboration. For example, SNL is funding (through DOE), Savannah River National Laboratories (SRNL) to look at bolt and seal degradation issues. SRNL has an MOU with BAM to collaborate on bolt and seal degradation during extended storage.

The presentation will provide an overview of the technical issues associated with extended storage and subsequent transportation, as well as the work underway at BAM and SNL that are addressing these issues.

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy's National Nuclear Security Administration under contract DEAC04-94AL85000. SAND2015-7061 A

Extended storage approach COVRA

Erika Neeft and Ewoud Verhoef

Central Organization for radioactive waste (COVRA), Nieuwdorp, the Netherlands

6th US/German Workshop on
Salt Repository Research, Design, and Operations
Dresden, Saxony, Germany
September 7-9, 2015

Abstract

The Netherlands used to dispose its low level radioactive waste on the ocean floor of the North- East Atlantic at sites selected by the Nuclear Energy Agency. When this practice ended in 1982, the Dutch government established a centralized waste management organisation for the collection, processing and storage of waste: COVRA.

In the Netherlands there are now some 1400 organisations that have a licence to work with radioactive material. Waste is collected by COVRA at these licence holders or sent to COVRA after processing Dutch waste in a foreign facility. The generators of radioactive waste are two nuclear power plants (one operational plant, the other being decommissioned), research institutes and all sorts of industries and hospitals. Most of them generate only small volumes of low and intermediate level waste. As a consequence the volume of radioactive waste in the Netherlands is small, e.g., 35.3 m^3 vitrified waste from reprocessing spent nuclear power fuel and 6.4 m^3 spent research reactor fuel were stored at COVRA's premises until 2014. The small volumes of waste available for direct disposal do not require an immediate final solution. Also the financial burden of a direct disposal facility is prohibitive for the small quantities concerned. The money has to be generated in a capital growth fund that is allowed to grow over a substantial time period.

All waste generators have to pay in advance for the collection, the processing, at least 100 years storage and the geological disposal of the waste. The period of 100 years allows the money for disposal to grow to the desired level in a dedicated capital growth fund. This fund brings the financial burden for today's waste to an acceptable level without transferring it to future generations.

During the long period for interim storage, COVRA prepares for the eventual disposal. The research on disposal in next decades will focus on the disposability of the types of waste stored at COVRA, obtaining the necessary information from suitable host formations in the Netherlands (rock salt and poorly indurated clay) and their surrounding formations, societal acceptability of geological disposal and international developments, including a multinational solution. A multinational solution can create financial benefits, and could result in a higher safety standard and a more reliable control for countries with small volumes of radioactive waste.

Far-field hydrogeologic modeling around a salt repository

Kristopher L. Kuhlman (SNL) and Anke Schneider (GRS)

6th US/German Workshop on
Salt Repository Research, Design, and Operations
Dresden, Saxony, Germany
September 7-9, 2015

Abstract

SNL and GRS are creating models of regional groundwater flow in the hydrogeologic units above the Salado salt formation at the Waste Isolation Pilot Plant (i.e., the Rustler Formation and the Dewey Lake Formation). SNL created three-dimensional transient basin-scale flow model in the 1990s (Corbet & Knupp, 1996), which was used in the certification of the Waste Isolation Pilot Plant. We are using this model implementation as a starting point for comparison of new generations of numerical flow and solute transport models. We show some initial development towards this collaborative comparison, and give a roadmap for future developments in both computer codes and comparisons between the models.

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy's National Nuclear Security Administration under contract DEAC04-94AL85000. SAND2015-7436A.

Deep borehole disposal: Pros & cons

Wilhelm Bollingerfehr

DBE TECHNOLOGY GmbH, Peine, Germany

6th US/German Workshop on
Salt Repository Research, Design, and Operations
Dresden, Saxony, Germany
September 7-9, 2015

Abstract

One of the first tasks of the German "Endlagerkommission" (Commission for the disposal of radioactive waste) was to reconsider all technical disposal ideas, concepts, and designs that exist throughout the world. In this context, a debate arises whether the idea of deep borehole disposal should be included in the list of disposal options and to what extend this idea should be considered or even promoted for further investigations. Consequently, a hearing was organized in summer 2015 and scientist from abroad presented the state of the art in science and technology. There are countries that carried out desk studies to investigate the potential of this idea; e.g., Sweden (SKB), the United Kingdom and United States (Sandia, Department of Energy). While Sweden concluded that no safety advantage will be expected, the United States decided to study the drilling technology as well as the disposal techniques in detail und will design, construct, and operate full-scale demonstration facilities in a 3-year program until 2017.

However, the situation in Germany is different. From the very beginning in the early1960s, the reference concept for the disposal of all radioactive waste considered the disposal of radioactive waste in mined repositories. The main reasons were that there were more than 100 years of experience in mining, and the intent was to have permanent access to the waste containers as long as the repository is in operation. With the exception of preliminary studies in the 1980s, no detailed studies for deep borehole disposal have been performed. Despite expected economic advantages, which may be confirmed or not, a series of questions arises, especially regarding safety, which have been summarized in a DAEF paper in summer 2015. Since September 2010, detailed safety requirements for the disposal of heat-generating radioactive waste have to be complied with in Germany. They include a safety and safety demonstration concept for the operational and for the post-closure phase. In this regard, the most challenging safety-relevant requirement is the demonstration of safe waste package retrieval because this is neither state of the art for a mined repository nor for the deep borehole disposal idea. Because the borehole has to withstand thermomechanical and chemical loads, liners will be needed. The drilling process usually requires fluids for cooling the tools and for the transport of excavated material. Clarification is needed if "dry alternatives" exist, in particular for huge diameters (several meters) or if the waste packages have to be designed accordingly. The safe transport of waste packages of several tons of mass down to a depth of up to 5000 m under the constraints of radiation protection requirements (shielded containers) has to be demonstrated as well. Thus, at least desk studies are needed to investigate if there is a realistic chance for the idea of deep vertical boreholes to become a disposal option.

APPENDIX F: PRESENTATIONS

A Path Forward on Nuclear Waste

Nancy Buschman
U.S. Department of Energy

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA · NWSA · ENERGY

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

A Path Forward on Nuclear Waste

for Tim Gunter, NE-53
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6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

U.S. DEPARTMENT OF ENERGY — Nuclear Energy

An Adaptive, Consent-Based Path to Nuclear Waste Storage and Disposal

- In January 2013, the Administration issued its Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste.
- The Strategy embraced the core findings of the Blue Ribbon Commission on America's Nuclear Future and affirmed that any workable solution for the final disposition of used fuel and nuclear waste must be based not only on sound science, but also on achieving public acceptance at the local, state and tribal levels.
- Consistent with the Administration Strategy, in March 2015, the Department of Energy announced it would move forward with planning for a defense repository in parallel with initial work to develop interim storage for commercial spent nuclear fuel. The Department will also begin development of a consent-based siting process for both types of facilities.

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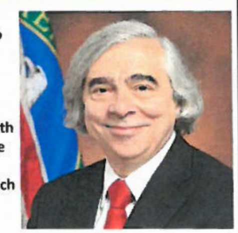
U.S. DEPARTMENT OF ENERGY — Nuclear Energy

Parallel Path Forward



On March 24, President Obama authorized the Energy Department to move forward with planning for a separate repository for high-level radioactive waste resulting from atomic energy defense activities.

In remarks before the Bipartisan Policy Center, Secretary Moniz discussed this path forward for defense waste as well as a parallel path for storage and disposal of commercial spent fuel, consistent with the Administration's January 2013 Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste, which built upon the work of the bipartisan Blue Ribbon Commission on America's Nuclear Future completed in January 2012.

Secretary Moniz announced three specific actions that the Department will undertake –

- Planning for a defense-only repository
- Moving forward with planning for interim storage of commercial spent fuel
- Moving forward with a consent-based siting process for both types of facilities

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U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Implementation of Administration's Strategy

- The Administration is committed to pursuing a path forward consistent with the Administration's *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* and the principles recommended by the Blue Ribbon Commission.
- Full implementation of the Administration Strategy will require new legislation, however, in the meantime the Department is taking action on the Strategy to the extent possible within existing authorities.
- The FY16 Budget Request includes $108.4 million to support this path forward by providing funds to continue laying the groundwork that could lead to one or more facilities for spent fuel management under a consent-based siting program and prepare for large-scale transport of used fuel.

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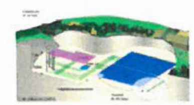
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Used Nuclear Fuel Disposition R&D

- **Elements of the Used Nuclear Fuel Disposition R&D Campaign include –**
  - Storage and Transportation R&D
    - Fuel retrievability and transportation after extended storage
    - Extended storage of used nuclear fuel
    - Transportation of high-burnup used nuclear fuel
  - Disposal R&D
    - Provide a sound technical basis for the assertion that the U.S. has multiple viable disposal options
    - Increase confidence in the robustness of generic disposal concepts
    - Evaluate the feasibility of the deep borehole disposal concept
    - Evaluate the technical feasibility of the direct disposal of existing storage and transportation canisters



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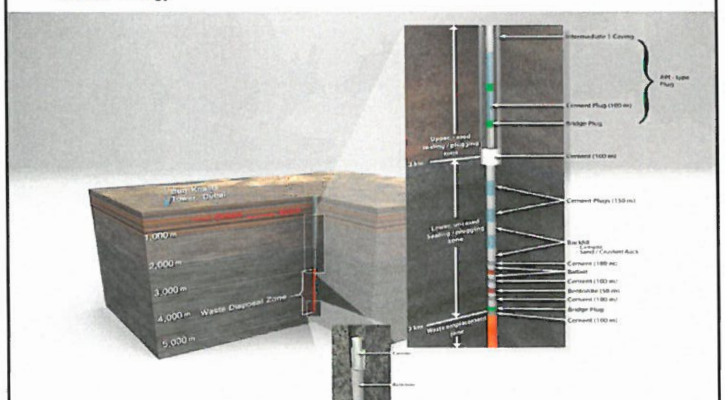
Nuclear Energy

Deep Borehole Disposal Concept



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U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Conclusion

The Department of Energy is committed to moving forward with development of management strategies and technologies for the transportation, storage and disposal of used nuclear fuel and high-level radioactive waste.

- Laying the foundation for the development of storage, transportation and disposal options.
- Planning for a defense-only repository
- Moving forward with planning for interim storage of commercial spent fuel
- Moving forward with a consent-based siting process for both types of facilities

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Then And Now – Assessing Updates to 1996 WIPP Modeling Assumptions

Kathleen Economy
U.S. Environmental Protection Agency
Washington, DC USA

Presented at:
6th US/Germany Workshop on Salt Repository Research, Design and Operation

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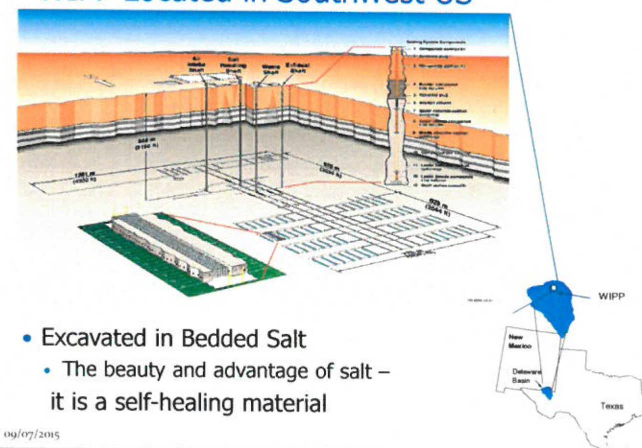
WIPP Located in Southwest US



- Excavated in Bedded Salt
  - The beauty and advantage of salt – it is a self-healing material

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EPA's Role at WIPP

- Per Act of Congress – EPA has a mandated role to implement radioactive waste disposal regulations (this applies to WIPP)
- The Regulation, Performance Assessment (PA) is required to demonstrate WIPP is compliant and below release limits
- **1998 – EPA Issues Certification for WIPP**
  - 24 Conceptual models reviewed and approved by EPA
  - Based on cycle of EPA review/question/response/DOE-modification
  - Built on extensive FEP screening exercise (~1993-1995)

    FEPS screening based on:
    - Computer modeling, spreadsheet calculations
    - Assumptions, reasoned arguments

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WIPP Recertified Every 5 years

- DOE Submitted Re-certifications in 2004 and 2009

  EPA Reviewed and Approved
- 2014 DOE submitted a Re-certification application to EPA

  EPA is still reviewing

What is required in DOE's recertification application ?

Must include updated information related to:
geology, geophysical setting, geochemical, hydrology chemistry, meteorological information, changes in physical features, etc.,

Must identify any activities or assumptions that deviate from the most recent compliance application.

In 2004 and 2009 - Minimal changes to repository, therefore most of the 1996 assumptions were adopted in these re-certifications

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Each WIPP PA Similar to A Layered Cake


WIPP PA 'CAKE'

- Baked (i.e. re-certified) every 5 years
- Each 'layer' a model
  - 24 layers (conceptual models)
- Each layer has unique ingredients

Ingredients = Assumptions/FEPs/Parameter Values

EPA reviews each conceptual model 'layer' asking:

- Did the recipe change since last 'baked'? i.e. have conceptual models or parameters been modified?
- Implementation - How does each layer fit with the one above and below?

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Then–EPA's 1996 CCA Review

Review of the Inputs and Assumptions…
An Extensive and Labor Intensive Process

- For 1996 Certification, EPA reviewed the 'reasonableness' of 24 Conceptual models
  - Assumptions acknowledged uncertainties at the time
  - Based on these uncertainties, EPA accepted:
    - Many unknowns =

      Adopting conservative assumptions

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Now, for the 2014 CRA ….

There Are Significant Changes That May Effect Previous Assumptions

Two 'Features' in the Repository Have Been Modified

These are:

- Panel Closure Design Changed – from "Option D" to Run-of-Mine Salt
- *More* Experimental and Non-waste Areas Planned To Be Mined

Couple this with….

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- *More* scientific data available on salt properties, behavior and response to excavation
- *More* computational capabilities

Now, relative to 1995, there is less uncertainty in many properties

EPA asking:

Do the FEP arguments/assumptions, need updating so they are aligned with current knowledge?

Answer: Probably ….

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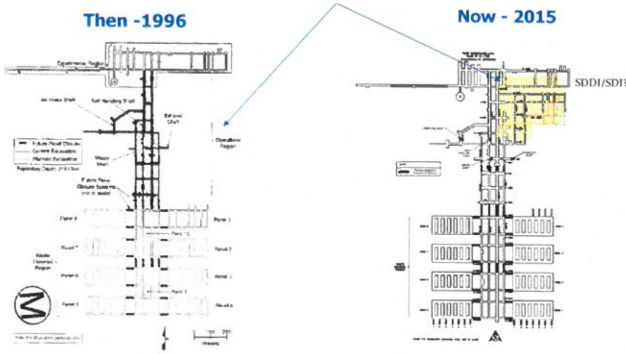
Repository Footprint Projected at Closure

Approximately 50% More Operations and Experimental Area (Non-Waste Area) Mined



In Current PA - Non-Waste Area Modeled 'Open' for 10,000 Year Period

- Long-term permeability high –10^{-11} m^2
- Long-term Porosity high – 18 %
- Not reflective of current knowledge and understanding of salt mechanics and behavior.
- EPA Question - *Why were these values adopted?*
  - DOE Response – *A 1995 FEP screening shows PA not sensitive to creep closure of non-waste areas.*

Now - EPA investigating assumptions adopted in 1995 FEP screening exercise

Historical Limitations in 1995 Built into FEP Analysis

#1: Knowledge of Salt Behavior in Repository

Assumption -

- DRZ Modeled as Open and Continuous - Permeability constant - 10^{-15} m^2
- Lack of known synergy between adjacent regions (i.e., one region static while another varies)

#2: Repository Design Not Finalized

- Panel Closure Design Not Finalized -
  - Therefore assume permeability constant - 10^{-12} m^2
- Backfill Presumed in Operations Room -
  - Therefore assume permeability constant - 10^{-12} m^2

#3: 1995 - Hardware and Computational Resources Limited

End Result: = FEP Screening Conclusion in 1995

- Creep Closure of the non-waste areas does not impact PA
- Non-waste areas modeled as open for 10,000 year modeled period

Is There An Assumption Disconnect With Current Knowledge? ...Probably Yes

From 1995, non-waste areas have been modeled as open in subsequent PAs and carried through to CRA 2014

- Is it realistic and reasonable to keep out-dated FEP arguments?
- *Does it Matter?*
- Will this effect WIPP long term performance?
- Is this confidence building?

For the CRA 2014 the properties of the non-waste area appear not to be reflective of present-day knowledge of salt behavior.

EPA Action Item – *EPA requesting a Sensitivity Study be conducted assuming non-waste areas creep close*

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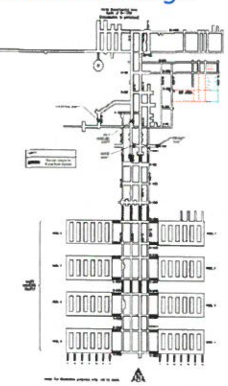
Second Major Change in WIPP 2014 CRA - Modification of Panel Closure Design

The Purpose of Panel Closures



- Used to satisfy RCRA Requirements (i.e., non-radiological exposures during operational period)
- Not required as part of radiological waste requirement, however....
- A Repository Feature –
  - Will effect long-term performance (i.e., fluid flow between waste panels)

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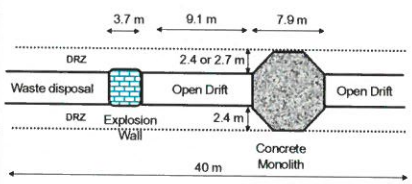
Panel Closure Design Changes

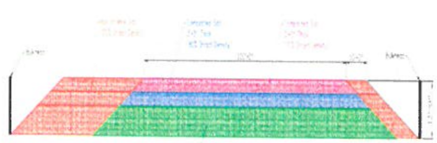
Then - 1998

- Uses multiple rigid concrete structures
- DRZ mined to anhydrite



Now - 2014 CRA

- Uses run-of-mine salt
- DRZ not mined to anhydrite



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PA Modeling For Panel Closures

Then

- Option D properties constant with time
- Flow properties of DRZ - reflective of rigid Option D material and anhydrite
- Shaft flow Properties – same properties as Option D design

Now

- ROM salt properties – modeled in 3 time periods
  - 0-100 years
  - 100 – 200 years
  - 200- 10,000 years
- DRZ modeled in 2 time periods
  - 0-200 years
  - 200-10000 years
- Shaft flow properties – same properties as Option D design

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2014 CRA Panel Closure Model

- 2014 –EPA is reviewing assumptions related to flow properties adopted for both the PCS and its adjoining DRZ
  - Of particular interest are the adopted assumptions for the end-point parameter values adopted for the run-of-mine salt PCS and adjoining DRZ during 200-10,000 year time period.
- EPA asking whether the values are realistic, reasonable, and in alignment with updated information related to salt properties?

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Review of Assumptions, Why is this Important?

One Definition - *A thing that is accepted as true or as certain to happen, without positive proof.*

Modeling assumptions should be based on basic science.

Periodic reviews of assumptions are necessary -

- Assures that conservative assumptions fall within gray edges of parameter distributions (i.e., still realistic and do not 'violate' adopted physical and chemistry models).
- Provides public trust that compliance is based on up-to-date science.
- IF Assumptions not in sync with science, THEN confidence in models and end results questioned
- **For WIPP** - IF WIPP Assumptions are scientifically sound, THEN they can be used as basis for inputs in more complex salt repository PAs.

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Summary

EPA's review of DOE's CRA 2014 PA – We are questioning many assumptions related to the current understanding of repository science and experimental data.

- Related to salt properties in the non-waste areas:
  - The adopted assumptions keep these areas artificially open and highly permeable for 10,000 years, the basis due to an outdated FEP analysis performed in the mid 1990s.
  - EPA is questioning the defensibility of using these old assumptions.

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Summary (continued)

- EPA is still reviewing DOE's modeling assumptions adopted for the ROM Salt Panel Closure System and Adjoining DRZ
  - EPA is especially interested in model assumptions adopted for the 200-10,000 year time-period.

We are continuing our review of the 2014 CRA. The basis of the review is to assure the submitted CRA will be 'Compliance Aligned with Science'.

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Exceptional service in the national interest

Sandia National Laboratories

PFLOTRAN: Coupled THC Simulations

S. David Sevougian, PhD
Sandia National Laboratories

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
Dresden, Germany
September 7-9, 2015

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Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2015-7345C.

Outline of Presentation

- **PA model/code development**
  - **PA objectives and development philosophy**
    - Conceptual and computational model guidelines
    - Model and code architecture
- **Application of enhanced PA model**
  - **Generic salt repository reference case**
  - **Demonstration simulations:**
    - Isothermal vs. thermal (heat-generating)
    - Single drift vs. multi-drift
- **Summary and future work**

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Acknowledgments

- **Conceptual model development: Paul Mariner, Geoff Freeze, Emily Stein, Payton Gardner**
- **Code development: Glenn Hammond**
- **Simulations: Payton Gardner, Emily Stein**

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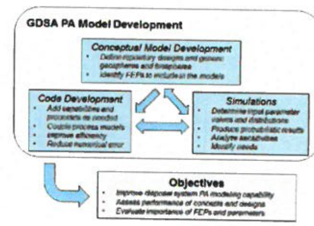
PA Model/Code Development Philosophy

- **Objective: More accurate solution to the coupled continuum field equations (mass, momentum, energy) over a large heterogeneous domain, including**
  - Quantification and propagation of uncertainties, both aleatory and epistemic
  - Direct representation in PA model of significant coupled multi-physics processes in three dimensions (3-D)
  - Realistic spatial resolution of features and processes
    - *Explicit representation of all waste packages*
- **Key points:**
  - Less reliance on assumptions, simplifications, and process abstractions
  - Adopt a numerical solution and code architecture that can evolve throughout the repository lifecycle (decades!) and is able from the outset to use the most advanced hardware and numerical solvers available
- **Goals: (1) Enhance confidence and transparency in safety case and (2) enable better decisions**



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PA Computational Model Guidelines

- **Required code capabilities:**
  - Parallel high-performance computing (HPC) environment
  - Open source development and distribution
    - *Transparency*
    - *Shareable among experts and stakeholders*
  - Flexible and extensible; scalable
    - *Modular implementation of simple and/or advanced PA component models and FEPs*
  - Domain scientist "friendly", e.g., Fortran 2003/2008
  - Leverage existing computational capabilities
    - *Meshing, visualization, HPC solvers, etc.*
  - Amenable to future advances in computational methods and hardware
  - Multiple realizations
  - Three-dimensional (3D) domain solvers
  - Appropriate CM and QA

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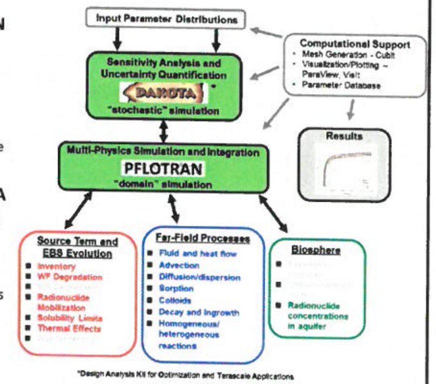
Enhanced PA Computational Model

- ***Domain simulation*, PFLOTRAN**
  - Coupled processes in 3-D
  - Spatial variability in features and processes
  - *Three major components:* source term and EBS processes; far-field natural system processes; biosphere processes
- ***Stochastic simulation*, DAKOTA**
  - Uncertainty quantification (UQ) and propagation of model input parameters, both aleatory and epistemic,
  - Sensitivity analysis of output metrics (e.g., biosphere dose) versus input parameters



*Design Analysis Kit for Optimization and Terascale Applications

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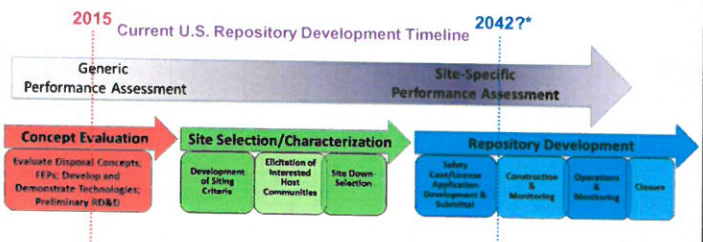
Uses of the Enhanced PA Capability

- **Use the PA model/code throughout the repository lifecycle to:**
  - Evaluate potential disposal concepts and sites in various host rock media
  - Help prioritize RD&D activities (initially *generic*; later *site-specific*)
  - Support safety case development during all phases of lifecycle



*DOE 2013

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Evolution of Computing Power

- Moore's Law: **"the number of transistors in a dense integrated circuit *doubles* approximately every *two* years."**
  - ⇒ 32-fold increase in a decade
  - ⇒ 33,000-fold in three decades

"IBM System360 Model 30" by Dave Ross - Flickr: IBM System/360 Model 30. Licensed under CC BY 2.0 via Wikimedia Commons
"Mira - Blue Gene Q at Argonne National Laboratory - Skin" by Courtesy Argonne National Laboratory. Licensed under CC BY 2.0 via Wikimedia Commons
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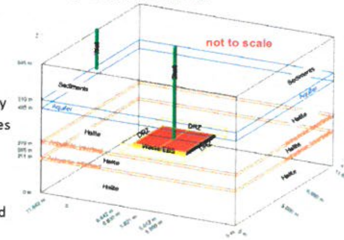
Application of Generic PA Model:

Salt Reference Case & TH Simulations

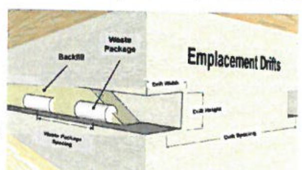
Salt Reference Case – Natural Barrier System (NBS)

- ***Reference Case*** **is a surrogate for site- and design-specific information**
  - Documents information and assumptions needed for *generic* disposal system models
  - Helps ensure consistency across analyses (e.g., PA, process modeling, UA/SA)
- **Salt host rock:**
  - Use parameters representative of five major bedded salt basins in the U.S.
- **Disturbed rock zone (DRZ):**
  - Typical properties from international studies and from WIPP
- **Interbeds:**
  - Types (e.g., dolomite, anhydrite) and frequency
  - Dimensions, location (near DRZ), and properties
- **Representative aquifer:**
  - A single-porosity, saturated, sedimentary formation
  - Depth above repository, thickness, physical and chemical characteristics



Salt Reference Case – EBS and Concept of Operations

- Waste inventory
  - ~70,000 MTHM SNF
  - ~13,400 WPs
  - Burn-up = 60 GWd/MT
  - Instant release fraction = 11.25%
- Drift spacing and WP loading based on 200°C thermal limit for salt
  - 12 PWR assemblies per WP; 7.5 kW/WP
- Repository layout
  - 84 pairs of 809-m drifts
    - Drift spacing = 20 m
    - 80 WPs (5-m-long) per drift with 10-m spacing
  - Crushed salt backfill in drifts
  - Sealed shafts (similar to WIPP)



Model Region	Permeability (m^2)	Porosity	Tortuosity	Effective Diffusion Coefficient* (m^2/s)	Longitudinal Dispersivity (m)	Saturated Thermal Conductivity (W/m·°K)	Specific Heat Capacity (J/kg·°K)
Waste Package	1.00 × 10[illegible]	0.500	1.00	6.90 × 10[illegible]	0.5	16.7	466
Backfill	1.00 × 10[illegible]	0.113	0.48	1.24 × 10[illegible]	0.2	2.6	927
Shaft seals	1.58 × 10[illegible]	0.113	0.48	1.24 × 10[illegible]	20.0	2.5	927
DRZ	1.12 × 10[illegible]	0.0179	0.25	6.82 × 10[illegible]	1.0	4.9	927
Halite	3.16 × 10[illegible]	0.0182	0.01	4.19 × 10[illegible]	50.0	4.9	927
Interbed (anhydrite)	1.26 × 10[illegible]	0.011	0.22	5.67 × 10[illegible]	50.0	4.9	927
Aquifer	1.00 × 10[illegible]	0.150	0.63	1.83 × 10[illegible]	50.0	1.5	950
Sediments	1.00 × 10[illegible]	0.20	0.58	2.67 × 10[illegible]	50.0	1.5	927

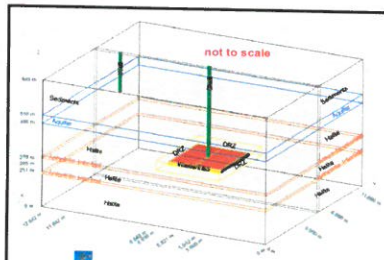
* Effective diffusion coefficient = (free water diffusion coefficient) × (tortuosity) × (porosity)

- Relatively fast SNF fractional degradation rate, $m(t)/m_0 = e^{-\lambda t}$, based on bromide-containing brines (from German program, Kienzler et al. 2012):

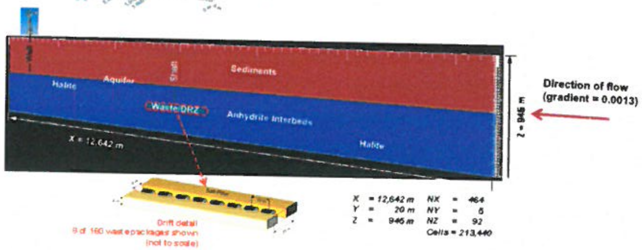
Case	λ (yr^{-1})	Time for 50% Degradation (yrs)	Time for 99% Degradation (yrs)
Deterministic	3.6525×10^{-4}	~ 1,900	~ 12,500
Probabilistic – Lower	3.6525×10^{-6}	~ 190,000	~ 1,250,000
Probabilistic – Upper	3.6525×10^{-3}	~ 190	~ 1,250

Simulations

"Quasi 2-D", Single-Drift Simulation Domain



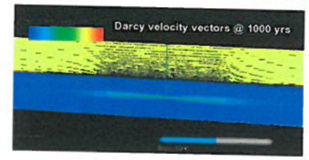
- 1 "drift pair" (80 WPs upstream and 80 WPs downstream of access shaft)
- 20-m wide pillar to pillar
- "3-D vertical slice"
- Reflection BCs at y = 0 and y = 20 m



Salt Repository, Single-Drift → Deterministic *Isothermal** Simulation

*non-heat generating waste

- **EBS:** source term for each waste package →
  - 5 radionuclides: ^{129}I, ^{241}Am, ^{237}Np, ^{233}U, ^{229}Th
  - Waste form (SNF) degradation rate controlled by kinetics
  - C: solubility limits, dissolved radionuclides can precipitate
- **NBS:** 3-D flow and transport
  - Primarily diffusion through DRZ and bedded salt
  - Primarily advection through aquifer and sediments
- **Peclet Number**, N_{Pe}, in various layers:



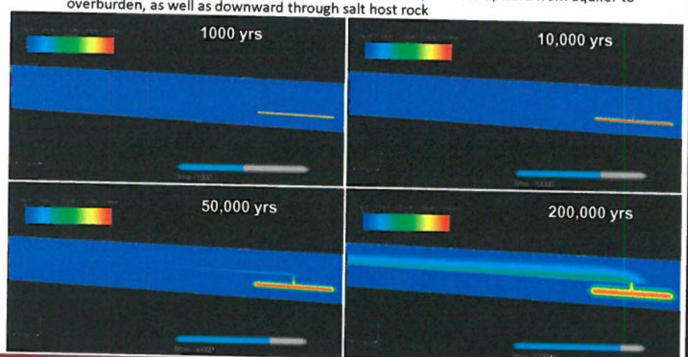
Region	Darcy velocity, u (m/s)	Effective Diffusion Coefficient, $D_{eff} = \phi\tau D_w$ (m²/s)	Longitudinal Dispersivity (m)	Longitudinal dispersion coefficient, $D_L = \alpha_L u$ (m²/s)	Peclet Number, N_{Pe}
Halite	$3.17 \cdot 10^{-19}$	$4.19 \cdot 10^{-13}$	50.0	$1.585 \cdot 10^{-17}$	0.0038
Interbed (anhydrite)	$1.90 \cdot 10^{-15}$	$5.57 \cdot 10^{-12}$	50.0	$9.5 \cdot 10^{-14}$	1.7
Aquifer	$1.58 \cdot 10^{-9}$	$1.83 \cdot 10^{-10}$	50.0	$7.9 \cdot 10^{-8}$	98
Sediments	$1.58 \cdot 10^{-11}$	$2.67 \cdot 10^{-10}$	50.0	$7.9 \cdot 10^{-10}$	75

$$N_{Pe} = \frac{uL_{sys}}{D_{eff} + \alpha_L u}$$

- Diffusion-dominated when N_{Pe} ~<10
  - Halite and anhydrite

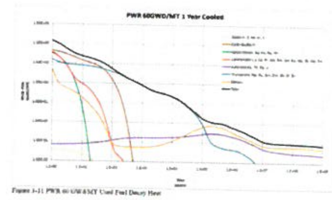
Salt Repository, Single-Drift → Deterministic *Isothermal** Simulation

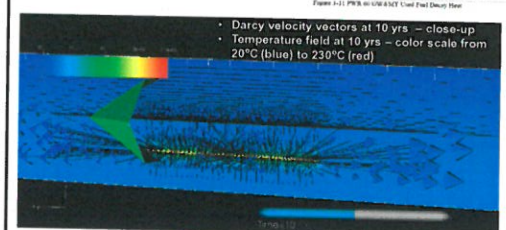
- **^{129}I dissolved concentration at various simulation times:**
  - reaches the aquifer and overburden sediments via upward diffusion through the shaft seals
  - advects downgradient through aquifer and overburden; diffuses upward from aquifer to overburden, as well as downward through salt host rock



Salt Repository, Single-Drift → Deterministic *Thermal* Simulation

- **Decay heat flux for 60 GWd/MT PWR SNF (Carter et al. 2012)**
- **Geothermal gradient of 8°C/km – similar to WIPP**

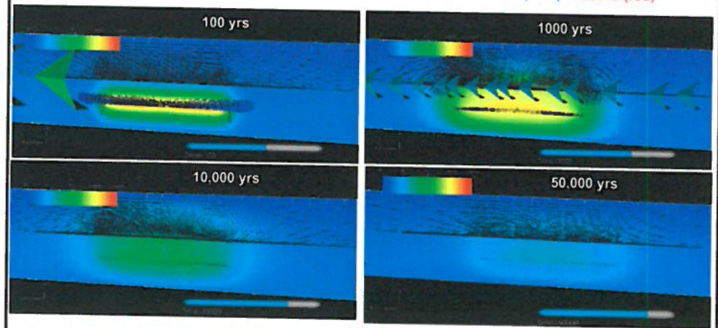




- **Outward fluid velocity from repository region at 10 years — due to *thermal expansion* of fluid**

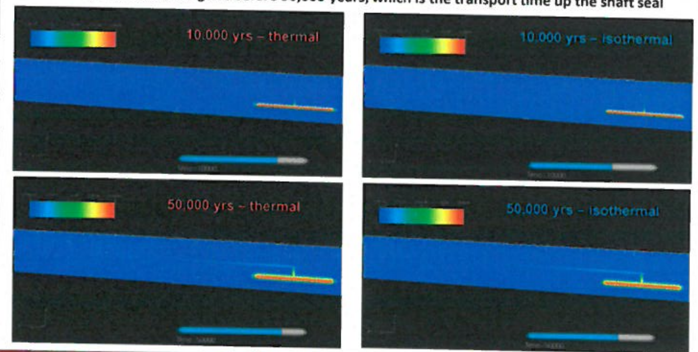
Salt Repository, Single-Drift → Deterministic *Thermal* Simulation

- Thermally-driven (buoyancy) fluid convection cells for more than 10,000 yrs:
  - Darcy velocity vectors at various times
  - Temperature field at various times – color scale from 20°C (blue) to 230°C (red)



Salt Repository, Single-Drift → Deterministic *Thermal* vs. *Isothermal*

- ^{129}I Concentration at 10,000 years and 50,000 years (thermal vs. isothermal)
  - Only small effect from heat pulse (at early times due to thermal expansion of fluid)
  - Convection cells gone before 50,000 years, which is the transport time up the shaft seal

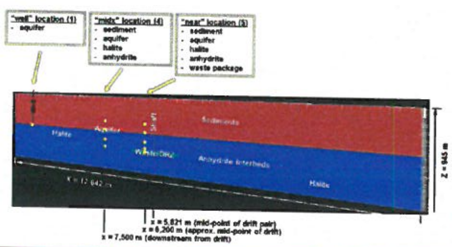


Salt Repository, Single-Drift → *Probabilistic* *Isothermal** Simulation

- 10 sampled parameters
- 50 realizations
- Sensitivity analyses with DAKOTA:
  - *Partial Rank Correlation Coefficient (PRCC)*, i.e., local sensitivity analyses, for max ^{129}I concentration over 1,000,000 years vs. input parameter(s)

Model Parameter	Deterministic Value	Probability Range	Distribution Type
Waste form degradation rate constant (mol/m²/s)	$4.8\cdot10^{-8}$	$1.00\cdot10^{-10} - 1.00\cdot10^{-7}$	Log uniform
^{129}I K_d (ml/g)	0.0	$9.28\cdot10^{-7} - 7.84\cdot10^{-5}$	Log uniform
^{237}Np K_d (ml/g)	5.5	1.0 – 10.0	Log uniform
Waste Package Porosity	0.30	0.05 – 0.50	Uniform
Backfill Porosity	0.113	0.010 – 0.200	Uniform
Shaft Porosity	0.113	0.010 – 0.200	Uniform
DRZ Porosity	0.0129	0.0010 – 0.1000	Uniform
Halite Porosity	0.0182	0.0010 – 0.0519	Uniform[a]
Anhydrite Interbed Permeability (m²)	$1.26\cdot10^{-19}$	$1.00\cdot10^{-21} - 1.00\cdot10^{-17}$	Log uniform[b]
Aquifer Permeability (m²)	$1.00\cdot10^{-13}$	$1.00\cdot10^{-14} - 1.00\cdot10^{-12}$	Log uniform

- Ten observation points:

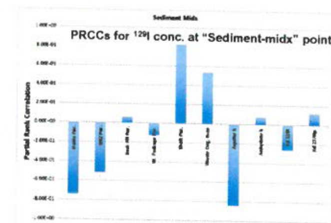


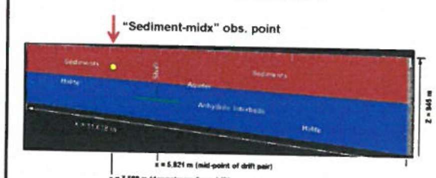
Probabilistic *Isothermal** Simulation, Single-Drift – Results at "Sediment-Midx" Observation Pt.

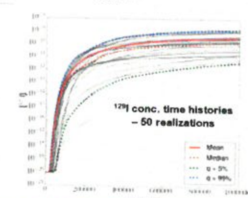
- Strong positive PRCC for shaft seal porosity – higher ϕ_{shaft} increases effective diffusion coefficient for transport to the aquifer:

$$(D_{eff})_{shaft} = (\phi\tau)_{shaft} D_w$$

- Strong negative PRCC for aquifer permeability – higher $k_{aquifer}$ increases dilution and lowers concentration gradient into overburden sediments
- Positive PRCC for WF degradation rate – higher rate increases source cell conc.
- Negative PRCC for DRZ porosity – higher porosity decreases source concentration







Single-Drift Simulation "Caveats"

- Main purpose is to demonstrate the capabilities of the enhanced multi-physics HPC performance assessment framework
- Transport behavior of ^{129}I is a result of the assumed material properties in the various regions – may or may not occur at a potential repository site
- ^{129}I concentrations are conservatively high because the lateral boundary conditions in the *y*-direction (i.e., at the sides of the 20-m-wide, 3-D slice) are zero-gradient, no-flow:
  - Would only be true of a repository with an "infinite" number of parallel drifts and, thus, does not account for dilution from lateral mass loss
  - Also implies one access shaft per drift (results in greater diffusive transport to aquifer)
- Additional "conservative" factor:
  - No meteoric infiltration flux at the surface

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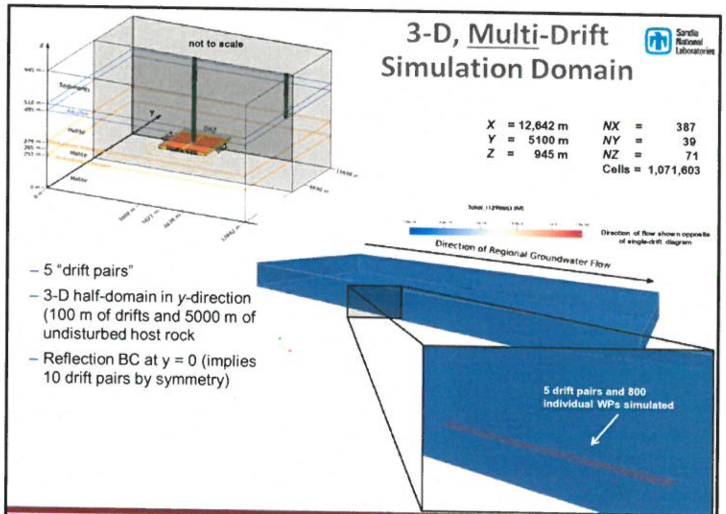
3-D, Multi-Drift Simulation Domain



- 5 "drift pairs"
- 3-D half-domain in *y*-direction (100 m of drifts and 5000 m of undisturbed host rock
- Reflection BC at y = 0 (implies 10 drift pairs by symmetry)

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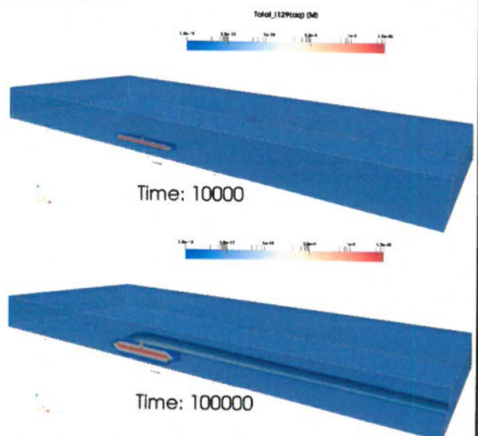
Salt Repository, Multi-Drift → Deterministic *Isothermal** Simulation

- ^{129}I dissolved concentration at various simulation times:
  - reaches the aquifer and overburden sediments via upward diffusion through the shaft seals
  - advects downgradient through aquifer and overburden; diffuses upward from aquifer to overburden



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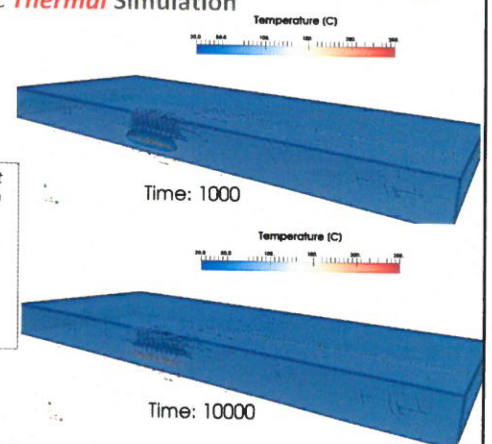
Salt Repository, Multi-Drift → Deterministic *Thermal* Simulation

- Darcy velocity vectors at various times, and
- Temperature field at various times

- *Thermally-driven, buoyant flow for more than 10,000 years*
- *Convection cells not obvious compared to single-drift simulation – perhaps dissipated in y-direction*



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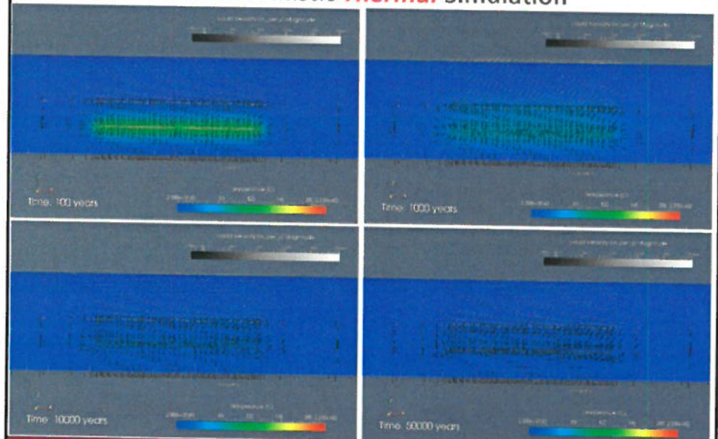
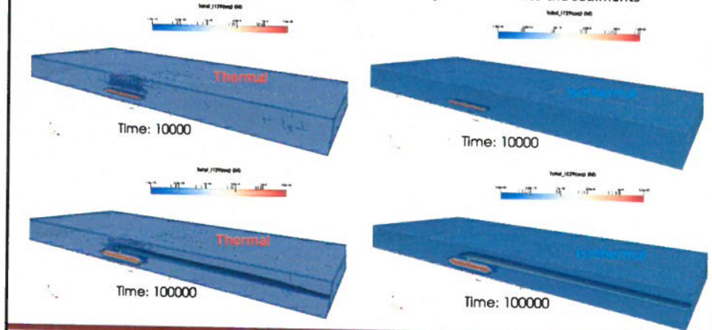
Salt Repository, Multi-Drift → Deterministic *Thermal* Simulation

- Darcy velocity vectors and
- Temperature field, at various times



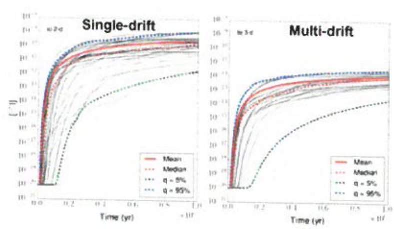
Salt Repository, Multi-Drift → Deterministic *Thermal* vs. *Isothermal*

- *^{129}I dissolved concentration at 10,000 years and 100,000 years*
  - Little effect from heat pulse at early times, prior to releases reaching the aquifer, via diffusion up the access shaft
  - Downwelling fluid flow in overburden sediments from heat pulse effects, downgradient of repository, seems to reduce the upward diffusive spread of ^{129}I into the sediments

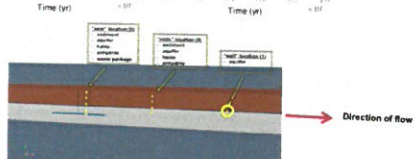


Multi-Drift vs. Single-Drift Comparison → *Probabilistic* *Thermal*

- The single-drift (20-m wide) reflection BC case (with effectively one shaft per drift-pair) and the five-drift half-domain (5100-m wide) represent two "bounds" for the effect of lateral dispersion/diffusion on peak concentration:



^{129}I conc. time histories – 50 realizations at "Well" obs. point



Summary and Future Work

- An enhanced PA modeling capability has been developed to:
  - Evaluate generic and/or specific disposal sites in various geologic media
    - High-fidelity representation of coupled processes in 3-D, using parallel HPC architecture and software
    - Including uncertainty and heterogeneity
  - Support prioritization of UFD RD&D activities
  - Enhance confidence and transparency in the safety case
- Application to a generic salt repository reference case
  - Some differences in PA results based on coupled T-H process effects on fluid flow, and based on the number of drifts simulated
- Ongoing and future work includes
  - 3-D simulations of a clay/shale reference case (recently completed)
  - 3-D simulations of the defense-only HLW in bedded salt (recently completed)
  - Grid refinement studies (begun already)
  - Application to deep borehole disposal in crystalline basement rock
  - Application to WIPP PA
  - Inclusion of all drifts/WPs in a half repository
  - Simulations in fractured crystalline rock to be started next fiscal year

Selected References

- Adams, B.M., M.S. Ebeida, M.S. Eldred, J.D. Jakeman, L.P. Swiler, W.J. Bohnhoff, K.R. Dalbey, J.P. Eddy, K.T. Hu, D.M. Vigil, L.E. Baumann, and P.D. Hough 2013a. *Dakota, a Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis, Version 5.3.1+ User's Manual.* SAND2010-2183, Updated May 22, 2013. Sandia National Laboratories, Albuquerque, NM. (http://dakota.sandia.gov/)
- Carter, J. T., A. J. Luptak, J. Gastelum, C. Stockman, and A. Miller 2012. *Fuel Cycle Potential Waste Inventory for Disposition.* FCRD-USED-2010-000031, Rev. 5. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition, Washington, DC.
- DOE (U.S. Department of Energy). 2013. *Strategy For The Management And Disposal Of Used Nuclear Fuel And High-Level Radioactive Waste*, U.S. Department of Energy, Washington, D.C., January 2013.
- DOE (U.S. Department of Energy). 2012. *Used Fuel Disposition Campaign Disposal Research and Development Roadmap.* FCR&D-USED-2011-000065, REV 1, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., September 2012.
- Freeze, G., M. Voegele, P. Vaughn, J. Prouty, W.M. Nutt, E. Hardin, and S.D. Sevougian 2013. *Generic Deep Geologic Disposal Safety Case.* FCRD-UFD-2012-000146 Rev. 1, SAND2013-0974P. Sandia National Laboratories, Albuquerque, NM.
- Freeze, G., W.P. Gardner, P. Vaughn, S.D. Sevougian, P. Mariner, V. Mousseau, and G. Hammond. 2013. *Enhancements to Generic Disposal System Modeling Capabilities.* FCRD-UFD-2014-000062. SAND2013-10532P. Sandia National Laboratories, Albuquerque, NM. November 2013.
- Hammond, G.E., P.C. Lichtner and R.T. Mills 2014. "Evaluating the Performance of Parallel Subsurface Simulators: An Illustrative Example with PFLORAN", *Water Resources Research*, 50, doi:10.1002/2012WR013483.
- Hansen, F.D. and C.D. Leigh. 2011. *Salt Disposal of Heat-Generating Nuclear Waste.* SAND2011-0161, Sandia National Laboratories Albuquerque New Mexico.
- Helton, J.C., C. W. Hansen, C. J. Sallaberry. 2014. "Expected dose for the nominal scenario class in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada," *Reliability Engineering and System Safety 122 (2014) 267–271.*
- Kienzler, B., M. Altmaier, C. Bube, and V. Metz 2012. *Radionuclide Source Term for HLW Glass, Spent Nuclear Fuel, and Compacted Hulls and End Pieces (CSD-C Waste)*, KIT Scientific Publishing, Report-Nr. KIT-SR 7624, Karlsruher Institut für Technologie (KIT), Straße am Forum 2, D-76131 Karlsruhe, www.ksp.kit.edu
- Lichtner, P. C., G. E. Hammond, C. Lu, S. Karra, G. Bisht, B. Andre, R. Mills, and J. Kumar 2014. *PFLOTRAN User Manual: A Massively Parallel Reactive Flow and Transport Model for Describing Surface and Subsurface Processes*, http://www.pflotran.org/docs/user_manual.pdf
- Sevougian, S. D., R. J. MacKinnon, B. A. Robinson, C. D. Leigh, and D. J. Weaver. 2013. *RD&D Study Plan for Advancement of Science and Engineering Supporting Geologic Disposal in Bedded Salt—March 2013 Workshop Outcomes*, FCRD-UFD-2013-000161, Rev. 0, SAND2013-4386P, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., May 31, 2013.
- Sevougian, S. D., G.A. Freeze, W.P. Gardner, G. E. Hammond, and P. Mariner 2014. *Performance Assessment Modeling and Sensitivity Analyses of Generic Disposal System Concepts.* FCRD-UFD-2014-000320, SAND2014-17658. Sandia National Laboratories, Albuquerque, NM, September 12, 2014.
- Sevougian, S. D., G.A. Freeze, W.P. Gardner, G. E. Hammond, P. E. Mariner, and R. J. MacKinnon. 2015a. "Performance Assessment Modeling of a Generic SNF/HLW Repository in Salt with Coupled Thermal-Hydrologic Effects – 15423," in *Proceedings of the WM2015 Conference*, March 15 – 19, 2015, Phoenix, Arizona USA.
- Sevougian, S. D., G. Freeze, M. Gross, J. Wolf, J. Mönig, and D. Buhmann 2015b. "Generic Salt FEPs Catalogue – Volume II," Rev. 0, June 29, 2015, Carlsbad, NM: Sandia National Laboratories, Waste Isolation Pilot Plant (WIPP) Records Center, Sandia Level Three Milestone: No. INT-15-01.

RepoTREND – A Program System for Safety Analysis

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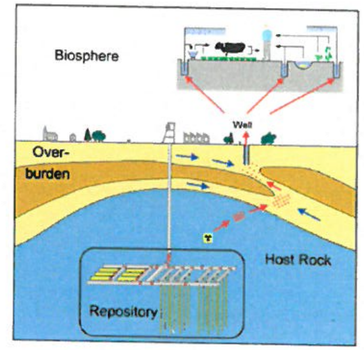
6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA Project Management Agency Karlsruhe · NNSA · ENERGY

Introduction

Numerical long-term performance assessment for a deep underground repository for radioactive waste

- Water intrusion cannot be excluded
- Canister corrosion and contaminant mobilization
- Fluid flow inside the underground facility, release to the geosphere
- Radionuclide (RN) transport through the far field by the groundwater
- Radioactive exposure of man

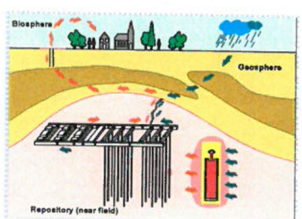


Simulations with the tool **RepoTREND** developed in GRS

RepoTREND: Transport and **RE**tention of **N**on-decaying and **D**ecaying contaminants in final **REPO**sitory

- RepoTREND is a new final repository simulator, developed in GRS since 2007
- Provides functionalities for simulating the
  - **release of contaminants** and
  - their **transport** through the near-field and far-field to the biosphere including
  - the **estimation of the radiological consequences** for man and environment.
- Applicable for different concepts of the final repository in different host formations

RepoTREND
- **BioTREND** radioactive exposure in the biosphere
- **GeoTREND** transport through the host rock
- **NaTREND** mobilisation and release of contaminants from the repository



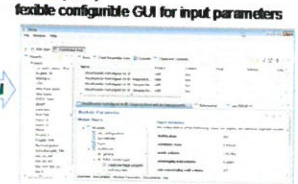
RepoTREND: Current Status (version 4.5) and Structure

- **LOPOS, CLAYPOS (old Fortran code) modified for a new data exchange format (JSON)**
- **GeoTREND-POSA (C++)** contaminant transport through fully SAturated POrous media
- **GeoTREND-FRAME (C++)** contaminant transport in FRActured MEmedia
- **GeoTREND-COFRAME (C++)** COlloid facilitated contaminant transport in FRActured MEmedia
- **BioTREND (C++)**
- **RepoSTAR (C++)** framework for probabilistical calculations (using SimLab 3.4)

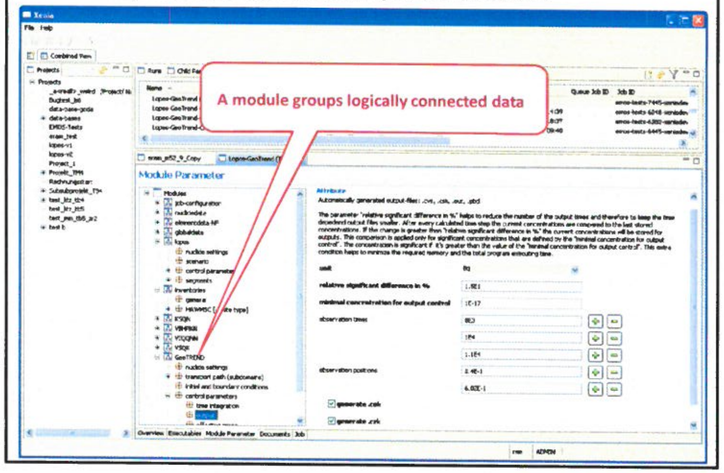
JSON

Database backend

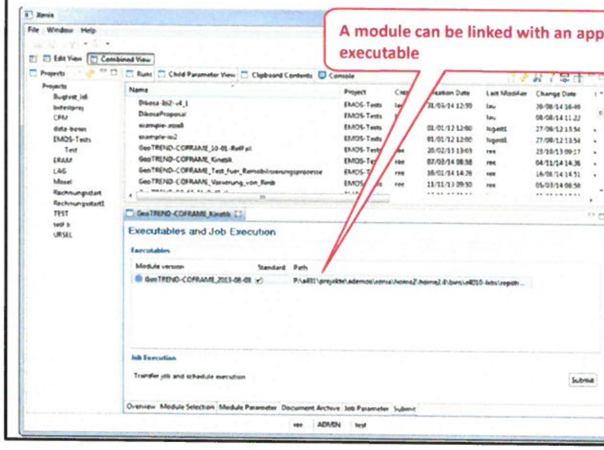
XENIA (Java) flexible configurible GUI for input parameters



XENIA: Graphical User Interface for Input of Parameters



XENIA: Program Start

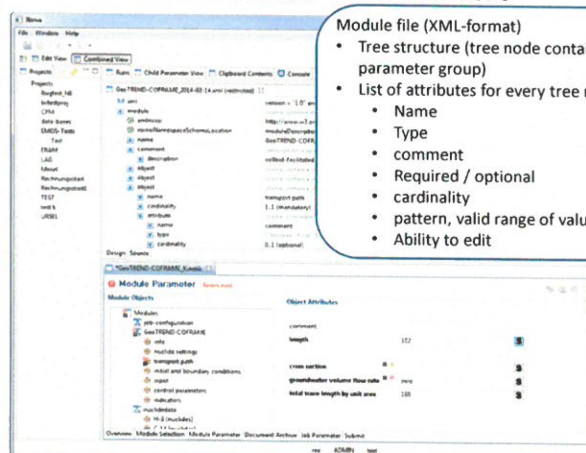


6

JSON

```
{
    "Modules":[{
        "OBJECTDEF_NAME":"nuda",
        "OBJECTDEF_VERSION":"01_02",
        "nuclides":[{
                "nuclide":"C-14",
                "half life":5730.0,
                "radiation type":"beta"
        },{
                "nuclide":"Th-227",
                "decay product":"Ra-223",
                "decay product (index offset)":1,
                "half life":0.0513,
                "radiation type":"alpha"
        }]
    }]
}
```


XENIA: XML-Editor for Definition of Parameter-Views

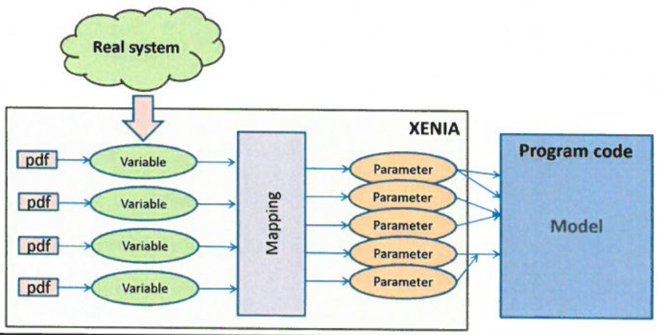


Module file (XML-format)
- Tree structure (tree node contains a parameter group)
- List of attributes for every tree node
  - Name
  - Type
  - comment
  - Required / optional
  - cardinality
  - pattern, valid range of values
  - Ability to edit

8

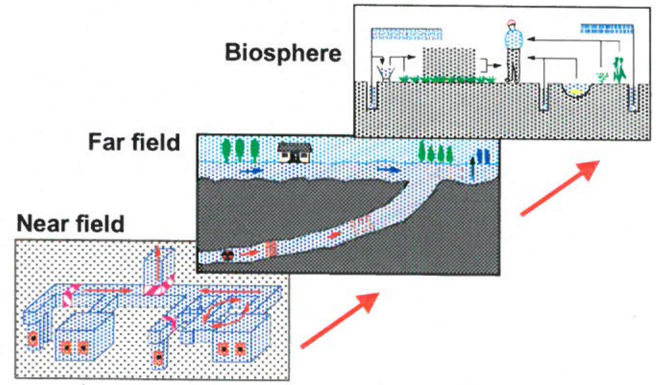
RepoSTAR – Framework for a Statistical Analysis

- Concept works for **any program code** connected to **XENIA** → universally applicable
- All statistical definitions are completely made in XENIA
- No modification of a program code!
- Highly flexible, easily extensible



9

Computational Modules for Repository Subsystems

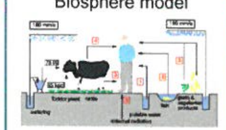


6th US/German Workshop on Salt Repository Research, Design, and Operation, Dresden September 7 - 9, 2015 10

BioTREND: Radiological Consequences in the Biosphere

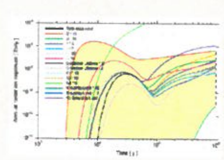
The results of a contaminant dissemination simulation – concentrations or/and flows at an interface with a biosphere

Input → **BioTREND** ← realized in – Biosphere model



Output

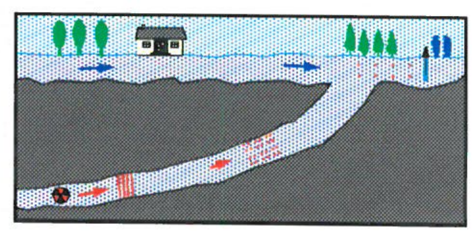
- Annual effective doses:
  - Radionuclide-specific and summed over certain nuclide groups
  - For a reference person and reference groups, tissue or organ adsorbed dose
- Safety indicators:
  - Radiotoxicity concentration in biosphere water
  - Radiotoxicity flux from the geosphere



11

GeoTREND: Transport Codes for the Far Field of a Repository

- GeoTREND-Family – contaminant transport in fully saturated media
  - **POSA** – fully SAturated POrous media
  - **FRAME** – FRActured MEdia
  - **COFRAME** – COlloid facilitated transport in porous-FRActured MEdia



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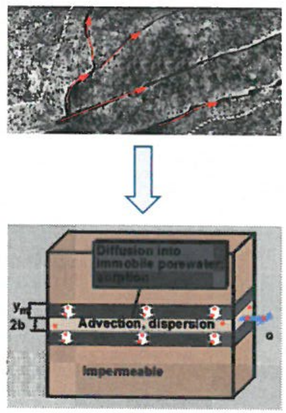
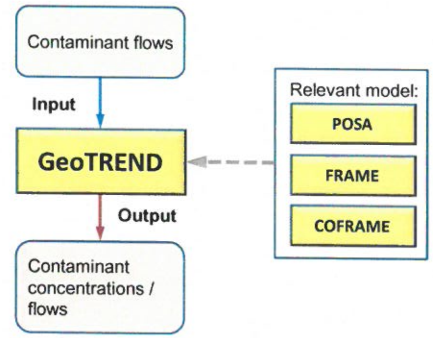
GeoTREND: Transport Codes for the Far Field of a Repository

- Processes:
  - Transport:
    - Advection
    - Diffusion
    - Dispersion
    - Colloid-bound transport
  - Retardation:
    - Element-specific sorption
    - Filtration / remobilization of colloids
    - Diffusion into the rock matrix
  - Radioactive decay
  - Dilution in near-surface aquifer
  - One or more source terms



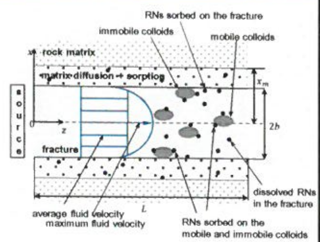
GeoTREND: Transport Codes for the Far Field of a Repository

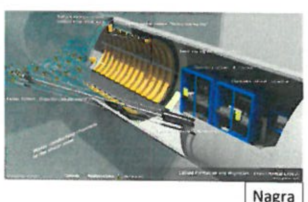
- Common model properties:
  - 1D-transport
  - Finite Difference (FD)
  - Implicit Crank-Nicolson time integration
  - C++
  - Object-oriented design
  - Algorithm parallelization with multithreading concept



COFRAME

- 1D-model of the migration of contaminants in a fractured-porous medium in the presence of colloids
- Distinguishing features: *kinetically controlled sorption* of contaminants on colloids and *kinetically controlled interaction* of colloids with fracture surface (filtration/remobilization)





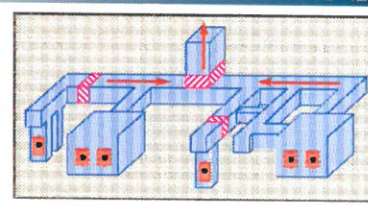
- Qualified by application to the data from some dipole tests performed in the frame of the international CFM project (Colloid Formation and Migration) at Grimsel Test Site (Switzerland)

Near Field Modules

LOPOS

Radionuclide mobilisation and one-phase transport in a repository in salt rock

- Corrosion of waste canisters
- Radionuclide mobilisation (corrosion of waste matrix)
- Advection, dispersion, diffusion
- Radioactive decay
- Salt creep (rock convergence)
- Compaction of crushed salt
- Temperature evolution (in time and space)
- Gas generation
- Sorption
- Precipitation / dissolution



CLAYPOS

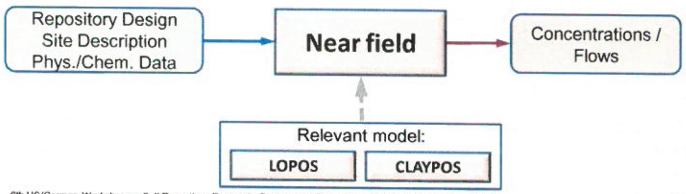
One-phase diffusive transport through a fully saturated clay barrier

- Radionuclide mobilisation
- Diffusion
- Radioactive decay
- Sorption
- Precipitation / dissolution
- Dilution in near-surface aquifer

Near Field Modules

Model properties:
- Based on Finite Difference (FD)
- Explicit time integration scheme
- Fortran (some program elements are over 30 years old)
- Procedure-oriented design
- Special design in LOPOS: segment model ("intelligent" grid blocks)

Problems:
- Some important processes / effects are not considered (e.g. two-phase transport)
- Not flexible enough (e.g. many restrictions to a grid, difficult integration of additional effects)
- Program code is difficult to develop and to maintain



NaTREND – New Near Field Module

Main challenges:
- The system to be modelled is highly complex.
- The model area is extremely heterogeneously. Individual system parts differ:
  - in their properties
  - in the relevance of the processes / effects
  - by different modelling of the same effect
- The requirements change because of the new legal requirements, development of the new repository concepts, scientific and technical progress.

NaTREND: Main Goals

Main goal:
- Program structure (software architecture) shall be highly modular and highly flexible to changes and new requirements in order to modify and develop the code easily, e.g.:
  - coupling of different transport models (such as transport in porous media and in case of the open flow)
  - incorporating / modifying of relevant effects
  - exchanging of the computational algorithms or incorporating of alternative algorithms…
- Taking into account the new requirements such as a two-phase transport

Example: Concept Idea for Considering of Different Effects

- Effects are: metal and waste matrix corrosion, rock convergence, interacting reactions…
- Effects affect the equation parameters (porosity, density, volume…)
- Different effects are relevant for different grid blocks

Goals for designing of the software architecture:
- Ability to choose any combination of available effects to be considered for a grid block
- Easy incorporation of new effects and modification of integrated effects
- Good performance + high accuracy

NaTREND: Mass Balance Equations for Two Phases

$$\begin{cases} \frac{\partial(\phi S_\alpha \rho_\alpha)}{\partial t} - div\left(\rho_\alpha \frac{k_{r\alpha}}{\mu_\alpha} k \nabla \psi_\alpha\right) - \rho_\alpha q_\alpha = 0 \quad \alpha \in \{w,g\} \\ S_w + S_g = 1 \\ p_c = p_g - p_w \end{cases}$$

4 equations
4 unknowns:
p_g, p_w, S_g, S_w

- Variable substitution → system of 2 flow equations (gas g and liquid w) with 2 primary variables

$$\left\{ \frac{\partial(\phi S_\alpha \rho_\alpha)}{\partial t} - div\left(\rho_\alpha \frac{k_{r\alpha}}{\mu_\alpha} k \nabla \psi_\alpha\right) - \rho_\alpha q_\alpha = 0 \quad \alpha \in \{w,g\} \right.$$

2 equations
2 unknowns
(primary variables):
p_g, S_w

$$S_g = 1 - S_w$$
$$p_w = p_g - p_c$$

2 equations
2 secondary variables:
p_w, S_g

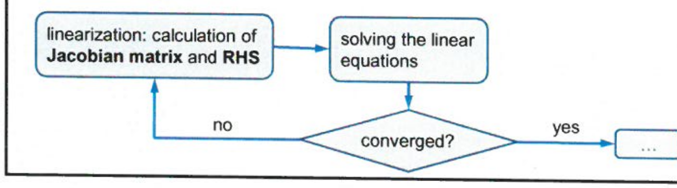
NaTREND: Solving Scheme

- Numerical scheme:
  - Finite Volume (FV) method for the discretization of the model area → N grid blocks
  - Time discretization: implicit, explicit, combination
- $2 \times N$ of nonlinear equations

(change in mass in a time step) – [(flow in) – (flow out)] = 0

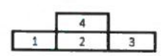
A_i accumulation term; $\sum_j F_{ij}$ flow term

- Solving method – Newton-Raphson:



Jacobian Matrix for Basic Equation System

Jacobian matrix of basis equations:
- Only 2 variables X, Y for every grid block i
- All parameters are constant



$$\begin{cases} [A_g(X,Y)]_i^{k+1} - \sum_j [F_g(X,Y)]_{ij}^{k+1,k} = 0 \\ [A_w(X,Y)]_i^{k+1} - \sum_j [F_w(X,Y)]_{ij}^{k+1,k} = 0 \end{cases}$$

A1	A12			X1 Y1
A21	A2	A23	A24	X2 Y2
	A32	A3		X3 Y3
	A42		A4	X4 Y4

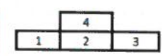
2 variables: X, Y

Block matrix:
- **Diagonal block submatrix** i contains entries for one grid block i (derivatives from A_i and F_{ij} with respect to variables of grid block i)
- **Upper and lower off-diagonal block matrices** contain derivatives of equations of grid block i with respect to variables of grid block j or rather derivatives of equations of grid block j with respect to variables of grid block i (derivatives from F_{ij} or rather F_{ji})

Considering the Rock Convergence

- Convergence (salt creeping) leads to the changing of the total pour volume V_p →
- One additional equation → one additional variable V_p

3 variables: X, Y, V_p



A1	B1	A12	B12				
C1	D1	0	0				
A21	B21	A2	B2	A23	B23	A24	B24
		C2	D2	0	0	0	0
		A32	B32	A3	B3		
		0	0	C3	D3		
		A42	B42			A4	B4
		0	0			C4	D4

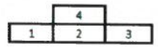
X1 Y1 Vp1 X2 Y2 Vp2 X3 Y3 Vp3 X4 Y4 Vp4

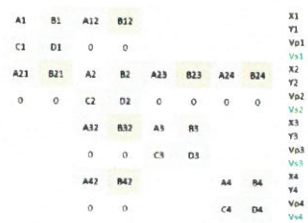
$$\begin{cases} [A_g(X,Y)]_i^{k+1} - \sum_j [F_g(X,Y,V_p)]_{ij}^{k+1,k} = 0 \\ [A_w(X,Y)]_i^{k+1} - \sum_j [F_w(X,Y,V_p)]_{ij}^{k+1,k} = 0 \\ \left[V_p^{k+1} + \Delta t \cdot [K(X,Y,V_p) \cdot (V_p + V_s)]^{k+1,k} - V_p^k\right]_i = 0 \end{cases}$$

Considering of Metal Corrosion

- Corrosion leads to the changing of the
  - total pour volume V_p → additional term in the equation for V_p
  - water and gas volume → source/sink terms in the flow equations
  - volume of solids → one additional equation for V_s (additional variable V_s)

4 variables: X, Y, V_p, V_s



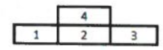


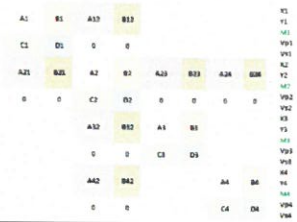
$$\begin{cases} [A_g(X,Y)]_i^{k+1} - \sum_j [F_g(X,Y,V_p,V_s)]_{ij}^{k+1,k} = 0 \\ [A_w(X,Y)]_i^{k+1} - \sum_j [F_w(X,Y,V_p,V_s)]_{ij}^{k+1,k} = 0 \\ \left[V_p^{k+1} + \Delta t \cdot [K(X,Y,V_p,V_s)\cdot(V_p+V_s) + r_{corr}(X)]^{k+1,k} - V_p^k\right]_i = 0 \\ [V_s^{k+1} + \Delta t \cdot [r_{corr}(X)]^{k+1,k} - V_s^k]_i = 0 \end{cases}$$

Carnallitite Dissolution and Reprecipitation

- Reaction depends on Mg^{2+}
- Leads to the changing
  - of the total pour volume V_p and volume of solids V_s → additional terms in the appropriate equations
  - Mg^{2+} concentration → one additional equation for Mg^{2+} (additional variable M)

5 variables: X, Y, V_p, V_s, M





$$\begin{cases} [A_g(X,Y)]_i^{k+1} - \sum_j [F_g(X,Y,V_p,V_s)]_{ij}^{k+1,k} = 0 \\ [A_w(X,Y)]_i^{k+1} - \sum_j [F_w(X,Y,V_p,V_s)]_{ij}^{k+1,k} = 0 \\ M_{le,l}^{k+1} - \Delta t \cdot [C_{le} r_{prim}(X, M_{le}) + Q_{le}]_i^{k+1,k} \\ \qquad - \Delta t \sum_j [F_w(X,Y,V_p,V_s)]_{ij}^{k+1,k} [f_{diss}(M_{le})]_{ij,ups}^{k+1,k} - M_{le,l}^k = 0 \\ \left[V_p^{k+1} + \Delta t \cdot \begin{bmatrix} K(X,Y,V_p,V_s)\cdot(V_p+V_s) + r_{corr}(X) \\ -C_{prim} r_{diss}(X, M_{le}) \end{bmatrix}^{k+1,k} - V_p^k\right]_i = 0 \\ \left[V_s^{k+1} + \Delta t \cdot [r_{corr}(X) + C_{prim} r_{diss}(X, M_{le})]^{k+1,k} - V_s^k\right]_i = 0 \end{cases}$$

Concept Idea

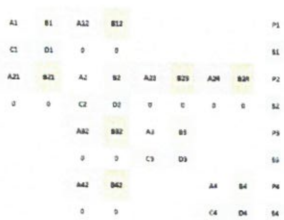
General aspects:

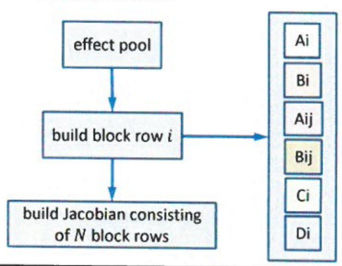
- The structure for a block row is always the same.
- Different effects are relevant in the different grid blocks. → The form of block submatrices is individual for every grid block.

⇨

Concept:

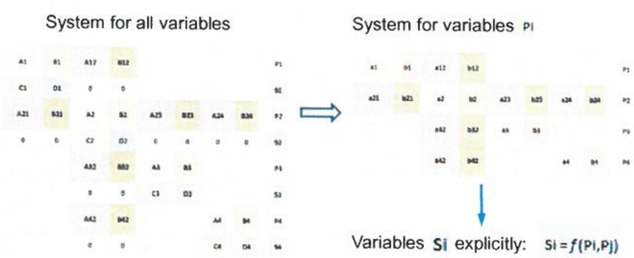
- Develop an effect collection (computational algorithms for calculation of the appropriate terms for the entries of the Jacobian matrix).
- Build a block row for one grid block according to the predetermined structure.
- Build Jacobian matrix from block rows for every grid block.





Solving of the System of Linear Equations

That block structure of the Jacobian matrix enables the application of the Schur-complement method to each block row → the original equation system can be considerably reduced (no additional errors!)



Optimisation

Further reducing of the equation system by calculation of some variables Pi explicitly:

Δt_{impl} - next time step for solving of the equation system implicitly

↓

estimate $\Delta t_{expl,i}$ next time step for the variable Pi in case of explicit scheme

↓

if $\Delta t_{expl,i} \leq \Delta t_{impl}$ → calculate Pi explicitly

Optimisation

Re-construction of a Jcobian matrix:

- Available libraries for solving of linear equation systems require the special input format for a matrix:

  $\boldsymbol{meta\ info} = \{\boldsymbol{number\ of\ rows\ and\ columns, number\ of\ non-zeros}, \ldots\}$

  $J_{ij} = [\boldsymbol{non-zero\ entries}]$ (array of values)

- → Re-construction of J_{ij}-array and $\boldsymbol{meta\ info}$ every iteration is required.
- Record J_{ij} as an array of pointers to the block submatrices:

  $J_{ij} = [A^*,\ B^*,\ C^*,\ D^*]$ (array of pointers)

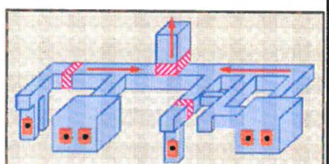
- → No re-constructing is required (changings occur only in a submatrix, but the matrix structure remains the same).
- Algorithms for the operations on the matrices have to be reformulated for the operations on the block matrix (no available libraries, but available algorithms can be easy modified).

NaTREND: Features

Radionuclide mobilisation and two-phase transport in a repository (porous media and in case of open flow):

- Corrosion of waste containers
- Radionuclide mobilisation (corrosion of waste matrix)
- Advection, dispersion, diffusion
- Radioactive decay
- Convergence (salt creep, convergence of clay)
- Compaction of crushed salt
- Temperature evolution (in time and space)
- Variation of parameters with temperature (viscosity, liquid density…)
- Gas generation
- Different gas and water sources
- Sorption
- Mineral precipitation / dissolution
- Structured and unstructured grids

new feature or new/modified model



Thank you for your attention!

Supported by:

Federal Ministry of Economics and Energy

on the basis of a decision by the German Bundestag

Evaluation of Current Knowledge for Building the Dutch Salt Safety Case (short version)

Jaap Hart, Jan Prij, Thomas Schröder
NRG Consultancy & Safety
Petten, Netherlands

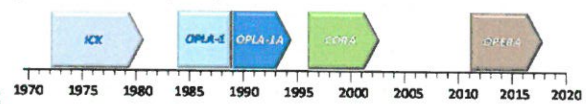
Dirk-Alexander Becker, Jens Wolf,
Ullrich Noseck (GRS)

Geert-Jan Vis (TNO)

September 2015

Research project *OSSC*

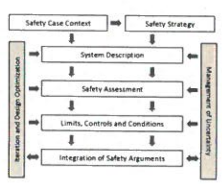
- From *ICK* to *OPERA*: the Netherlands has a history of more than 40 years of research on disposal in rock salt
- Some discontinuity in research can be observed, but as part of the ongoing national research programme *OPERA* - focussing on disposal in Boom Clay - a single project, *OSSC*, was devoted to disposal in rock salt
- Main objectives of *OSSC*:
  - ➢ Evaluate the present knowledge about the safety and feasibility of a final disposal facility in rock salt in the Netherlands
  - ➢ Analyse available national (ICK, OPLA, CORA), and international (German and US) information about the final disposal in rock salt
  - ➢ Put the information in the framework of a Safety Case
  - ➢ Assess whether the available information is sufficient to build a Dutch Safety Case for the geological disposal in rock salt
- Project Partners: NRG, GRS, TNO



2

Conclusions of *OSSC*

- The *OSSC* project provides an evaluation of current knowledge for building the Safety Case for salt based repositories in the Dutch context – which is presented in the form of a Safety Case
- Although previous Dutch efforts provide good arguments for safety, these efforts and arguments do show numerous loose ends – and thus need to be updated and integrated into the framework of a Safety Case
- Subsequently, all Safety Case related aspects need to be revisited, updated - if deemed necessary - and assembled into an integrated Safety Case
- The main recommendation to continue with the development of the Salt Safety Case in the Netherlands is to follow a three-step approach, making maximum use of existing knowledge, the OPERA outcomes, and international developments on that topic



3

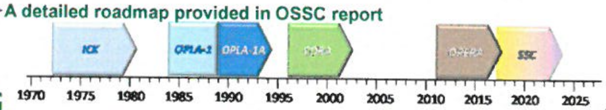
Roadmap for a Safety Case on rock salt

To develop a Salt Safety Case, comparable to the (intended) Dutch *OPERA* Safety Case on Boom Clay, a stepwise approach is recommended:

- **Phase 1**: Base model compilation & First safety assessment
  - ❖ Update of previous safety assessments, utilizing existing tools
- **Phase 2**: Completion of process representation & Refinement of disposal concept
  - ❖ Incorporation of relevant process models into SA tool
- **Phase 3**: Delivery of Rock Salt Reference Model & Development of initial Safety Case
  - ❖ Providing the Dutch initial salt Safety Case

➢ Many components necessary to provide a Salt Safety Case can be used from the *OPERA* research on Boom Clay, e.g. waste inventory, radionuclide migration model in geosphere and biosphere, safety indicators and uncertainty approach, or methodology of scenario development

➢ **A detailed roadmap provided in OSSC report**



4

OSSC project reports

All results of the OSSC project are reported in two documents:

- *J. Hart, J. Prij, G.-J. Vis, D.-A. Becker, J. Wolf, U. Noseck, and D. Buhmann. Collection and analysis of current knowledge on salt-based repositories, OPERA-PU-NRG221A, 15 July 2015*
- *J. Hart, J. Prij, T.J. Schröder, G-J. Vis, D.-A. Becker, J. Wolf, U. Noseck, and D. Buhmann. Evaluation of current knowledge for building the Safety Case for salt-based repositories, OPERA report OPERA-PU-NRG221B, 3 Augustus 2015*

After approval by COVRA, these reports will made available at www.covra.nl

Acknowlegdement

- Messrs. Jacques Grupa, Arjen Poley and other colleagues from NRG for their support, input and review efforts
- The German colleagues from GRS for providing valuable feedback and relevant input
- The research leading to these results has received funding from the Dutch research programme on geological disposal OPERA

OPERA

NRG

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Exceptional service in the national interest — Sandia National Laboratories

Joint US-German Activities on the FEP Catalogue and Scenario Development

Geoff Freeze, Sandia National Laboratories
Jens Wolf, GRS

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA Project Management Agency Karlsruhe · NNSA · U.S. Department of Energy

Outline

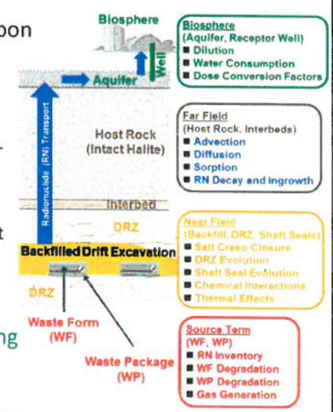
- Objectives / Motivation
- Feature, Event, and Process (FEP) Analysis Overview / Review
- Update on Collaborative Results
  - Populate FEP Matrix
  - NEA Participation
- Future Work
- Participants
  - SNL: Geoff Freeze, David Sevougian, Michael Gross, Christi Leigh
    - DOE Used Fuel Disposition (UFD) Campaign
    - Waste Isolation Pilot Plant (WIPP)
  - GRS: Jens Wolf, Jörg Mönig, Dieter Buhmann
    - Vorläufige Sicherheitsanalyse Gorleben (VSG)

Objectives / Motivation

- U.S. – German collaboration to produce a common FEP list
  - Identify relevant FEPs for disposal of heat-generating waste (SNF and HLW) in salt
    - Applicable to all potential salt concepts and sites
    - Can support site selection
  - Promote dialogue of experts to review FEP analysis approaches
    - Adopted FEP Matrix approach
- NEA Salt Club
  - Produce a FEP Catalogue for use by all NEA Salt Club members
    - Countries with potential interest in salt repositories
  - Consistency with the pending update to the NEA International FEP Database

FEP Analysis Overview

- A FEP is a Process or Event acting upon or within Feature(s)
- FEP Identification
  - Develop and classify a comprehensive list of FEPs potentially relevant to long-term repository performance
- FEP Screening
  - Specify a subset of important FEPs that individually, or in combination, that contribute to long-term repository performance
- Scenario Development and Screening
  - Identify and screen scenarios (i.e., combinations/sequences of FEPs)
    - Nominal/reference, disruptive/alternative



FEP Matrix Overview

- Two-dimensional FEP organizational structure to guide FEP identification and screening
  - Matrix Rows = Feature (and Component) Categories
  - Matrix Columns = Process and Event Categories
- Related FEPs are grouped by Matrix Cell (or by Row or Column)
  - Matrix Cell contains all FEPs related to the "Process/Event" acting upon or within the "Feature"
- FEP Identification "Numbering" Scheme
  - Developed a new alpha-numeric identification scheme indicating where a FEP is mapped in the FEP Matrix (row and column)
    - More descriptive than strictly numeric identifiers
    - Can still be mapped to NEA Database numbering for traceability

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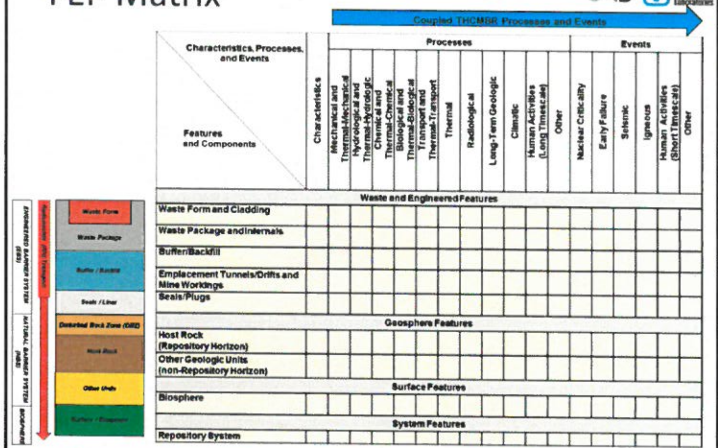
FEP Matrix



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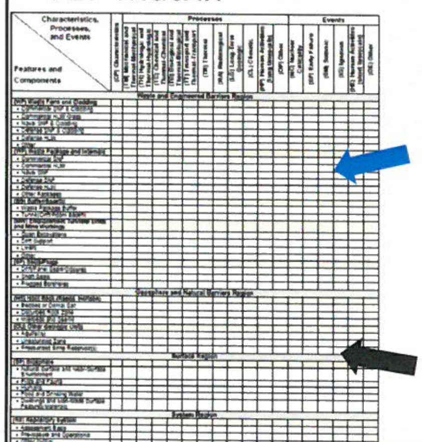
FEP Matrix



U.S.
~200 UFD Bedded Salt FEPs
(Sevougian et al. 2012)

- Modified from generic FEPs (Freeze et al. 2011) to be more salt-specific
- Derived from NEA FEP Database (1999, 2006)
- Cross-checked against WIPP FEP catalogue (DOE 2009)

Germany
~100 Gorleben VSG FEPs
(Wolf et al. 2012a,b)

- Derived from NEA FEP Database (1999, 2006)
- Specific to a salt dome in Northern Germany

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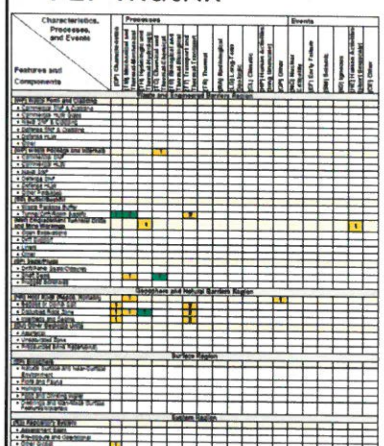
FEP Matrix



Combined Salt FEPs
(Freeze et al. 2014)
(Sevougian et al. 2015)

- 25 Matrix-based FEPs, derived from initial US and German FEPs
- Focus on FEPs which emphasize differences between bedded and domal salt

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Combined Salt FEPs (to date)

Waste and Engineered Barrier FEPs (11)

Waste Package
- WP.00.TC.01 Gas Generation at Waste Packages

Backfill
- BB.02.CP.01 Backfill Materials
- BB.02.TM.01 Mechanical Effects on Backfill or from Backfill
- BB.02.TM.02 Thermal-Mechanical Effects on Backfill or from Backfill
- BB.02.TT.01 Advection of Dissolved Radionuclides in Backfill
- BB.02.TT.02 Diffusion/Dispersion of Dissolved Radionuclides in Backfill

Emplacement Drifts / Mine Workings
- MW.00.TH.01 Thermal-Hydrologic Effects of Gas in Emplacement Drifts / Boreholes
- MW.00.TM.01 Mechanical Response of Mine Workings to External Stress
- MW.00.HE.01 Human Intrusion into the Emplacement Drifts

Seals
- SP.02.TM.01 Mechanical Effects on Shaft Seals or from Shaft Seals
- SP.02.TC.01 Chemical Interaction of Groundwater with Shaft Seals

System FEPs (1)
- RS.03.CP.01 Repository Design

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Combined Salt FEPs (to date)

Geosphere and Natural Barrier FEPs (13)

Host Rock (General)
- HR.00.TM.01 Mechanical Effects on the Host Rock
- HR.00.OP.01 Alteration and Evolution of Flow Pathways in the Host Rock

Bedded or Domal Salt
- HR.01.CP.01 Stratigraphy and Properties of Bedded and Domal Salt
- HR.01.TT.01 Advection of Dissolved Radionuclides in Bedded or Domal Salt
- HR.01.TT.02 Diffusion/Dispersion of Dissolved Radionuclides in Bedded or Domal Salt

Disturbed Rock Zone (DRZ)
- HR.02.CP.01 Stratigraphy and Properties of the Disturbed Rock Zone in the Host Rock
- HR.02.TM.01 Mechanical Effects on the Evolution of the DRZ
- HR.02.TH.01 Flow Through the DRZ
- HR.02.TT.01 Advection of Dissolved Radionuclides in the Disturbed Rock Zone
- HR.02.TT.02 Diffusion/Dispersion of Dissolved Radionuclides in the Disturbed Rock Zone

Interbeds and Seams
- HR.03.CP.01 Stratigraphy and Properties of Interbeds and Seams in the Host Rock
- HR.03.TT.01 Advection of Dissolved Radionuclides in Interbeds and Seams
- HR.03.TT.02 Diffusion/Dispersion of Dissolved Radionuclides in the Interbeds and Seams

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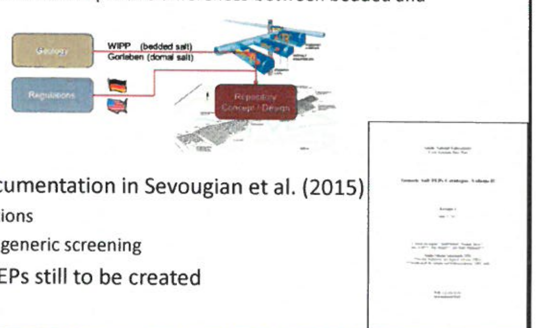
Combined Salt FEPs

- 25 Matrix-based FEPs
  - Derived from initial US and German FEPs
  - Focus on FEPs which emphasize differences between bedded and domal salt



- Extensive Documentation in Sevougian et al. (2015)
  - FEP Descriptions
  - Preliminary, generic screening
- Many more FEPs still to be created

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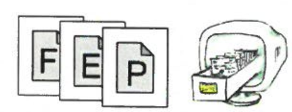
NEA Participation – Salt Club

- Produce a FEP Catalogue for use by all NEA Salt Club members
  - Countries with potential interest in salt repositories
- Deliverable due at end of current Salt Club Mandate Period (2014-16)
  - Full Salt FEP Catalogue will not be complete
  - Deliverable content TBD



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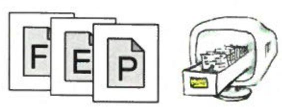
NEA Participation – FEP Database

- US and German participation in the NEA FEP Task Group Meeting
  - Presentation of Salt FEPs Approach and Content
- Inform the pending update to the NEA International FEP database (completion date is TBD)
  - Existing NEA FEPs
  - Capability for user uploading of new FEP lists
- Currently beta testing web-based Version 0.3



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NEA Participation – Scenario Development

- US and German participation in the NEA Scenario Development Workshop (June 1-3, 2015) in Paris
  - Presentation of National approaches for FEP Analysis and Scenario Development, including comprehensiveness
  - Support development of an NEA Report on Scenario Development

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NEA Scenario Development Workshop

- Main outcomes / developments since NEA (2001)
  - Scenario development is an integral part of any safety case
  - Basic ideas are consistent in all discussed safety cases
    - Mixture of bottom-up and top-down approaches
    - Different classes of scenarios
    - Human intrusion → separate scenario category
    - What-if cases → robustness
  - Main efforts in the last decade
    - Comprehensiveness of scenarios
    - Traceability of decisions (regulatory expectations!)
    - Documentation in the safety case
  - Open issues
    - Communicating the role and choice of scenarios
    - Assigning probabilities to scenarios/FEPs

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Future Work

- Salt FEP Catalogue
  - Continuation of matrix-based FEP identification and documentation
  - Both countries are in a site selection process
    - Generic FEPs only, hard to screen
  - Filling out the entire matrix with fully described FEPs requires significant resources
    - Maybe just identify FEP names?
  - Electronic FEP Database under development → saltfep.org
- NEA Participation
  - Need to identify "Product" for Salt Club
  - Complete NEA FEP Database beta testing
  - Complete NEA Scenario Development documentation

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Acknowledgements

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on the basis of a decision by the German Bundestag

References

- DOE (U.S. Department of Energy) 2009. *Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application for the Waste Isolation Pilot Plant, Appendix SCR-2009 Feature, Event, and Process Screening for PA.* DOE/WIPP 09-3424, U.S. Department of Energy, Carlsbad Area Office, Carlsbad, New Mexico.
- Freeze, G., Mariner, P., Blink, J.A., Caporuscio, F.A., Houseworth, J.E., and Cunnane, J.C. 2011. *Disposal System Features, Events, and Processes (FEPs): FY11 Progress Report.* SAND2011-6059P, Sandia National Laboratories, Albuquerque, NM.
- Freeze, G., Sevougian S.D., Leigh, C., Gross, M., Wolf, J., Mönig, J., and Buhmann, D., 2014. *Development of a Salt Repository FEP Catalogue.* SAND-2014-2423P, Sandia National Laboratories, Albuquerque, New Mexico.
- NEA (Nuclear Energy Agency) 1999. *An International Database of Features, Events and Processes.* Paris, France: Organisation for Economic Co-operation and Development.
- NEA (Nuclear Energy Agency) 2001. *Scenario Development Methods and Practice. An evaluation based on the NEA Workshop on Scenario Development Madrid, Spain, May 1999.* Paris, France: Organisation for Economic Co-operation and Development.
- NEA (Nuclear Energy Agency) 2006. *The NEA International FEP Database: Version 2.1.* Paris, France: Organisation for Economic Co-operation and Development.
- Sevougian S. D., G. A. Freeze, M. B. Gross, Joon Lee, C. D. Leigh, P. E. Mariner, R. J. MacKinnon, and P. Vaughn, 2012. *TSPA Model Development and Sensitivity Analysis of Processes Affecting Performance of a Salt Repository for Disposal of Heat-Generating Nuclear Waste*, FCRD-UFD-2012-000320 Rev 0, U.S. Department of Energy, Office of Nuclear Energy, Used Fuel Disposition Campaign, Washington, D.C.
- Sevougian S.D., Freeze, G., Gross, M., Wolf, J., Mönig, J., and Buhmann, D., 2015. *Generic Salt FEPs Catalogue, Volume II, Revision 0, June 29, 2015*, Waste Isolation Pilot Plant (WIPP) Records Center, Sandia Level Three Milestone: No. INT-15-01. Sandia National Laboratories, Carlsbad, New Mexico.
- Wolf, J., Altmaier, M., Behlau, J., Beuth, T., Bracke, G., Bube, C., Buhmann, D., Dresbach, C., Hammer, J., Keller, S., Kienzler, B., Klinge, H., Krone, J., Lommerzheim, A., Metz, V., Mönig, J., Mrugalla, S., Popp, T., Rübel, A., Weber, J.R., 2012a: *Konzept und Aufbau des FEP-Kataloges.* Bericht zum Arbeitspaket 7, Vorläufige Sicherheitsanalyse für den Standort Gorleben, GRS-282, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Köln, 2012.
- Wolf, J., Altmaier, M., Behlau, J., Beuth, T., Bracke, G., Bube, C., Buhmann, D., Dresbach, C., Hammer, J., Keller, S., Kienzler, B., Klinge, H., Krone, J., Lommerzheim, A., Metz, V., Mönig, J., Mrugalla, S., Popp, T., Rübel, A., Weber, J.R., 2012b: *FEP-Katalog.* Bericht zum Arbeitspaket 7, Vorläufige Sicherheitsanalyse für den Standort Gorleben, GRS-283, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Köln.

Uncertainty Management in Performance Assessment

Dirk-Alexander Becker, GRS
Thanks to: Sabine Spiessl, GRS

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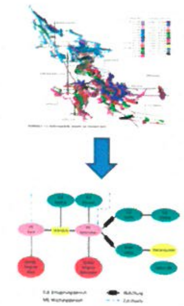
Assessment of Repository Safety

Will the repository be safe now and forever?

- We cannot prove it
- We cannot do experiments over more than a few years
- We have to assess the safety by numerical modeling



But how do we know the simplified model calculates the right results?

- There are lots of uncertainties: model, scenario, parameters
- Can we trust the model if it says the repository is safe?
- Somehow we have to take the uncertainties into account ...

Integrated Performance Assessment

Near Field
- Intrusion of water or brine
- Radionuclide mobilization from containers
- Dissolution and precipitation
- Sorption
- Chemical processes
- Mechanical processes
- Gas production and pressure build-up
- Fluid flow
- Transport of radionuclides
- Release to the far field

Far Field
- Dilution by groundwater
- Fluid flow through geological layers
- Precipitation
- Sorption
- Release to the biosphere

Biosphere
- Concentration of radionuclides in nutrition products
  - Contamination of drinking water
  - Uptake of radionuclides by fish
  - Irrigation of fields
  - Cattle watering
- Direct radiation
- Individual equivalent dose per year

- - - - - Radioactive Decay - - - - -

Uncertainties

Aleatory uncertainties:
- *alea* (latin)= dice
- due to random influences
- cannot be reduced

Epistemic uncertainties:
- *episteme* (greek) = knowledge
- due to lack of knowledge
- can be reduced by research

Scenario uncertainties:
- will the system develop as expected?

Model uncertainties:
- do our models describe the system correctly?

Parameter uncertainties:
- did we chose the right values for all input parameters?

Uncertainty management

Two questions:

- How has the modelling setup (scenario, model, parameters) to be chosen to become adequate for estimating future risks?
- *Provided it is*, how do the uncertainties influence the model results?
  - How uncertain are the calculation results?
  - How big is the risk that the permissible limits are exceeded?
  - Which uncertainties have the highest influence on the calculation results?

The first question has to be addressed via expert judgement

The second question can be answered by mathematical analysis

Uncertainty Quantification by Expert Judgement

- Scenario development
  - FEP description
  - FEP interaction
  - estimation of FEP probabilities
- Mathematical description
  - physical and chemical effects
  - interactions
- Model development
  - simplification
  - conservatism
- Parameter estimation
  - knowledge assessment
  - aleatory/epistemic?
  - best estimate values
  - probability density functions (pdf)

This is hard and time-consuming work!

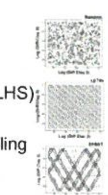
- "Modelling setup" as input for mathematical uncertainty/sensitivity analysis
- All steps should be properly justified
- Subjectivity should be minimized
- Unique and transparent procedures required
- Treatment of aleatory uncertainties?
- Necessary for proper quantification of uncertainties and sensitivities of the safety statements
- Further research required!

The modelling setup

- A unique scenario
  - minor scenario uncertainties can be mapped to model parameters
  - major scenario uncertainties should be treated in different setups
- A computational model
  - adequate to describe the scenario
  - a "black box", calculating an output value from a number of model parameters
  - minor model uncertainties can be mapped to parameters
  - represents a mathematical function with many arguments
- A set of probabilistic variables
  - represent uncertain influences
  - unique mapping to model parameters (not necessarily one-to-one)
  - probability density functions (pdf) for all variables
  - correlations (or other statistical dependencies) can be defined

Probabilistic Analysis

- Decide about number of runs
  - intended kind of evaluation
  - required degree of confidence
  - robustness
  - computational limitations
- Decide about sampling of statistical variables
  - intended kind of evaluation
  - type of uncertainties
  - robustness
  - different schemes:
    - (pseudo-)random
    - stratified sampling (e.g. LHS)
    - quasi-random
    - evaluation-specific sampling



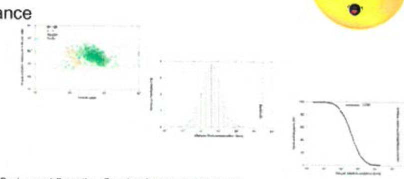
- Perform calculation
  - automatic assignment of parameter values for each run
- Collect model output
  - time-dependent data
  - maximum data
  - additional information?
- Evaluate
  - uncertainty analysis
  - sensitivity analysis
  - graphic presentations

GRS

Uncertainty Analysis

Analyze the model output without any reference to the input (statistical variables)

- Define a set of model output values
  - at a specific point in time
  - maximum of each run
- Interpret the values as a sample, representing the unknown distribution of model output
- Calculate statistical measures
  - mean, median, standard deviation, statistical moments, ...
    - use corrected (unbiased) formulas
- Estimate risk of limit exceedance
  - binomial distribution
- Generate plots
  - scatterplots
  - frequency histograms
  - CCDF



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Sensitivity Analysis

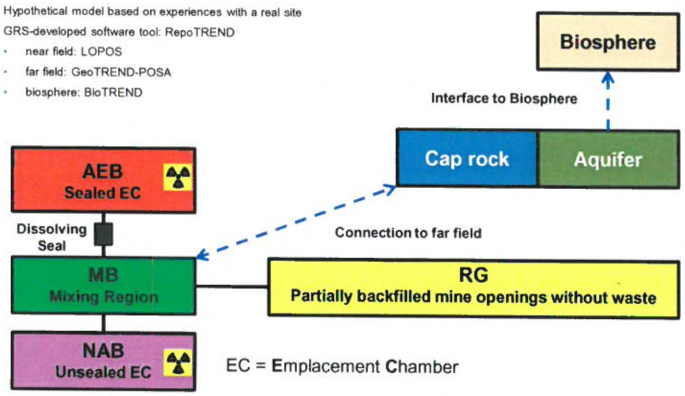
Analyze the influences of the uncertainty of the statistical variables on the uncertainty of the model output

- Analyze the relations between the model output and the variable values
  - Linear methods
    - correlation between input and output
    - linear regression
    - best adequate for close-to-linear models
  - Variance-based methods (ANOVA)
    - first- and higher-order Sobol sensitivity indices
    - various methods available
- Generate plots
  - scatterplots
  - mean rank plots
  - CSM/CSV plots

GRS

Test model: repository for low- and intermediate-level waste (LILW)

Hypothetical model based on experiences with a real site
GRS-developed software tool: RepoTREND
- near field: LOPOS
- far field: GeoTREND-POSA
- biosphere: BioTREND



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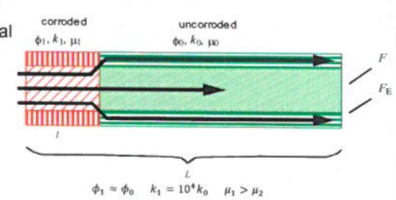
Seal failure

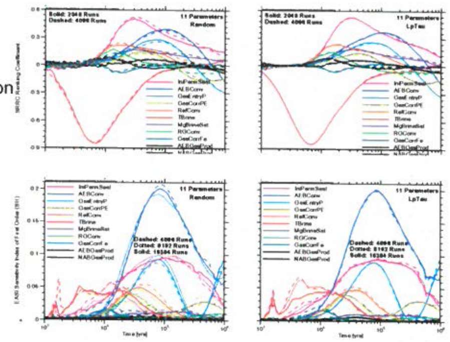
Seal isolating the waste emplacement chamber from the mine
- Cementitious material
- Chemically corroded by magnesium containing brine
- Dissolution front travelling through the seal
- Flow resistance is determined by intact part
- Sealing effect lost almost instantly when the front reaches the end
  - sudden increase of output (dose) at some point in time
- Time of seal failure determined by
  - initial permeability of seal material
  - magnesium content of brine
  - pressure differences



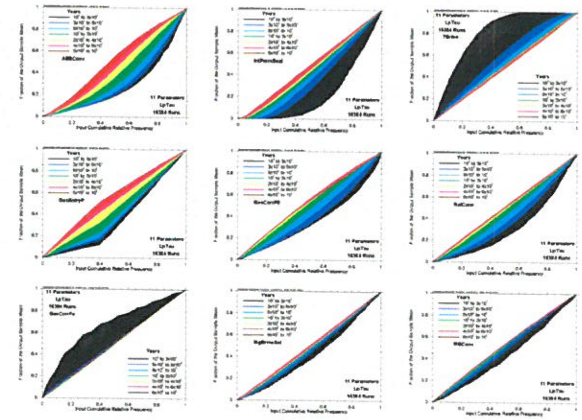
Sensitivity Analysis: Random Sampling vs. Quasi-Random (LpTau)

Linear method:
Standardized rank regression (SRRC)

Variance-based method:
EASI



Sensitivity Analysis: CSM plots



What do We Learn from Probabilistic Analysis?

Uncertainty Analysis

- What are the statistical characteristics of the modelling setup?
- How uncertain are the results produced by the modelling setup?

Sensitivity Analysis

- Which parameters are most influential in the modelling setup?
- Is this consistent with our understanding of the model?
  - If not, is the inconsistency due to improper understanding or maybe to an error?
- Can we reduce the overall uncertainty by targeted research (narrowing pdfs)?

Such investigations analyze the modelling setup but do not directly support conclusions about the real system!

Uncertainty Management: Research Needs

Qualification of the modelling setup

- Develop and test procedures/criteria for
  - identifying all relevant uncertainties
  - distinguishing between aleatory and epistemic uncertainties
  - quantifying scenario and model uncertainties
  - analysis of knowledge
  - expert elicitation
  - pdf derivation for uncertain parameters

Uncertainty/Sensitivity Analysis

- Treatment of aleatory and epistemic uncertainties
- Preferable sampling schemes
- Treatment of parameter dependencies
- Pre-processing of data for analysis
- Preferable methods of SA
  - new methods keep being developed
  - computer capacities increase!
- Presentation and interpretation of results
- Drawing conclusions from UA/SA

Considerable work was already done in PAMINA and national projects, but a practicable, internationally accepted approach still does not exist

IGD-TP Joint Activity 8:
Handling of Uncertainties in the Safety Case for Deep Geological Repositories

Technical/scientific working group (TSWG):

ANDRA (FR)	NRG (NL)
ENRESA (ES)	NWMO (CA)
Galson Ltd (UK)	Posiva Oy (FI)
GRS (DE)	Sandia Labs (USA)
JAEA (JP)	SKB (SE)
NAGRA (CH)	SURAO (CZ)
NDA (UK)	TU-Clausthal (DE)
NIRAS/ONDRAF (BE)	UJV (CZ)

Planned collaboration:

WP 1: Management of uncertainties
- Task 1.1: Strategies for managing uncertainty
- Task 1.2: Management of uncertainties in different time frames of disposal system evolution
- Task 1.3: Regulatory decision-making under uncertainty
- Task 1.4: Communication of uncertainty

WP 2: Uncertainty identification and quantification
- Task 2.1: Expert judgement
- Task 2.2: PDF derivation
- Task 2.3: Identification and quantification of correlations

WP 3: Sensitivity analysis
- Task 3.1: Survey and assessment of methods in view of PA
- Task 3.2: Comparison of methods by numerical experiments
- Task 3.3: R&D triggering

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IGD-TP Joint Activity 8:
Handling of Uncertainties in the Safety Case for Deep Geological Repositories

Next steps
- Workshop on Uncertainty management
  - Harwell, UK
  - September 23-24, 2015
  - Three technical sessions:
    - Quantification of uncertainties
    - Modelling issues
    - Sensitivity Analysis
- IGD-TP Exchange Forum
  - London, UK
  - November 3-4, 2015
- Co-ordinated Technical Project or free collaboration?
  - Financial support from IDG-TP questionable
  - Possible start not until 2017

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Project MOSEL

Subject:
- Identification and testing of modern numerical methods for sensitivity analysis with regard to final repository performance assessment

Organization:
- Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Germany

Collaboration with
- Institute of Disposal Research, Clausthal University of Technology, Germany

Sponsor:
- The work presented is being financed by the German Federal Ministry for Economics and Energy (BMWi) under sign 02E10941

Supported by:

Federal Ministry of Economics and Energy

on the basis of a decision by the German Bundestag

Thank You for Your Attention!

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Probabilistic and deterministic safety assessment approach for shaft hoisting systems

Ramon Gasull Anguera
Wolfgang Filbert
DBE TECHNOLOGY GmbH

6th US/German Workshop on Salt Repository Research, Design, and Operation
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Sandia National Laboratories
DBE TEC
PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology
NNSA
U.S. Department of Energy

Outline

1. Importance of Operational Safety
2. Shaft Hoisting Systems
3. Operational Safety Assessment Approach
4. Potential Safety-Relevant Events
5. Probabilistic Safety Analysis
6. Deterministic Safety Analysis
7. Conclusions & Next Steps

Importance of Operational Safety Assessment

Safety Assessment of a Radioactive Waste Repository
To protect people and environment from harmful effects of ionizing radiation

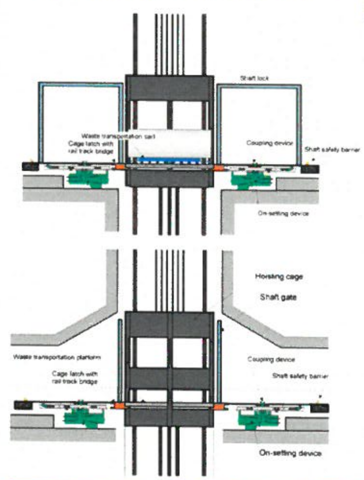
Long-term Safety Assessment
To demonstrate that protection of future generations can be guaranteed

Operational Safety Assessment
To ensure that operational personnel, public and environment are protected against radiological risks of normal and abnormal operation of the repository as well as against potential consequences of accident conditions

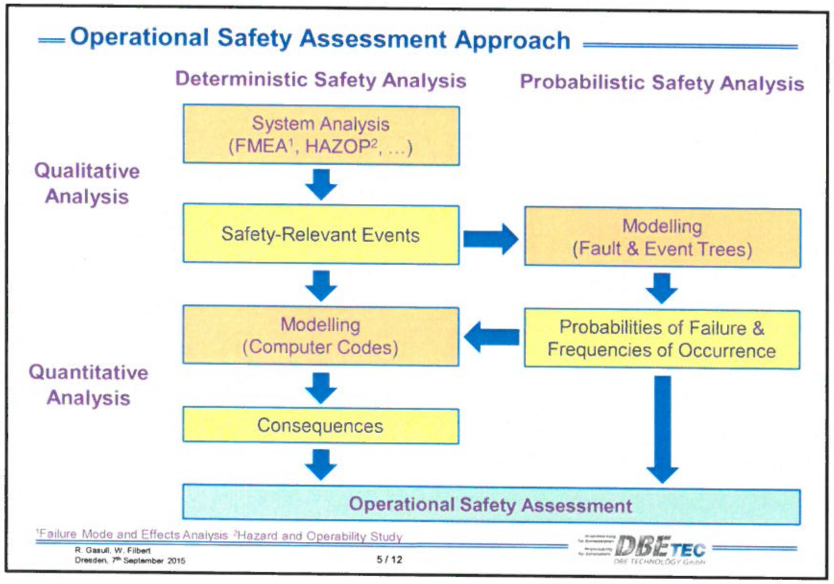
Shaft Hoisting System
To demonstrate safe shaft hoisting of radioactive waste packages

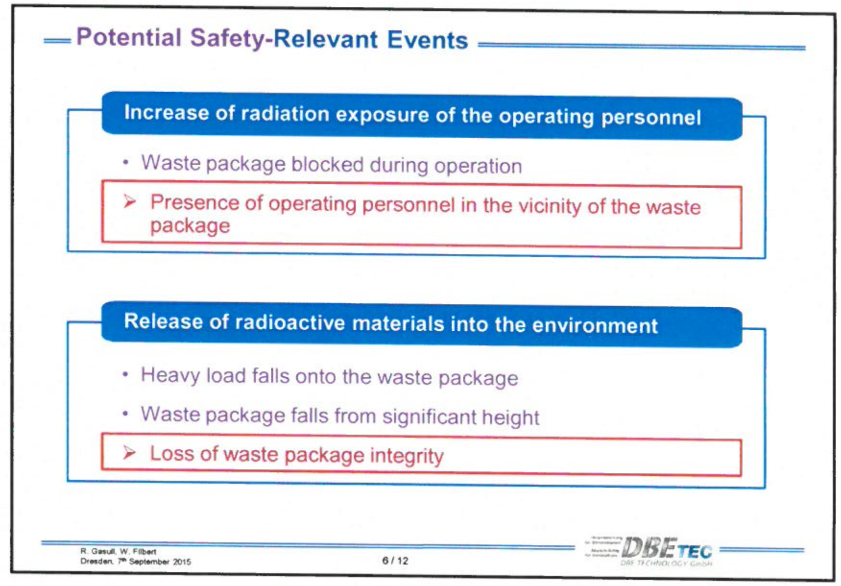
Conceived as a risky operation as a failure could result in a fall of a waste package (WP) down the shaft

Shaft Hoisting System



Main Operations	Sub-operations
Loading of Hoisting Cage	- Open gate ... - Lock gate
Shaft Transport	- Lifting of hoisting cage to surface level ... - Sinking of hoisting cage to underground loading level
Unloading of Hoisting Cage	- Unlock shaft gate ... - Open coupling


Operational Safety Assessment Approach
Deterministic Safety Analysis
Probabilistic Safety Analysis
Qualitative Analysis
Quantitative Analysis
System Analysis (FMEA¹, HAZOP², ...)
Safety-Relevant Events
Modelling (Fault & Event Trees)
Modelling (Computer Codes)
Probabilities of Failure & Frequencies of Occurrence
Consequences
Operational Safety Assessment
¹Failure Mode and Effects Analysis ²Hazard and Operability Study
R. Gasull, W. Filbert
Dresden, 7th September 2015
5 / 12
DBE TEC


Potential Safety-Relevant Events
Increase of radiation exposure of the operating personnel
Waste package blocked during operation
Presence of operating personnel in the vicinity of the waste package
Release of radioactive materials into the environment
Heavy load falls onto the waste package
Waste package falls from significant height
Loss of waste package integrity
R. Gasull, W. Filbert
Dresden, 7th September 2015
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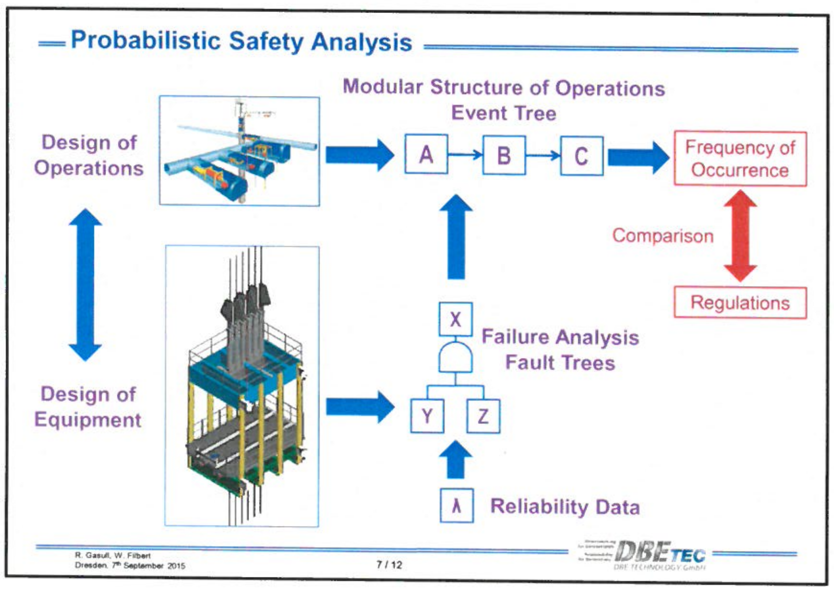
Probabilistic Safety Analysis
Design of Operations
Design of Equipment
Modular Structure of Operations
Event Tree
A
B
C
Frequency of Occurrence
Comparison
Regulations
X
Y
Z
Failure Analysis
Fault Trees
λ
Reliability Data
R. Gasull, W. Filbert
Dresden, 7th September 2015
7 / 12
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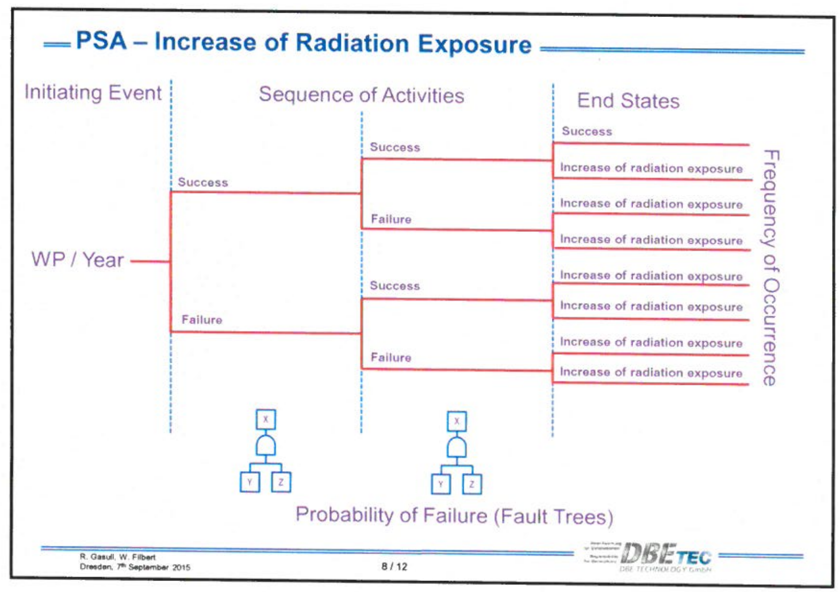
PSA – Increase of Radiation Exposure
Initiating Event
Sequence of Activities
End States
WP / Year
Success
Failure
Success
Failure
Success
Failure
Success
Increase of radiation exposure
Increase of radiation exposure
Increase of radiation exposure
Increase of radiation exposure
Increase of radiation exposure
Increase of radiation exposure
Increase of radiation exposure
Frequency of Occurrence
Probability of Failure (Fault Trees)
R. Gasull, W. Filbert
Dresden, 7th September 2015
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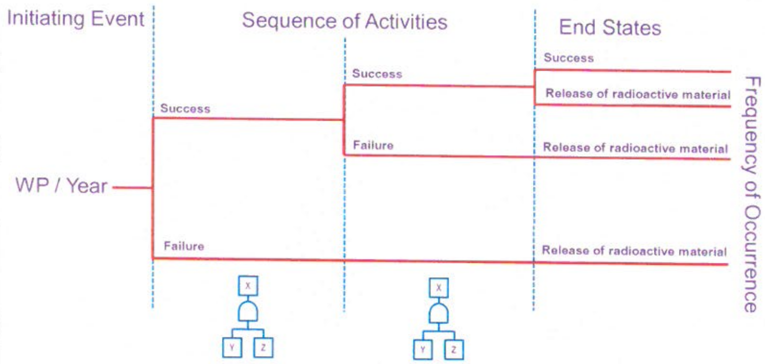
PSA – Release of Radioactive Material



➢ **Availability of Mitigation Systems → Next PSA Level**

R. Gasull, W. Filbert
Dresden, 7th September 2015 9 / 12

Deterministic Safety Analysis

- **Release of radioactive material → Quantification of consequences**

➢ **Main Input**
- ✓ Radionuclide content
- ✓ Design of the repository
- ✓ Meteorological conditions
- ✓ Availability of mitigation systems

➢ **Output**
- ✓ Radionuclides released
- ✓ Radiation dose

Comparison

Regulations

- **Increase of radiation exposure → Quantification of consequences**

➢ **Main Input**
- ✓ Radionuclide content
- ✓ Design of the waste package
- ✓ Distance between WP and operational personnel
- ✓ Repair time

➢ **Output**
- ✓ Radiation dose

Comparison

Regulations

R. Gasull, W. Filbert
Dresden, 7th September 2015 10 / 12

Conclusions & Next Steps

Conclusions

- ✓ Complementary probabilistic and deterministic methods (similar to NPPs) for a complete safety assessment
- ✓ PSA as design tool in addition to a safety assessment tool
- ✓ International cooperation for developing an accepted operational safety assessment approach for repositories (similar to NPPs)

Next Steps

- ❖ Regulatory implementation of operational safety assessment approach
- ❖ Transfer of NPP PSA methods to repositories
- ❖ Modelling of sequence of operations and of failures and collection of reliability data

R. Gasull, W. Filbert
Dresden, 7th September 2015 11 / 12

Thank you

Thank you for your attention

R. Gasull, W. Filbert
Dresden, 7th September 2015 12 / 12

Balancing operational phase and post-operational phase safety

J. Wolf[1], W. Bollingerfehr[2], W. Filbert[2], U. Noseck[1]
[1]GRS gGmbH, [2]DBE Technology

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Background

- International standard: Safety Case for HLW waste repositories
  - pertains to operational and post closure phase
    → both operational safety and long term safety must be addressed
  - Safety assessment ≠ radiological impacts of the facility
  - Emphasis is on the performance of the disposal facility and the assessment of its impact after closure
  - Operational safety often addressed but not discussed in detail (e.g. IAEA SSG-23)

- Projects move towards licensing and realisations
  - Constructability
  - Mining safety and
  - Operational safety

  are getting more and more important

2

International Activities

- OECD/NEA, IGSC
  - Safety Case Symposium 2013
  - Scenario Development Workshop 2015
  - Expert Group on Operational Safety (since 2013)
    - share experience in operational safety
    - identify plausible hazards in a geological repository
    - share and improve know-how on the practical assessment of hazards
    - define technical solutions for risk prevention and mitigation

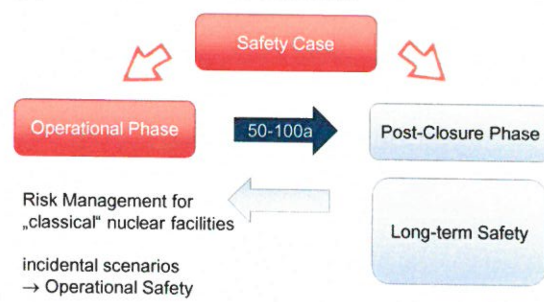
- IAEA, GEOSAF projects
  - WG dedicated on Operational Safety (since 2010), focus on hazards identification for the operational phase
  - Besides considerations on methodologies for hazards assessment, **strong relationships between operational safety and post-closure safety were outlined**:
    'On the one hand, design and operational constraints are set by post-closure safety requirements, while on the other hand, operation has some impact on post-closure safety.'

GEOSAF Position Paper

3

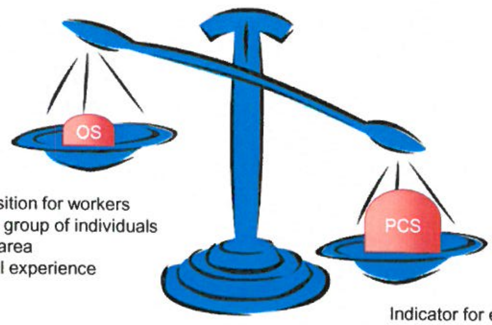
Challenge

The development of the safety case for a disposal facility is based on methods applied to other (nuclear / mining) facilities.
But compared to the safety case for nuclear facilities of other types it has to address post-closure safety in conjunction with operational safety e.g. preservation of the host rock formation).



4

How to balance operational and post-closure safety?



Real exposition for workers
- Defined group of individuals
- Known area
- practical experience

Indicator for exposition
- Area?
- Individuals??

5

Understanding Interdependencies

1. Impact of operation, including construction, on post-closure safety, e.g. the analysis of incidents and accidents during the operational phase with regard to post-closure safety.
2. Impacts of post-closure constraints on the design and implementation of the geological disposal facility and its safety for the operational phase

Operational Phase	Post-Closure Phase
System description	System description
by hazards → FEP?	by FEP / Scenarios
Comprehensiveness? → „walk through the facility"	Comprehensiveness? → International FEP list

6

Understanding Interdependencies

- Example: Hazard assessment (GEOSAF-II)
  - Identifying plausible hazards
  - Identifying targets to be protected
  - Describe reference design and operation processes
  - hazard
    - → operational safety
    - → post-closure safety
  - Hazard matrix (Fire, Earthquake, Flooding, …)
    → Relevance to DGR
- Is a hazard assessment enough?
  - Consequence of lining
  - Ramp vs. shaft

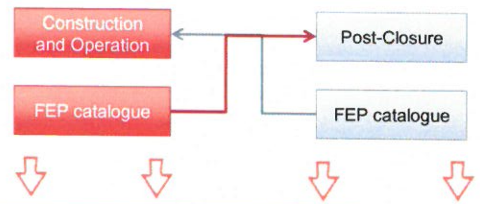
7

Project proposal (I)

- Basics
  - Legal framework
  - International R&D and recommendations
  - Disposal concepts
  - FEP post-closure phase
- Safety concept for the operational phase
- FEP operational phase
- FEP operational phase → FEP post-closure phase
- FEP post-closure phase → FEP operational phase
- Methods for illustrating (documenting) and balancing safety aspects

8

Project proposal (II)



Synthesis
- Relevant Interdependencies between Operational Phase and Post-Closure Phase
- Harmonization of safety concepts possible / necessary?
- Methods to deal with these interdependencies in a Safety Case?
- **How to balance Operational Safety and Post-Closure Safety**

9

Discussion for the US-German Workshop

- Is this aspect of interest for the US-German cooperation?
- Is this aspect worth starting a project?
- If yes, what about the proposed procedure?
  - e.g. hazard matrix vs. FEP catalogue
- Next steps?

10

Monitoring of HLW repositories (EC-Projects MoDeRn and MODERN2020)

Michael Jobmann
DBE TECHNOLOGY GmbH

6[th] US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA · NNSA · ENERGY

MoDeRn

Monitoring of HLW Repositories

2009
Missing: Common international framework or guideline for repository monitoring

MoDeRn — **Mo**nitoring **De**velopments for safe **R**epository operation a**n**d staged closure

MoDeRn project aimed at providing a reference framework for development and implementation of monitoring activities

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MoDeRn

18 partners - 12 countries **2009 - 2013**

Social Sciences:
University of Antwerpen,
University of Gothenburg,
University of East Anglia

Underground Laboratories :
Grimsel (Switzerland)
Mol (Belgium)
Bure (France)

EU Countries:
France (Andra),
Spain (Enresa and Aitemin),
Germany (DBETEC),
Belgium (Euridice, UA),
United-Kingdom (NDA, UEA, GSL),
Netherlands (NRG),
Finland (Posiva),
Czeck Republic (RAWRA),
Sweden (SKB, UGOT)

Non-EU Countries:
Japan (RWMC),
USA (Sandia),
Switzerland (Nagra, ETH Zurich)

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MoDeRn

MoDeRn proposed a ***Monitoring Reference Framework*** as a structured approach to follow from development, to implementation and operation of a monitoring program, providing guidance on:

- How monitoring objectives may be developed and their role in the disposal process understood: to develop these objectives into clear information requirements which can then be related to key safety functions and thus to parameters to be monitored.
- How monitoring systems may be designed and what strategies may help in attaining the monitoring objectives – to assess technological feasibility, implementation strategies and technical limitations.
- How monitoring should be addressed as part of the overall governance of the disposal process by providing general notions on how monitoring might be related to management decisions.
- How monitoring might contribute to stakeholder confidence, especially by clarifying their expectations.

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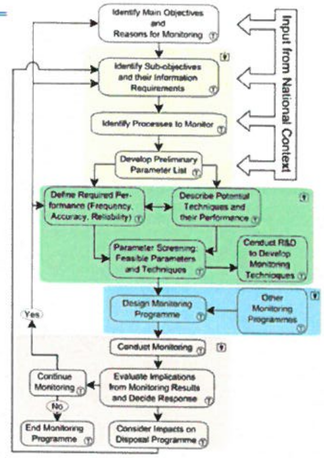
MoDeRn

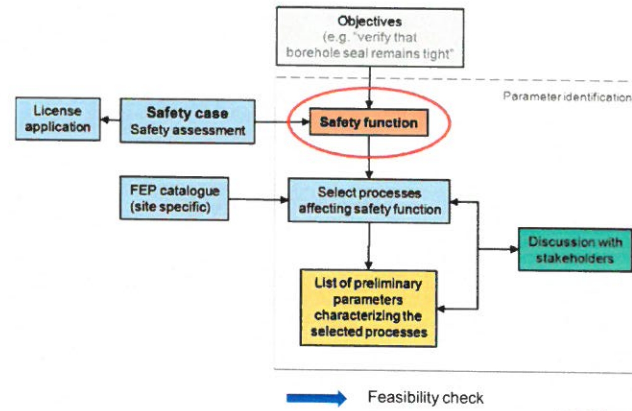
The ***MoDeRn Monitoring workflow*** illustrates this structural approach and provides an overview of key steps to consider when developing a monitoring program

Key stages in developing and managing a monitoring program are:

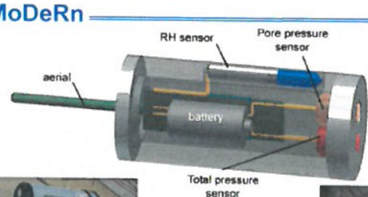
1. Analysis of overarching goals and objectives and relating these to processes and parameters to identify a preliminary parameter list for monitoring.
2. Analysis of requirements and available monitoring technology to design a monitoring program.
3. Conducting a monitoring program and using the results as basic information for decision making.



MoDeRn

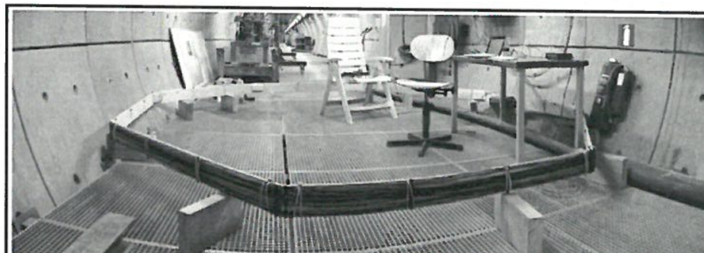


MoDeRn



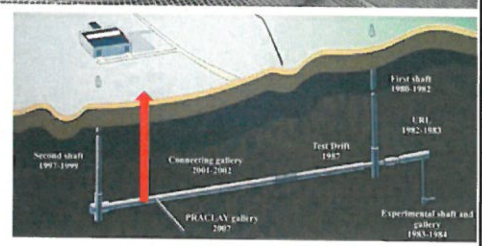
Aitemin, Spain

Short distance transmission



Long distance transmission

NRG, The Netherlands



MoDeRn

WDT (short distance): A high-frequency wireless node that allows measurement of several parameters (e.g. pore pressure, total pressure and water content), and transmission of the measured data over distances of **a few meters** has been designed, developed and tested. This potentially provides a method for wireless transmission of monitoring data through an EBS.

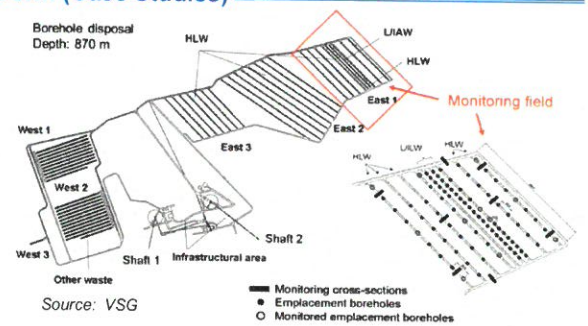
WDT (long distance): A low-frequency data transmission system, capable of transmitting data through **225 m** of an electrically highly-conductive geological medium, at frequencies up to 1.7 kHz has been designed, developed and tested at the HADES URL. This potentially provides a method for wireless transmission of monitoring data from a repository to the surface following repository closure.

In addition, research has been done regarding the improvement of different sensing systems like distributed fiber optic sensors, seismic tomography.

Main open Issues:

- The need to further develop WDT systems (short and long distance) and qualify them for long-term monitoring purposes under real conditions.
- Development of sustainable power supplies

MoDeRn (Case Studies)



Source: VSG

Open Issue:
Monitoring concept for individual EBS

MoDeRn

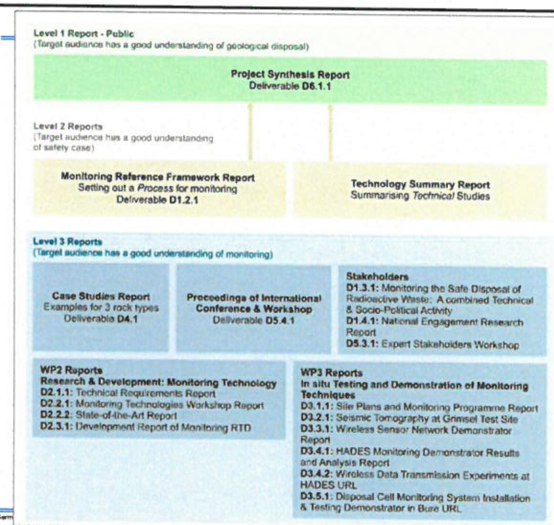
The main conclusions from the work on **stakeholder involvement** are as follows:

- Public stakeholders expressed a view that the checking of repository performance should be comprehensive and linked to an overall science program. A continuation of research and development on repository monitoring techniques was expected
- Some public stakeholders do have expectations regarding post-closure monitoring, mainly in view of being able to prepare for (and respond to) unanticipated events or evolutions. Individual programs will need to decide on ways to respond to this expectation.
- Communication of the understanding of remaining uncertainties, and a preparedness to respond to changes in the expected evolution of the repository (e.g. closure being postponed) could be beneficial to addressing stakeholders' expectations.
- Monitoring can contribute to confidence building if it can address expectations from stakeholders. They expect an
  - approach to decision making,
  - and an approach to public and stakeholder engagement.

Open Issues:

- Response plans
- approach to decision making and stakeholder engagement

MoDeRn



MODERN 2020
Development and Demonstration of monitoring strategies and technologies for geological disposal

The ambition of **Modern2020** is to address the key challenges and to advance the state-of-the-art associated with:

- ***Strategy:*** Identify methods to link a monitoring program design to real-world safety cases and repository implementation programs
- ***Technology:*** Address key technology gaps existing with (wireless) data transmission, power supply, (new) sensing systems, reliability and qualification
- ***Demonstration and Practical Implementation:*** Illustrate how monitoring systems can be designed to the requirements identified by the strategy work and to use the technologies developed
- ***Societal concerns and Stakeholder Involvement:*** Evaluate the active engagement of public stakeholders in monitoring research and monitoring program specification
- ***Dissemination:*** Develop ways of establishing a common understanding on monitoring requirements and approaches.

This project receives funding from the Euratom research & training program 2014-2018 under GA n°662177

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MODERN 2020
Development and Demonstration of monitoring strategies and technologies for geological disposal

2015 - 2019

Total budget: 9.6 Mill €
EC funding: 6.0 Mill €

28 Partners

AITEMIN
Andra
Areva
CTU
DBE TEC
EDF
ENEA
ENRESA
ETH
ESV EURIDICE GIE
Galson Science
IRSN
Nagra
Nidia
NRG
Ondraf/Niras
POSIVA
RWM
RWMC
SKB
TUL
UANTWERP
USTRAT
VTT
SURAO
XLIM
UOOT
UMONS

12 Countries

France
Spain
Czech Republic
Germany
Italy
Switzerland
Belgium
United Kingdom
The Netherlands
Finland
Japan
Sweden

This project receives funding from the Euratom research & training program 2014-2018 under GA n°662177

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MODERN2020 (Strategy)

- Compare and evaluate existing monitoring strategies
- Identify decisions requiring support from monitoring data and responsibilities for these decisions, focusing on specific national programs
- Identify and update approaches that could be used to compile and screen parameter lists.
- Involve Stakeholders to explore how their early involvement in developing monitoring plans should be addressed appropriately

Two classes of data-based decisions will be considered:

- Major program decisions: Decisions to move from one stage of the project to another, i.e. progression or reversal of the stepwise implementation of geological disposal
- Engineering/operational decisions: Decisions made during the on-going implementation of disposal operations

Major decisions in each national program will be identified. The types of data that will be required for the decisions will be described including:

- Identification of milestones requiring major decisions in national programs.
- For identified decisions, identify what the decision might require in terms of monitoring data.

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MODERN2020 (Strategy)

Focus: Development of monitoring concepts for EBS.

Monitoring of the EBS may be undertaken with a focus on long-term safety or to respond to operational management requirements (operational safety or, in the case of France, responding to the reversibility principle).

Compiling and screening EBS parameters is a significant step in development of the monitoring program. The methods used to compile and screen parameter lists will include consideration of the individual safety case as well as identified reference and alternative evolutions of the repository based on case/site specific features, events and processes (FEPs).

A preliminary workflow for parameter screening has been developed during MoDeRn. This way of screening will be further developed and adapted in more detail to the different national programs and safety cases.

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MODERN2020 (DBETEC contribution)

Development of **monitoring concepts** for **EBS**

⇩

Development of "synthetic" monitoring results in and around the EBS for different scenarios

⇩ ⇧

Identification of how "bad" monitoring results must be to indicate a risk for the safety of a repository by sensitivity analysis of barrier (component) performance

⇩

Set up **"trigger values"** or "trigger evolutions" for EBS monitoring concepts

⇩ ⇩

Identify specific **requirements for sensing system**

Development of **response plans** for scenarios exceeding specific trigger values

Stakeholder input

MODERN2020 (Technology)

State-of-the-art Technology: Update the state-of-the-art on monitoring technology based on the *MoDeRn* status and highlighting gaps that still need to be bridged by making a clear overview of the Technology Readiness Levels (TRL).

Wireless Data Transmission: Develop systems for wireless data transmission (WDT). The required progress in WDT is related to the enhanced propagation of radio waves across the different repository materials and components. Research will focus on development of antennas and its coupling with the different media encountered.

Sustainable Power Supply: Investigate power supply sources capable of extending the expected life time of the WDT in order to have an alternative to "traditional" chemical batteries. (One of the conclusions of *MoDeRn* was that although several principal options exist, currently no mature alternative solution is available).

Sensor System Improvements: Further develop and adapt available (or new) technology to improve their capability to respond to specific monitoring needs especially for the EBS. (e.g. reduce volume and energy need, multi-parameter sensing, eliminate weak points)

Qualification: Develop a common multi-stage qualification methodology applicable to each component of a monitoring system.

MODERN2020 (Demonstration and Implementation)

In-situ EBS system test at ONKALO (Finland): Demonstrate the applicability of EBS monitoring strategies for long-term monitoring setups used for operation of spent fuel deposition.

Disposal Cell Demonstrator at Bure (France): test and demonstrate the feasibility of integrating a monitoring system into the construction of a vitrified waste disposal cell and to provide comprehensive monitoring results of the disposal cell and of its near-field.
A monitoring program will be implemented at Cigeo from the construction phase and throughout its operational life, to keep track of repository safety-related parameters.

Long-Term Rock Buffer Monitoring (LTRBM) at Tournemire (France): This test will be realized by IRSN in collaboration with AITEMIN, ENRESA and NRG. In this set-up, the new monitoring devices developed in the project (mainly wireless devices including long-term power supply solutions) will be installed to assess the real performance of the solutions.

Full-Scale Emplacement (FE) Experiment at the Mont Terri URL (Switzerland): this is a full-scale multiple heater test in Opalinus Clay based on the Swiss disposal concept. The main aim of this experiment is to investigate SF/HLW repository-induced THM coupled effects mainly in the host rock but also in the EBS in the early phase after closure.
Several hundred sensors (standard, prototypes, and fiber-optic sensing systems) will be installed.

MODERN2020 (Stakeholder Involvement)

Stakeholder Engagement Activity: will be set up throughout the project's lifetime, and in direct relation to the R&D work developed during the project. At various stages in the project, exchange meetings or workshops will be set up, during which interaction between the researchers in the different strands, the concerned implementers and the participating local citizens, will be organized.

The stakeholder engagement activity will be organized and researched at two levels

1. Direct participation of a selected group of stakeholder representatives during Modern2020 meetings and workshops, and
2. Linking this activity back to the respective local communities, to investigate how the representatives connect to the local work and to observe possible impact on the local level.

Conclusions

MODERN → Open Issues → MODERN 2020

18 Partners
12 Countries

28 Partners
12 Countries

- **Strategy:** EBS monitoring concepts
- **Technology:** WDT, power supply, improvement of sensing systems, qualification
- **Demonstration:** Illustrate how monitoring systems can be designed to the requirements identified
- **Stakeholder Involvement:** explore their early involvement

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THANK YOU !

Sandia National Laboratories
DBE TEC
PTKA
NNSA
ENERGY

Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B

Dr. Andreas Hampel

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories
DBE TEC
PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology
NNSA
ENERGY

Joint Project III (2010 – 2016)

Partner	Constitutive Model	Num. Program
Dr. Andreas Hampel, Hampel Consulting, Mainz, Germany	CDM (Composite Dilatancy Model)	FLAC3D
Institut für Gebirgsmechanik (IfG), Leipzig, Germany	Günther/Salzer Model, Minkley Model	FLAC, FLAC3D
Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany	KIT Model	ADINA
Leibniz Universität Hannover (LUH), Hannover, Germany	Lubby-MDCF Model	FLAC3D
Technische Universität Clausthal (TUC), Clausthal-Zellerfeld, Germany	Lux/Wolters Model	FLAC3D
Technische Universität Braunschweig (TUBS) Braunschweig, Germany	TUBSsalt	FLAC3D, ANSYS
Sandia National Laboratories, Albuquerque & Carlsbad, NM, USA	MD Model	Sierra Mechanics Code Suite

Main Objectives of Joint Project III

Detailed checks, comparisons and documentation of the modeling of relevant deformation phenomena with the participating constitutive models.

Procedure:

- Performance of many systematic lab tests (creep tests, strength tests, ...)
- Back-calculation of the lab tests, determination of salt-type-specific parameter values
- Simulation of real in-situ situations

1. Temperature influence on deformation:
   - a) salt type: Speisesalz from the Asse mine in Germany (domal salt)
     in-situ situation: borehole tests IFC (isothermal) and HFCP (heated) } ARMA 2013 (paper 456)
   - b) salt types: clean & argillaceous salt from WIPP in NM, USA (bedded salt)
     in-situ situation: Room D (isothermal) and Room B (heated) at WIPP } this presentation (work in progress)
2. Damage reduction & healing of rock salt:
   - salt type: Speisesalz from the Asse mine in Germany (domal salt)
     in-situ situation: "Dammjoch" (bulkhead) in the Asse mine } Saltmech VIII (Proc. page 349ff)

Rooms B and D on the 650 m level at WIPP / Room B with heaters below the floor

(top views)

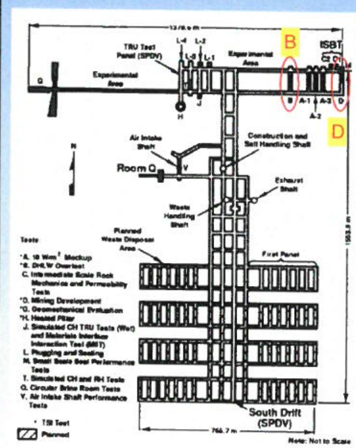
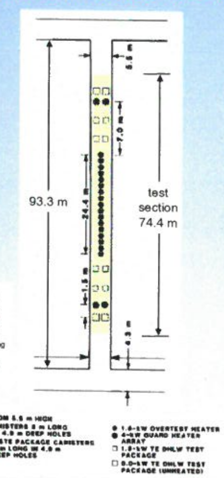
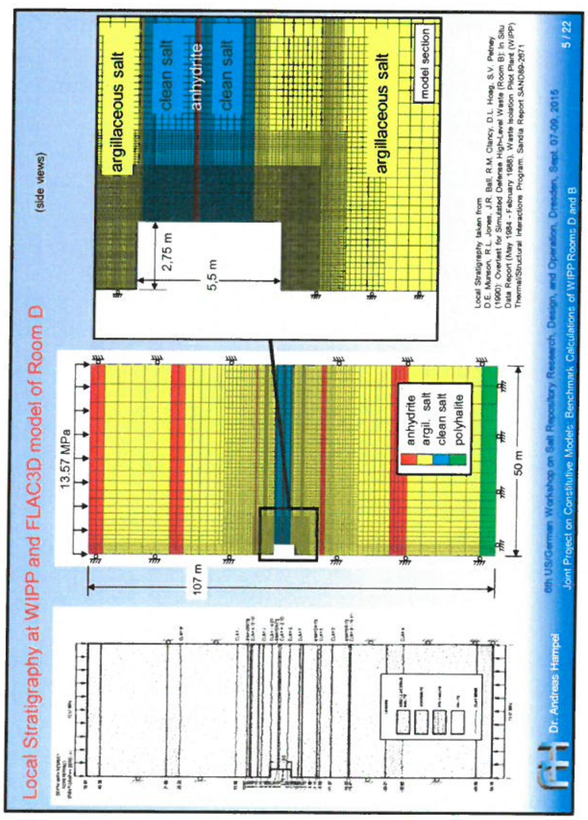


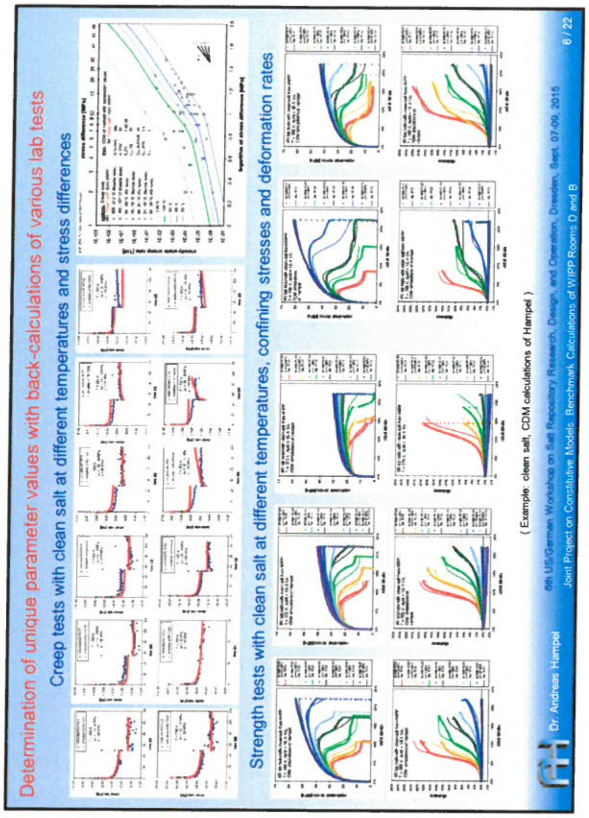
Fig. 1. Plan view of WIPP underground.

D.E. Munson, J.R. Weatherby, K.L. DeVries (1993): Two- and Three-Dimensional Calculations of Scaled In Situ Tests using the M-D Model of Salt Creep. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 30, No. 7, pp. 1345-1350, Pergamon Press

J.S. Rath & J.G. Argüello (2012): Revisiting Historic Numerical Analyses of the Waste Isolation Pilot Plant (WIPP) Room B and D in-situ Experiments Regarding Thermal and Structural Response. Sandia Report SAND2012-7525




Local Stratigraphy at WIPP and FLAC3D model of Room D
(side views)
13.57 MPa
107 m
50 m
anhydrite
argil. salt
clean salt
polyhalite
2,75 m
5,5 m
argillaceous salt
clean salt
anhydrite
clean salt
argillaceous salt
model section
Local Stratigraphy taken from
D.E. Munson, R.L. Jones, J.R. Ball, R.M. Clancy, D.L. Hoag, S.V. Petney (1990): Overtest for Simulated Defense High-Level Waste (Room B): In Situ Data Report (May 1984 - February 1988). Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program. Sandia Report SAND89-2671
Dr. Andreas Hampel
6th US/German Workshop on Salt Repository Research, Design, and Operation, Dresden, Sept. 07-09, 2015
Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
5 / 22


Determination of unique parameter values with back-calculations of various lab tests
Creep tests with clean salt at different temperatures and stress differences
Strength tests with clean salt at different temperatures, confining stresses and deformation rates
(Example: clean salt, CDM calculations of Hampel)
Dr. Andreas Hampel
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Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
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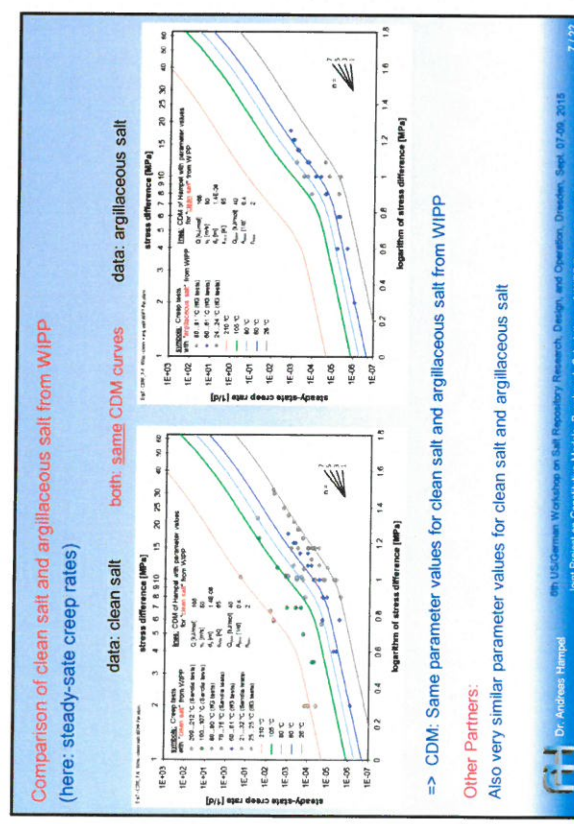
Comparison of clean salt and argillaceous salt from WIPP
(here: steady-sate creep rates)
data: clean salt
both: same CDM curves
data: argillaceous salt
stress difference [MPa]
steady-state creep rate [1/d]
logarithm of stress difference [MPa]
=> CDM: Same parameter values for clean salt and argillaceous salt from WIPP
Other Partners:
Also very similar parameter values for clean salt and argillaceous salt
Dr. Andreas Hampel
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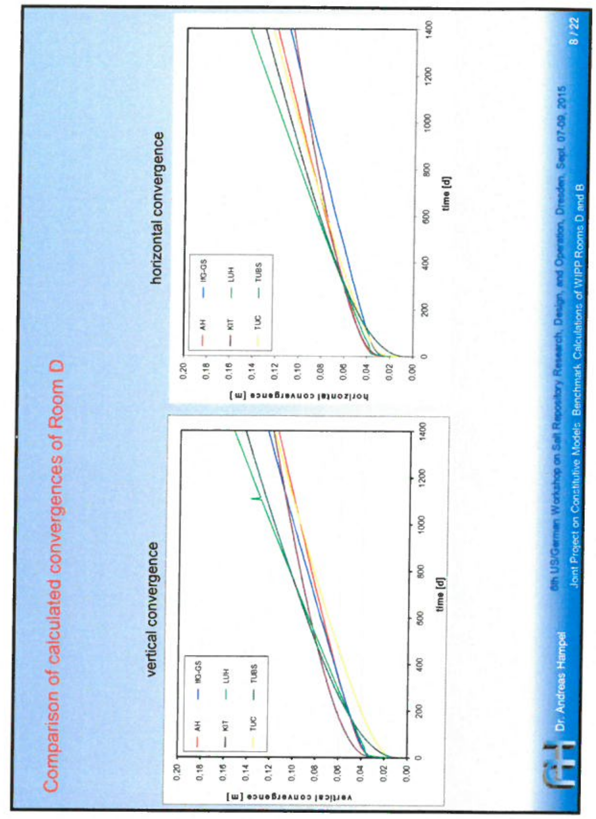
Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
7 / 22


Comparison of calculated convergences of Room D
vertical convergence
horizontal convergence
AH
IfG-GS
KIT
LUH
TUC
TUBS
vertical convergence [m]
horizontal convergence [m]
time [d]
Dr. Andreas Hampel
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Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
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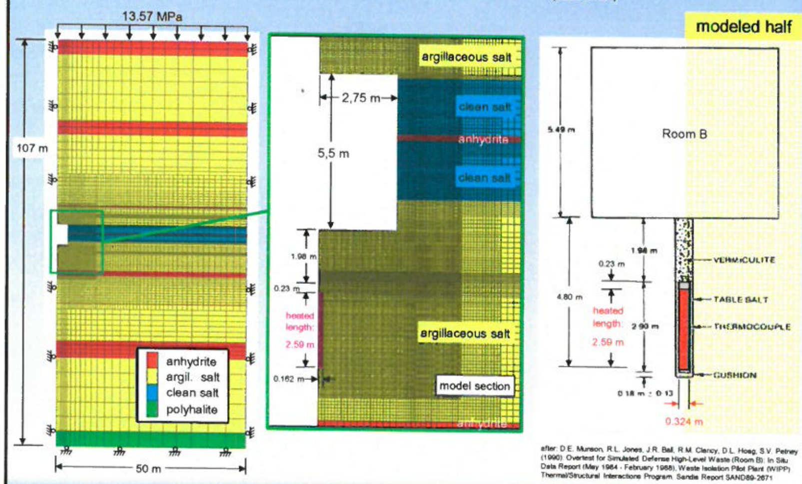
FLAC3D model of Room B with a heater below the floor

(side views)



after: D.E. Munson, R.L. Jones, J.R. Ball, R.M. Clancy, D.L. Hoag, S.V. Petney (1990): Overtest for Simulated Defense High-Level Waste (Room B): In Situ Data Report (May 1984 - February 1988), Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program. Sandia Report SAND89-2671

Temperature measurements around Room B close to its center

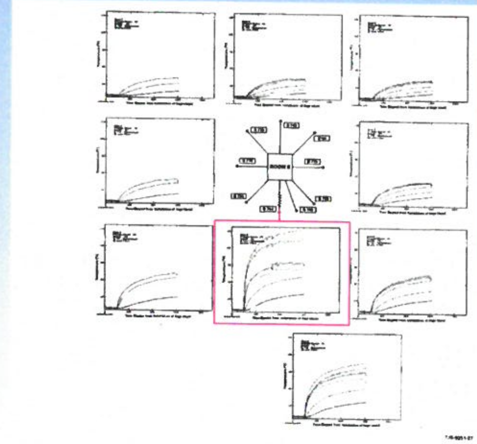


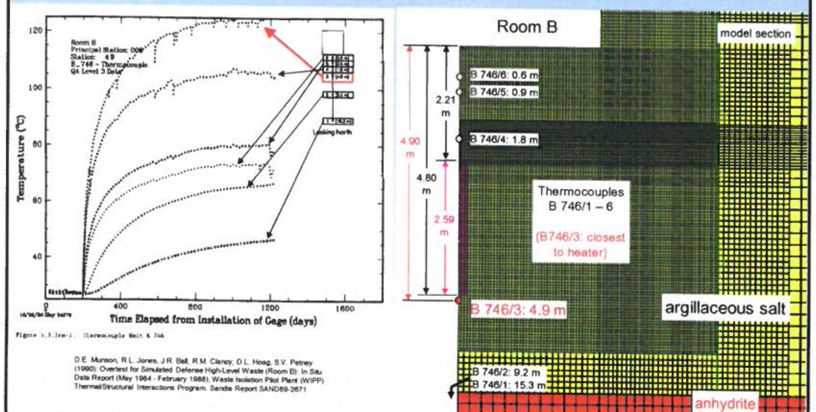
Figure 2.3.2. Reduced-size Composite of Temperatures at Principal Station -5

"The temperature distribution around the room is illustrated in the composite shown previously in Figure 2.3.2 and by observing the individual data plots. The composite is that for **Principal Station - 5 but is generally typical of the principal stations near the center of the room**."

D.E. Munson, R.L. Jones, J.R. Ball, R.M. Clancy, D.L. Hoag, S.V. Petney (1990): Overtest for Simulated Defense High-Level Waste (Room B): In Situ Data Report (May 1984 - February 1988), Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program. Sandia Report SAND89-2671

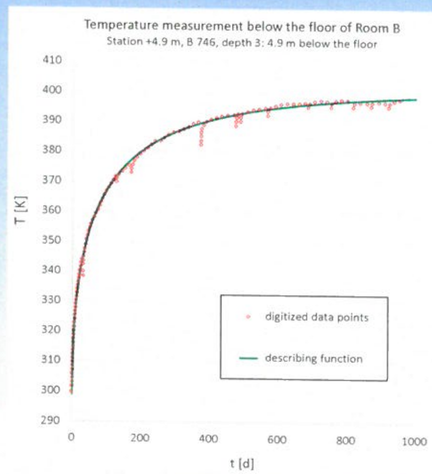
Temperature measurements at 6 different depths below the floor

Example: Thermocouple B 746 in the floor at principal station 005, i.e. 4.9 m from the center of the room to the South



D.E. Munson, R.L. Jones, J.R. Ball, R.M. Clancy, D.L. Hoag, S.V. Petney (1990): Overtest for Simulated Defense High-Level Waste (Room B): In Situ Data Report (May 1984 - February 1988), Waste Isolation Pilot Plant (WIPP) Thermal/Structural Interactions Program. Sandia Report SAND89-2671

Description of temperature measurement B 746/3 below the floor close to the heater



Function to describe the data points:

$$T = a_1 + a_2 \cdot \left(1 - \exp\left\{-(a_3\, t)^{a_4}\right\}\right)$$

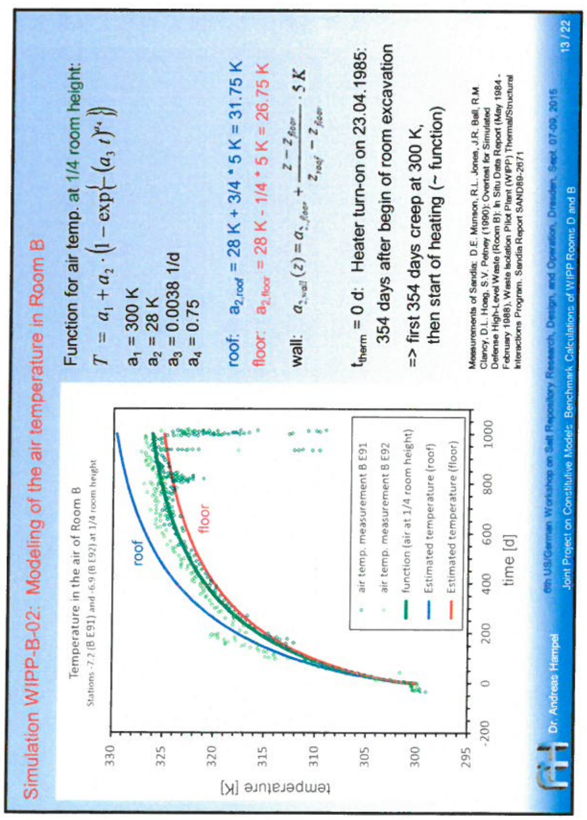
a_1 = 300 K
a_2 = 101 K
a_3 = 0.012 1/d = 0.012/86400 1/s
a_4 = 0.52

t_{therm} = 0 d:

Heater turn-on on 23.04.1985:

354 days after begin of room excavation

=> first 354 days creep at 300 K, then start of heating (~ function)


Simulation WIPP-B-02: Modeling of the air temperature in Room B
Temperature in the air of Room B
roof
floor
air temp. measurement B E91
air temp. measurement B E92
function (air at 1/4 room height)
Estimated temperature (roof)
Estimated temperature (floor)
time [d]
temperature [K]
Function for air temp. at 1/4 room height:
$T = a_1 + a_2 \cdot (1 - \exp\{-(a_3\, t)^{a_4}\})$
a_1 = 300 K
a_2 = 28 K
a_3 = 0.0038 1/d
a_4 = 0.75
roof: $a_{2,roof}$ = 28 K + 3/4 * 5 K = 31.75 K
floor: $a_{2,floor}$ = 28 K - 1/4 * 5 K = 26.75 K
t_{therm} = 0 d: Heater turn-on on 23.04.1985: 354 days after begin of room excavation
=> first 354 days creep at 300 K, then start of heating (~ function)
Dr. Andreas Hampel
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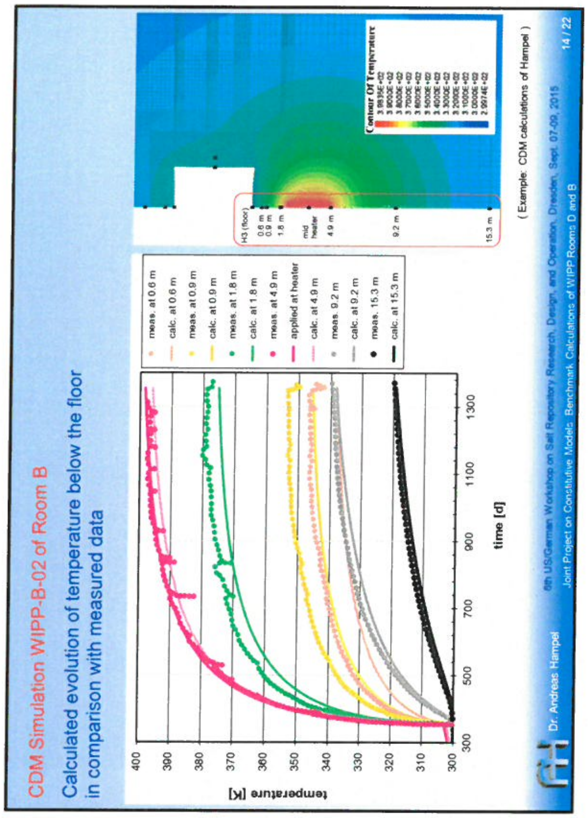
CDM Simulation WIPP-B-02 of Room B
Calculated evolution of temperature below the floor in comparison with measured data
temperature [K]
time [d]
(Example: CDM calculations of Hampel)
Dr. Andreas Hampel
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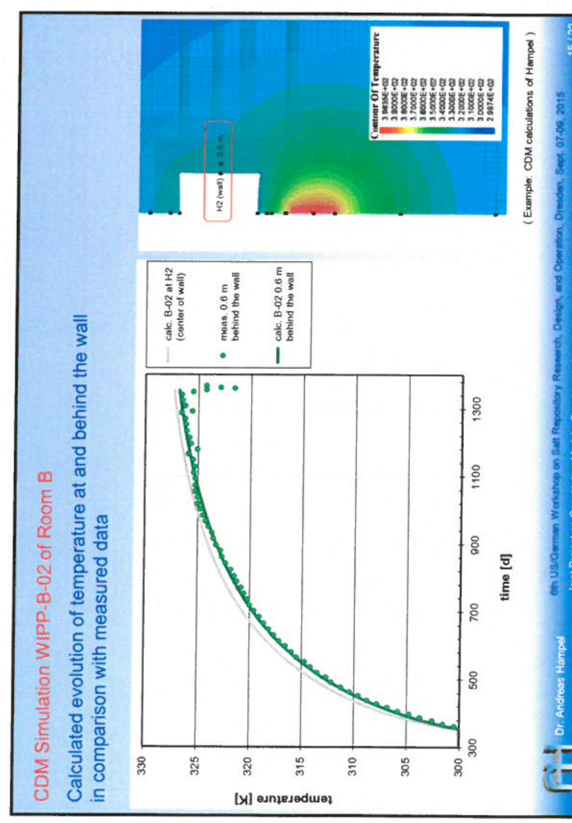
CDM Simulation WIPP-B-02 of Room B
Calculated evolution of temperature at and behind the wall in comparison with measured data
calc. B-02 at H2 (center of wall)
meas. 0.6 m behind the wall
calc. B-02 0.6 m behind the wall
temperature [K]
time [d]
(Example: CDM calculations of Hampel)
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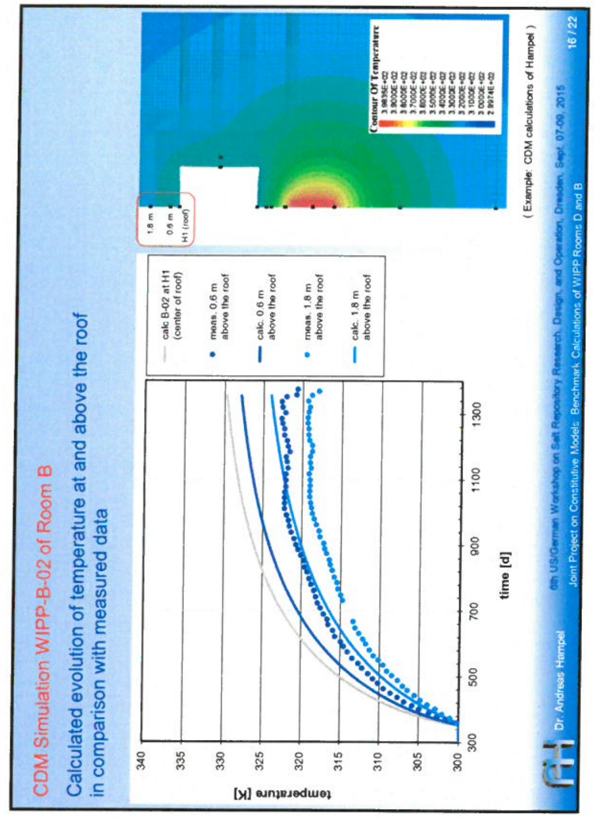
CDM Simulation WIPP-B-02 of Room B
Calculated evolution of temperature at and above the roof in comparison with measured data
calc. B-02 at H1 (center of roof)
meas. 0.6 m above the roof
calc. 0.6 m above the roof
meas. 1.8 m above the roof
calc. 1.8 m above the roof
temperature [K]
time [d]
(Example: CDM calculations of Hampel)
Dr. Andreas Hampel
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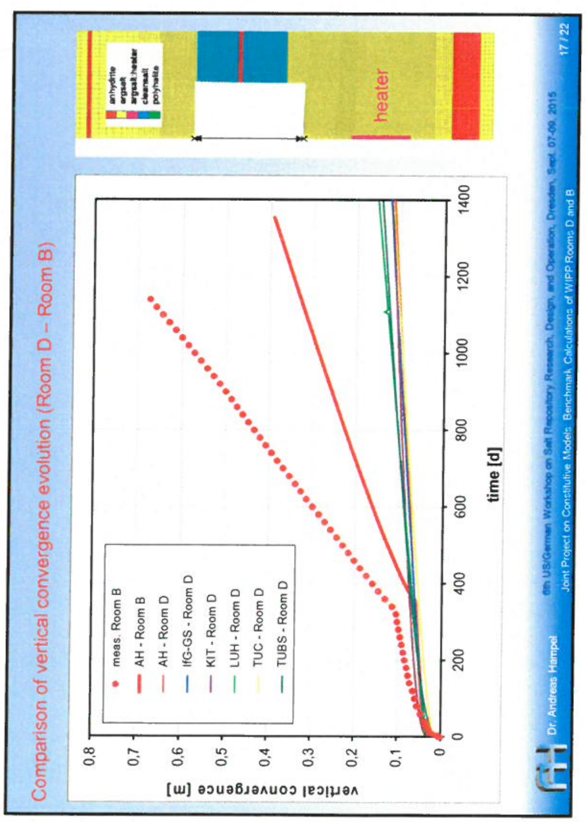
Comparison of vertical convergence evolution (Room D – Room B)
vertical convergence [m]
time [d]
meas. Room B
AH - Room B
AH - Room D
IfG-GS - Room D
KIT - Room D
LUH - Room D
TUC - Room D
TUBS - Room D
anhydrite
argsalt
argsalt:heater
cleansalt
polyhalite
heater
Dr. Andreas Hampel
6th US/German Workshop on Salt Repository Research, Design, and Operation, Dresden, Sept. 07-09, 2015
Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
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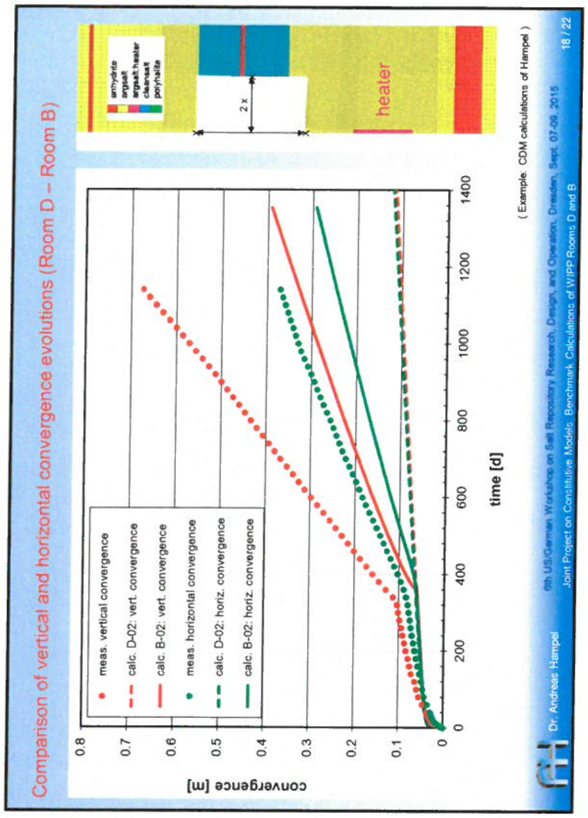
Comparison of vertical and horizontal convergence evolutions (Room D – Room B)
convergence [m]
time [d]
meas. vertical convergence
calc. D-02: vert. convergence
calc. B-02: vert. convergence
meas. horizontal convergence
calc. D-02: horiz. convergence
calc. B-02: horiz. convergence
anhydrite
argsalt
argsalt:heater
cleansalt
polyhalite
2 x
heater
(Example: CDM calculations of Hampel)
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6th US/German Workshop on Salt Repository Research, Design, and Operation, Dresden, Sept. 07-09, 2015
Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
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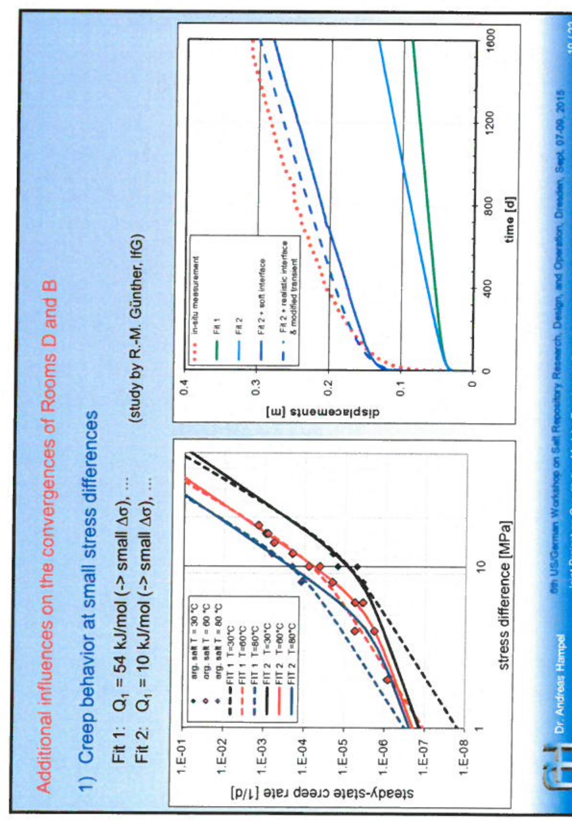
Additional influences on the convergences of Rooms D and B
1) Creep behavior at small stress differences
Fit 1: Q1 = 54 kJ/mol (-> small Δσ), ...
Fit 2: Q1 = 10 kJ/mol (-> small Δσ), ...
(study by R.-M. Günther, IfG)
steady-state creep rate [1/d]
stress difference [MPa]
displacements [m]
time [d]
in-situ measurement
Fit 1
Fit 2
Fit 2 + soft interface
Fit 2 + realistic interface & modified transient
Dr. Andreas Hampel
6th US/German Workshop on Salt Repository Research, Design, and Operation, Dresden, Sept. 07-09, 2015
Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
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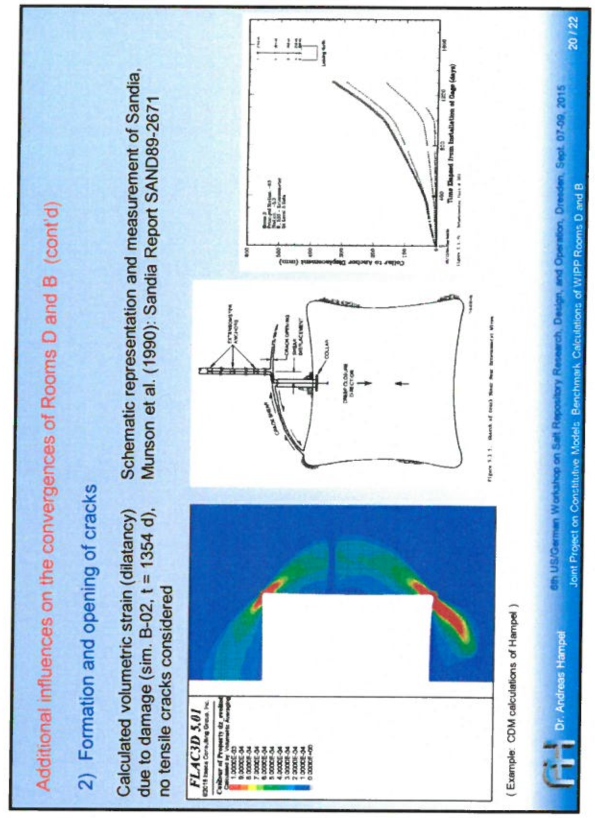
Additional influences on the convergences of Rooms D and B (cont'd)
2) Formation and opening of cracks
Calculated volumetric strain (dilatancy) due to damage (sim. B-02, t = 1354 d), no tensile cracks considered
Schematic representation and measurement of Sandia, Munson et al. (1990): Sandia Report SAND89-2671
FLAC3D 5.01
(Example: CDM calculations of Hampel)
Dr. Andreas Hampel
6th US/German Workshop on Salt Repository Research, Design, and Operation, Dresden, Sept. 07-09, 2015
Joint Project on Constitutive Models: Benchmark Calculations of WIPP Rooms D and B
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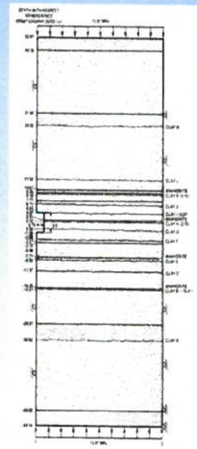
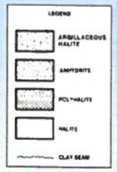
Additional influences on the convergences of Rooms D and B (cont'd)

3) Behavior of layer boundaries
(e.g. sliding on clay seams)





Munson et al. (1990):
Sandia Report SAND89-2671

Outlook: Planned Joint Project (2016 – 2019)

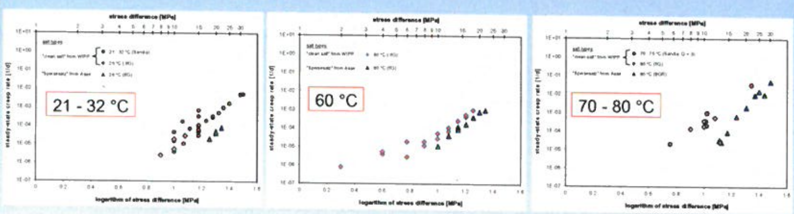
"Further Development and Qualification of Constitutive Models and Procedures for Modeling a HLW Repository in Rock Salt"

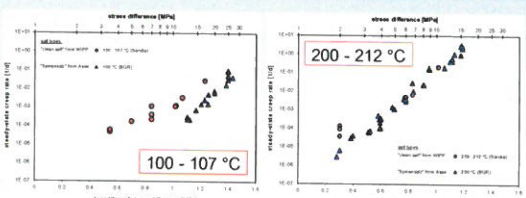
Identified subjects:

1. Deformation behavior at small deviatoric stresses
2. Deformation behavior resulting from tensile stresses
3. Influence of inhomogeneities (layer boundaries, interfaces) on deformation
4. Influence of temperature and stress state on damage reduction

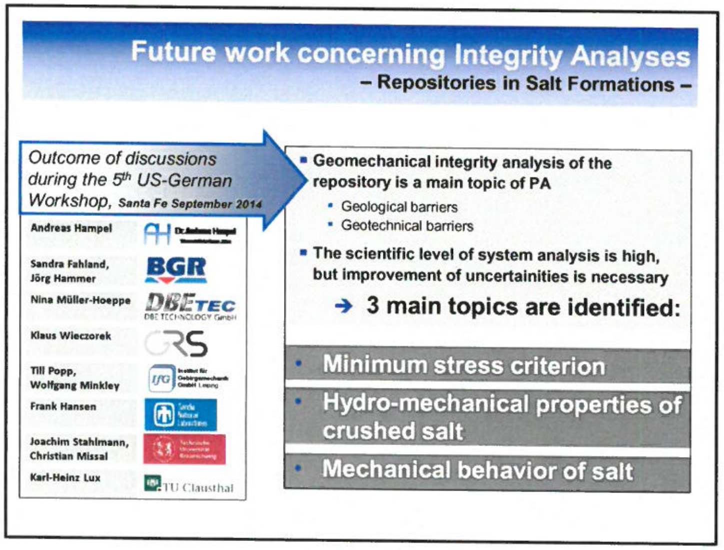
→ Laboratory tests, microstructural investigations, optional: in-situ measurements.
→ Back-calculations of the lab tests, simulations of in-situ structures.
→ Further development of the constitutive models.
→ Comparison of results, validation and qualification of the models and modeling procedures.

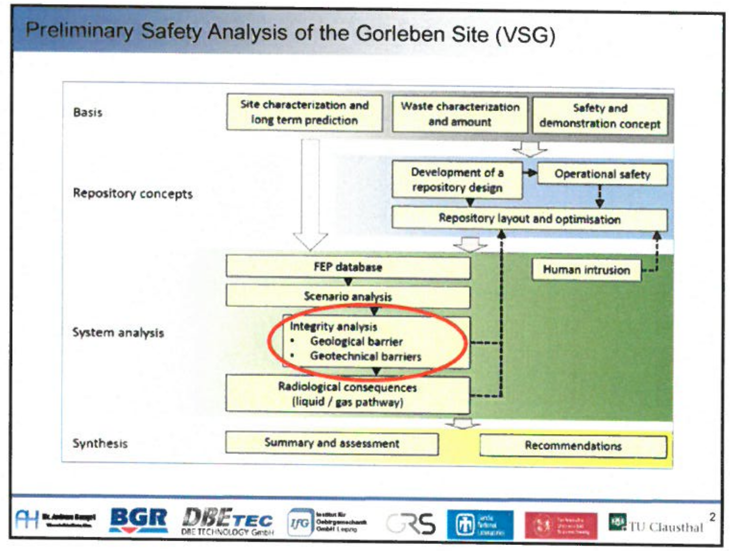
Comparison of steady-state creep rates of clean salt from WIPP (bedded salt, ●◇) with Asse-Speisesalz (domal salt, ▲)

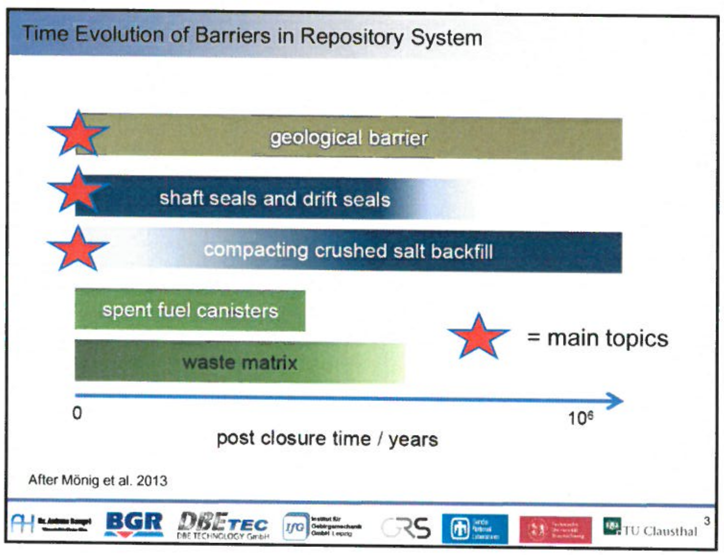


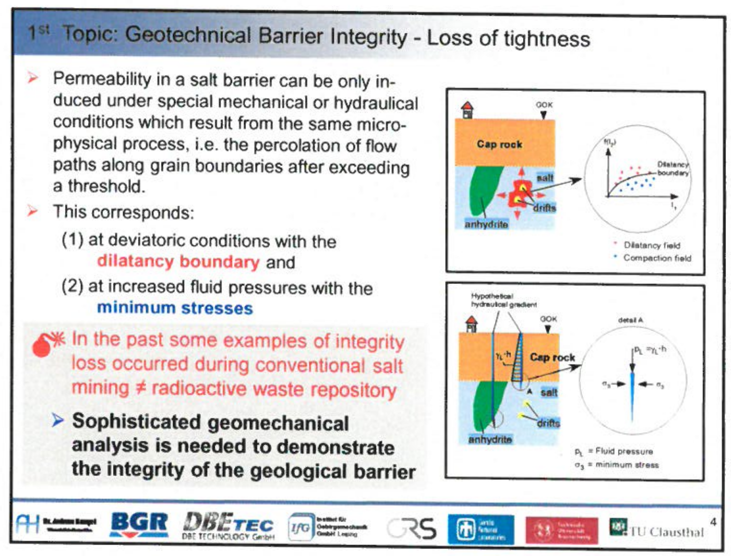


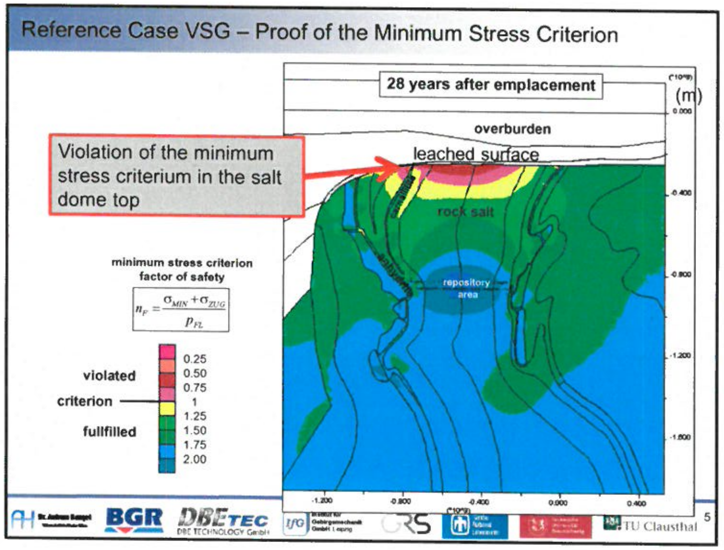
Result:
WIPP salt (clean & argillaceous) creeps a little faster than Asse-Speisesalz, especially at smaller stress differences and lower temperatures.

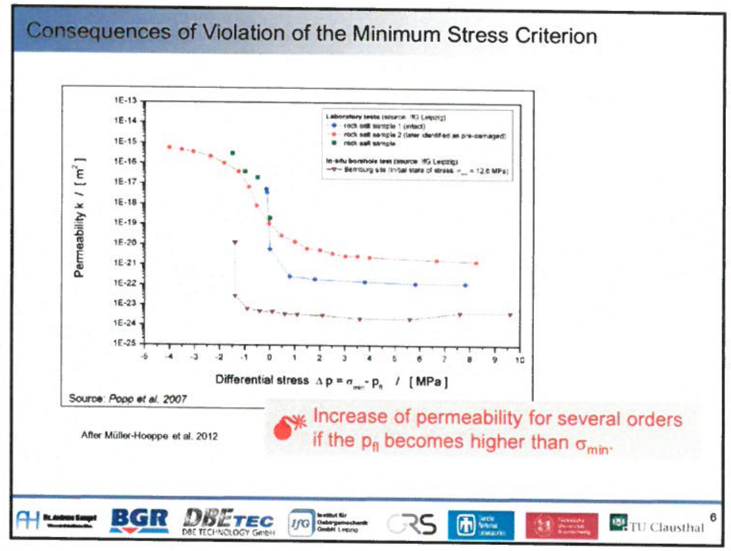

Future work concerning Integrity Analyses
– Repositories in Salt Formations –
Outcome of discussions during the 5th US-German Workshop, Santa Fe September 2014
Andreas Hampel
Sandra Fahland, Jörg Hammer
Nina Müller-Hoeppe
Klaus Wieczorek
Till Popp, Wolfgang Minkley
Frank Hansen
Joachim Stahlmann, Christian Missal
Karl-Heinz Lux
BGR
DBE TEC
GRS
TU Clausthal
Geomechanical integrity analysis of the repository is a main topic of PA
Geological barriers
Geotechnical barriers
The scientific level of system analysis is high, but improvement of uncertainities is necessary
→ 3 main topics are identified:
Minimum stress criterion
Hydro-mechanical properties of crushed salt
Mechanical behavior of salt


Preliminary Safety Analysis of the Gorleben Site (VSG)
Basis
Site characterization and long term prediction
Waste characterization and amount
Safety and demonstration concept
Repository concepts
Development of a repository design
Operational safety
Repository layout and optimisation
System analysis
FEP database
Human intrusion
Scenario analysis
Integrity analysis
Geological barrier
Geotechnical barriers
Radiological consequences (liquid / gas pathway)
Synthesis
Summary and assessment
Recommendations
2


Time Evolution of Barriers in Repository System
geological barrier
shaft seals and drift seals
compacting crushed salt backfill
spent fuel canisters
waste matrix
= main topics
0
10^6
post closure time / years
After Mönig et al. 2013
3


1st Topic: Geotechnical Barrier Integrity - Loss of tightness
Permeability in a salt barrier can be only induced under special mechanical or hydraulical conditions which result from the same micro-physical process, i.e. the percolation of flow paths along grain boundaries after exceeding a threshold.
This corresponds:
(1) at deviatoric conditions with the dilatancy boundary and
(2) at increased fluid pressures with the minimum stresses
In the past some examples of integrity loss occurred during conventional salt mining ≠ radioactive waste repository
Sophisticated geomechanical analysis is needed to demonstrate the integrity of the geological barrier
Cap rock
salt
drifts
anhydrite
Dilatancy field
Compaction field
Hypothetical hydraulical gradient
detail A
p_L = Fluid pressure
σ_3 = minimum stress
4


Reference Case VSG – Proof of the Minimum Stress Criterion
28 years after emplacement
(m)
overburden
leached surface
rock salt
repository area
Violation of the minimum stress criterium in the salt dome top
minimum stress criterion factor of safety
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
violated
criterion
fullfilled
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
BGR
DBE TEC
TU Clausthal
5


Consequences of Violation of the Minimum Stress Criterion
Permeability k / [m²]
Differential stress Δp = σ_min - p_fl / [MPa]
Source: Popp et al. 2007
After Müller-Hoeppe et al. 2012
Increase of permeability for several orders if the p_{fl} becomes higher than σ_{min}.
BGR
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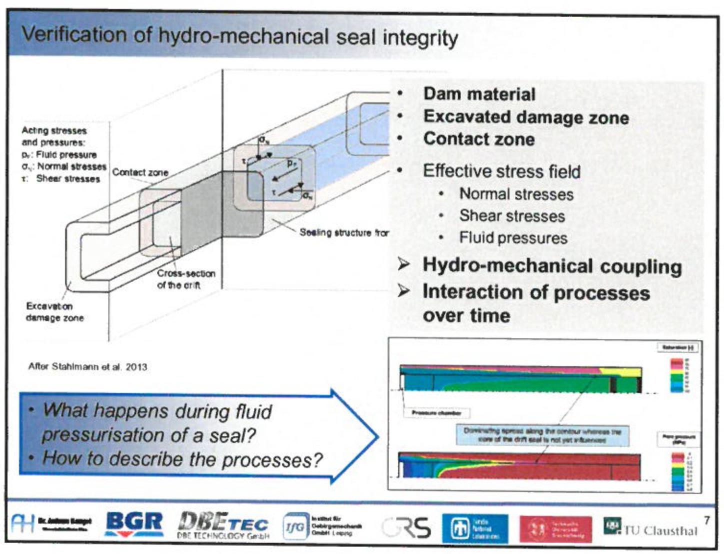
Verification of hydro-mechanical seal integrity
Acting stresses and pressures:
Contact zone
Sealing structure for
Cross-section of the drift
Excavation damage zone
After Stahlmann et al. 2013
Dam material
Excavated damage zone
Contact zone
Effective stress field
Normal stresses
Shear stresses
Fluid pressures
Hydro-mechanical coupling
Interaction of processes over time
What happens during fluid pressurisation of a seal?
How to describe the processes?
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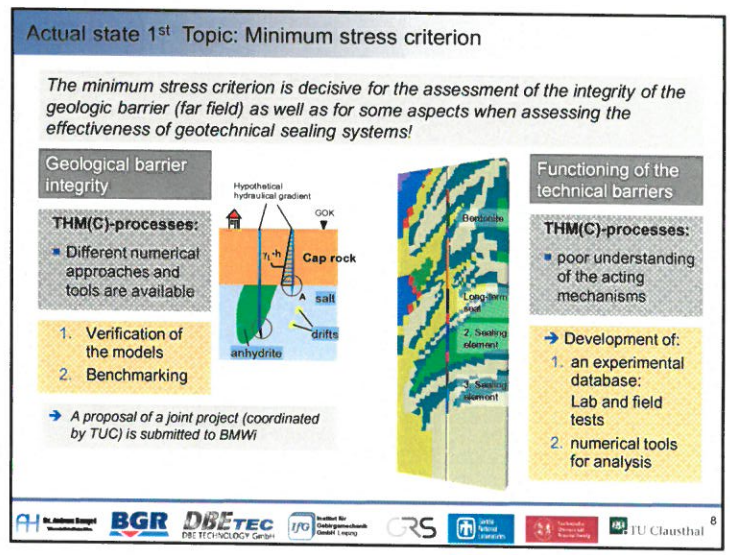
Actual state 1st Topic: Minimum stress criterion
The minimum stress criterion is decisive for the assessment of the integrity of the geologic barrier (far field) as well as for some aspects when assessing the effectiveness of geotechnical sealing systems!
Geological barrier integrity
THM(C)-processes:
Different numerical approaches and tools are available
1. Verification of the models
2. Benchmarking
A proposal of a joint project (coordinated by TUC) is submitted to BMWi
Hypothetical hydraulical gradient
GOK
Cap rock
salt
drifts
anhydrite
Functioning of the technical barriers
THM(C)-processes:
poor understanding of the acting mechanisms
Development of:
1. an experimental database: Lab and field tests
2. numerical tools for analysis
BGR
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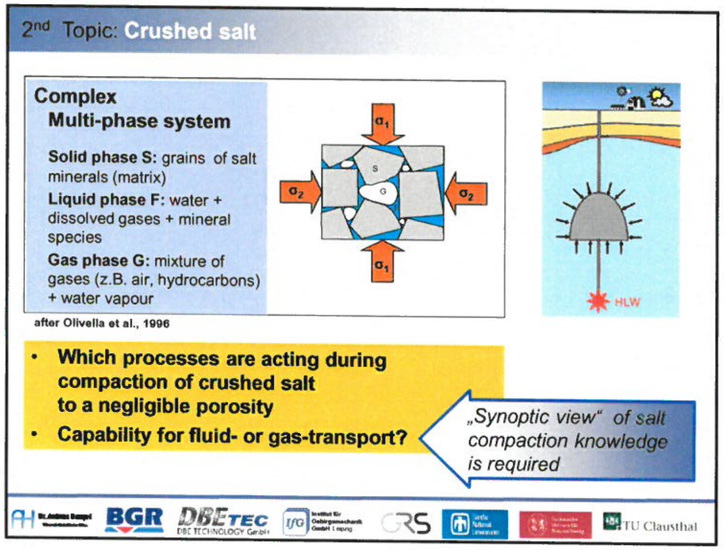
2nd Topic: Crushed salt
Complex
Multi-phase system
Solid phase S: grains of salt minerals (matrix)
Liquid phase F: water + dissolved gases + mineral species
Gas phase G: mixture of gases (z.B. air, hydrocarbons) + water vapour
after Olivella et al., 1996
σ1
σ2
HLW
Which processes are acting during compaction of crushed salt to a negligible porosity
Capability for fluid- or gas-transport?
„Synoptic view" of salt compaction knowledge is required
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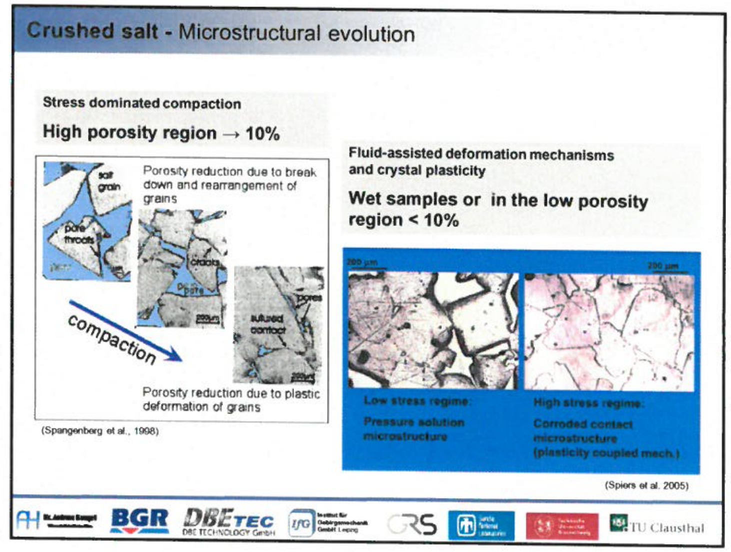
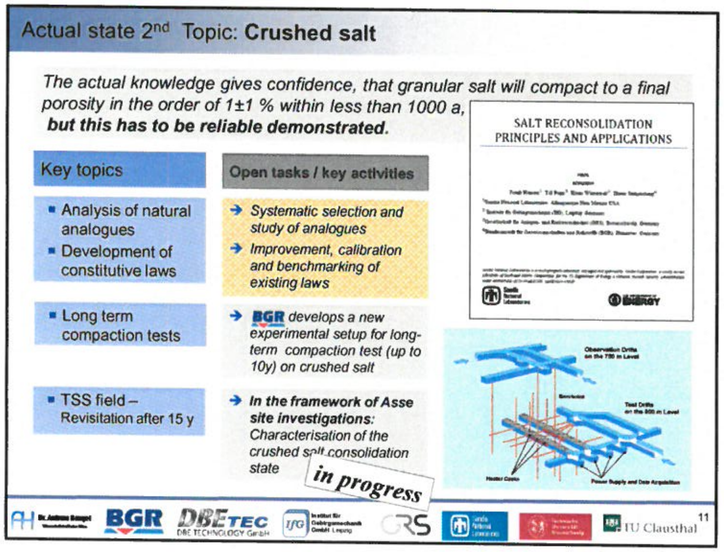
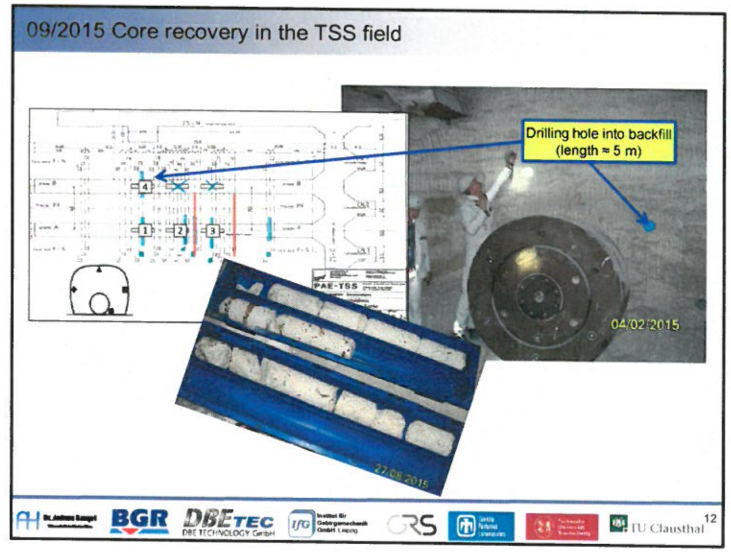
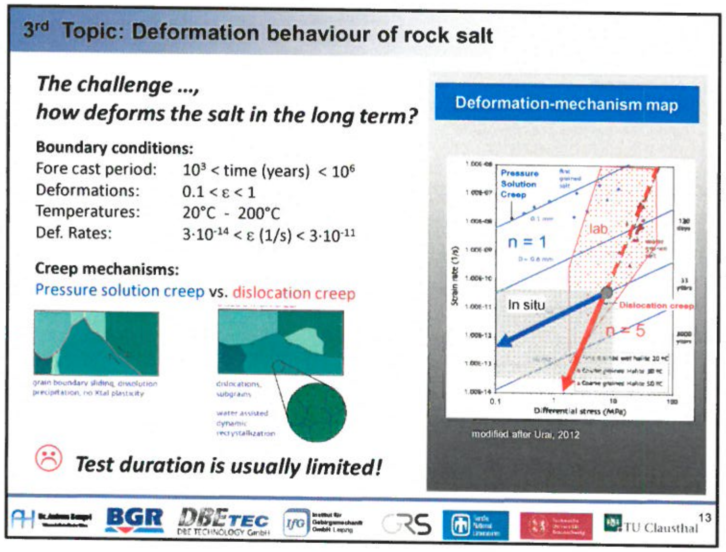
DBETEC
TU Clausthal


Crushed salt - Microstructural evolution
Stress dominated compaction
High porosity region → 10%
Porosity reduction due to break down and rearrangement of grains
compaction
Porosity reduction due to plastic deformation of grains
(Spangenberg et al., 1998)
Fluid-assisted deformation mechanisms and crystal plasticity
Wet samples or in the low porosity region < 10%
Low stress regime:
Pressure solution microstructure
High stress regime:
Corroded contact microstructure (plasticity coupled mech.)
(Spiers et al. 2005)
BGR
DBETEC
TU Clausthal


Actual state 2nd Topic: Crushed salt
The actual knowledge gives confidence, that granular salt will compact to a final porosity in the order of 1±1 % within less than 1000 a,
but this has to be reliable demonstrated.
Key topics
Open tasks / key activities
Analysis of natural analogues
Development of constitutive laws
Systematic selection and study of analogues
Improvement, calibration and benchmarking of existing laws
Long term compaction tests
BGR develops a new experimental setup for long-term compaction test (up to 10y) on crushed salt
TSS field – Revisitation after 15 y
In the framework of Asse site investigations: Characterisation of the crushed salt consolidation state
in progress
SALT RECONSOLIDATION PRINCIPLES AND APPLICATIONS
BGR
DBETEC
TU Clausthal
11


09/2015 Core recovery in the TSS field
Drilling hole into backfill (length ≈ 5 m)
04/02/2015
27/08/2015
BGR
DBETEC
TU Clausthal
12


3rd Topic: Deformation behaviour of rock salt
The challenge ...,
how deforms the salt in the long term?
Boundary conditions:
Fore cast period: 10³ < time (years) < 10⁶
Deformations: 0.1 < ε < 1
Temperatures: 20°C - 200°C
Def. Rates: 3·10⁻¹⁴ < ε (1/s) < 3·10⁻¹¹
Creep mechanisms:
Pressure solution creep vs. dislocation creep
Deformation-mechanism map
Pressure Solution Creep
n = 1
lab
In situ
Dislocation creep
n = 5
Differential stress (MPa)
modified after Urai, 2012
Test duration is usually limited!
BGR
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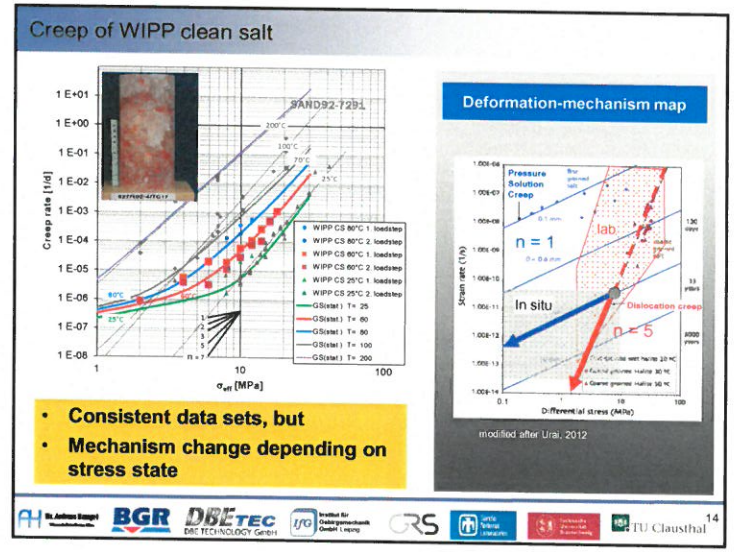
13


Creep of WIPP clean salt
SAND92-7291
Creep rate [1/d]
σeff [MPa]
Consistent data sets, but
Mechanism change depending on stress state
Deformation-mechanism map
Pressure Solution Creep
n = 1
lab
In situ
Dislocation creep
n = 5
Differential stress (MPa)
modified after Urai, 2012
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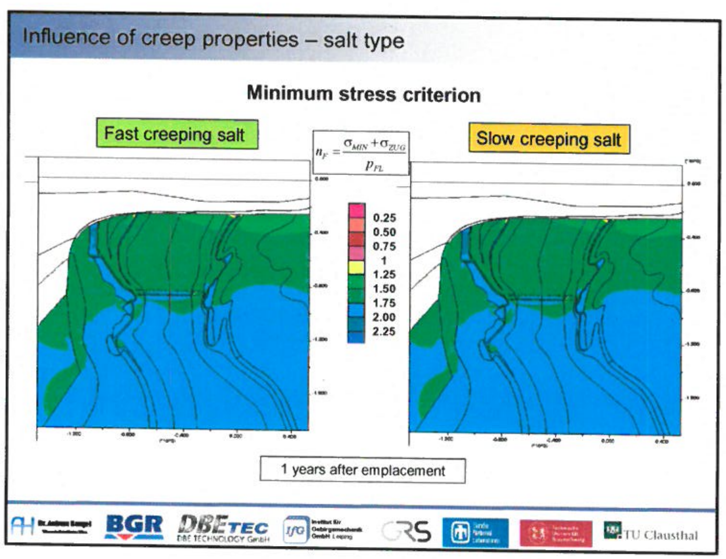
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
1 years after emplacement
BGR
DBETEC
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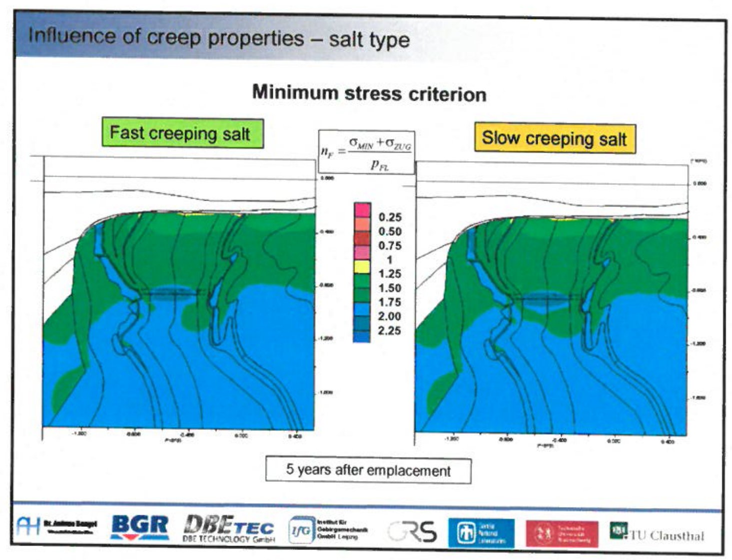
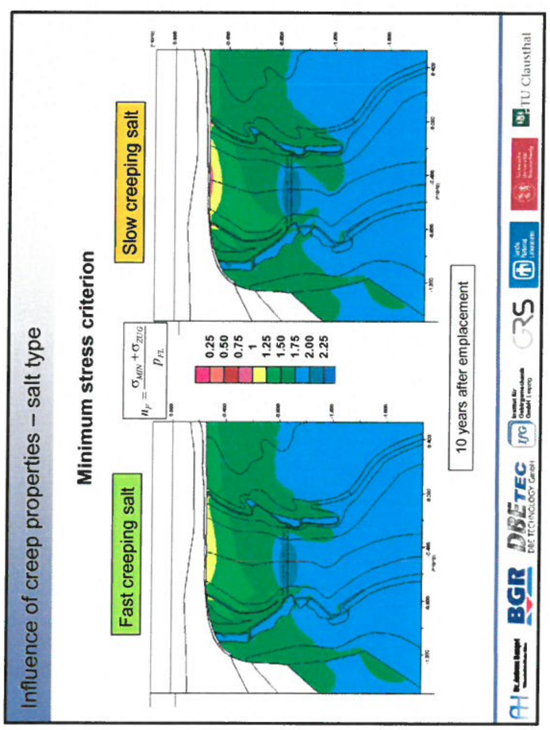
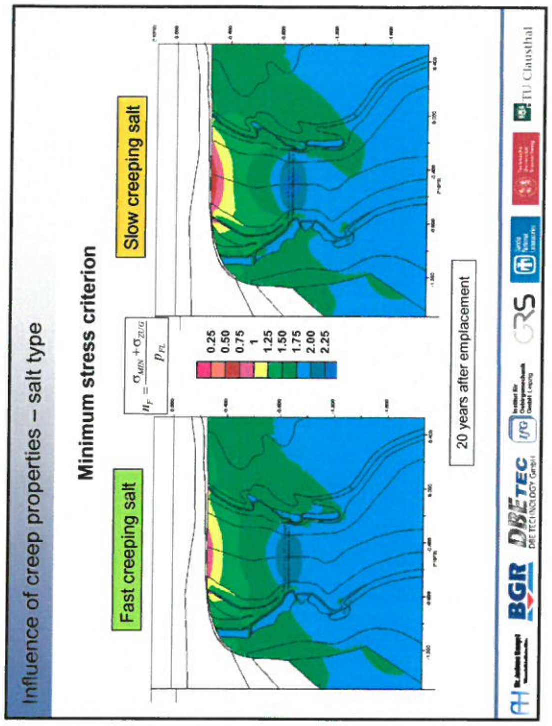
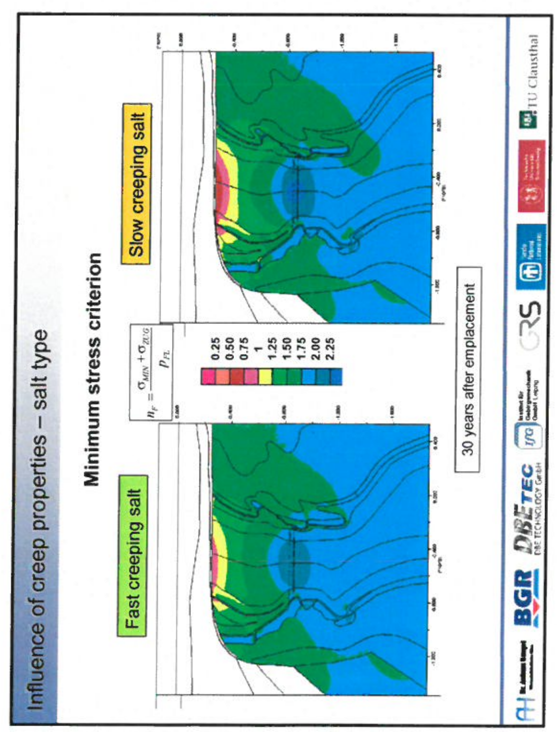
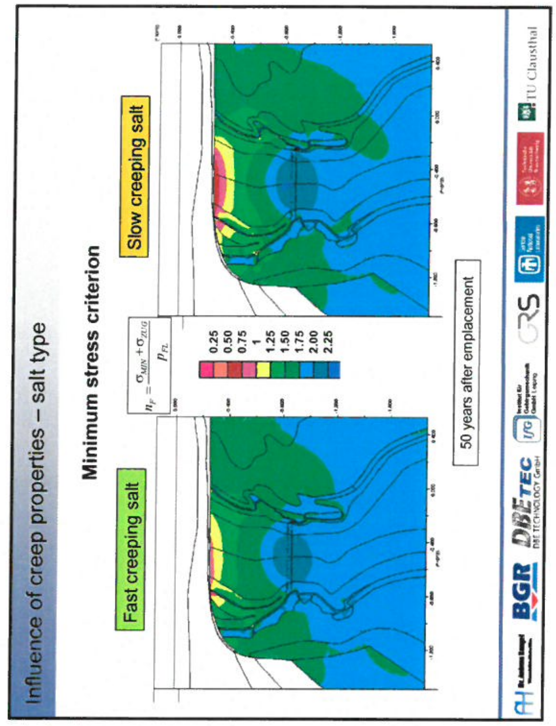
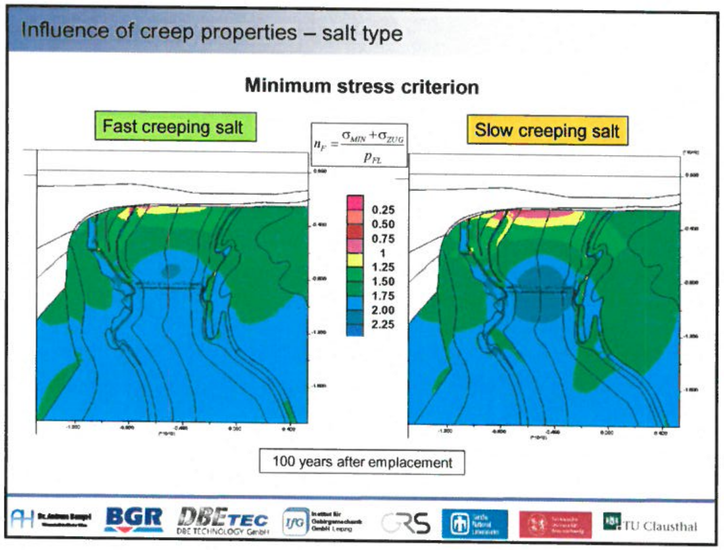

Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
5 years after emplacement
BGR
DBETEC
TU Clausthal

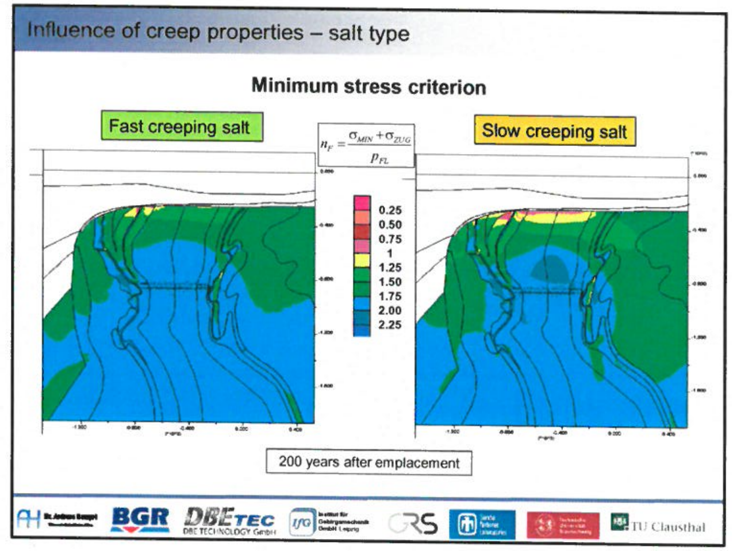

Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
10 years after emplacement
BGR
DBE TEC
IfG
GRS
TU Clausthal

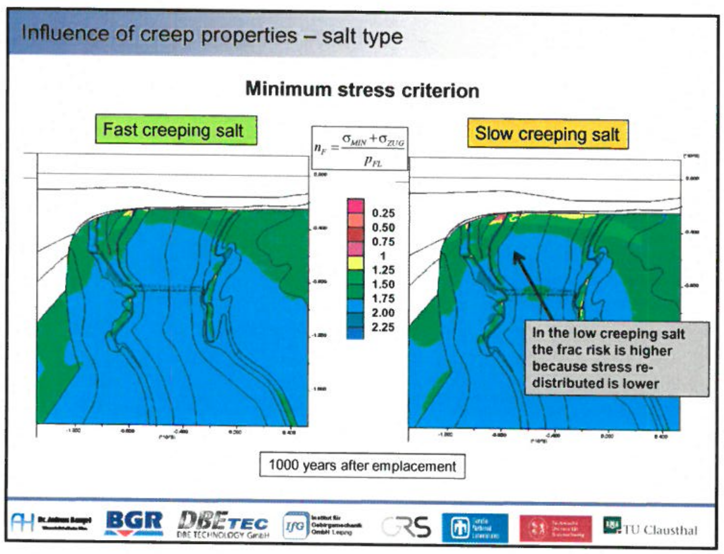

Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
20 years after emplacement
BGR
DBE TEC
IfG
GRS
TU Clausthal


Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
30 years after emplacement
BGR
DBE TEC
IfG
GRS
TU Clausthal


Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
50 years after emplacement
BGR
DBE TEC
IfG
GRS
TU Clausthal


Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
100 years after emplacement
BGR
DBETEC
TU Clausthal


Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
200 years after emplacement
BGR
DBETEC
TU Clausthal


Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
In the low creeping salt the frac risk is higher because stress re-distributed is lower
1000 years after emplacement
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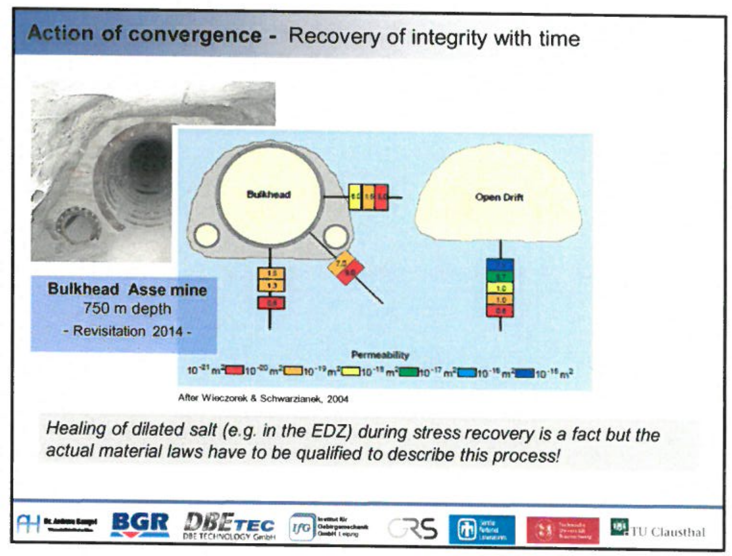
Action of convergence - Recovery of integrity with time
Bulkhead
Open Drift
Bulkhead Asse mine
750 m depth
- Revisitation 2014 -
Permeability
After Wieczorek & Schwarzianek, 2004
Healing of dilated salt (e.g. in the EDZ) during stress recovery is a fact but the actual material laws have to be qualified to describe this process!
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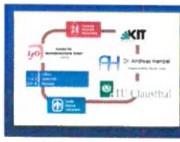
3rd Topic: Mechanical behavior of salt



BMWi – Joint Project III: Comparison of current constitutive models salt

Ongoing research and cooperation since 2004 ….

→ ***New project is in preparation*** *(start 09/2016):*

Development and qualification of current material laws and methods for modeling a HAW repository in rock salt

Forthcoming key topics

- Deformation behaviour at small deviatoric stresses
- Healing at different P, T-conditions
- Discontinuums mechanics, i.e. role of interfaces in salt
- Evaluation of the failure state at tensional stress state conditions
- Application to bedded salt

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Summary / Outlook

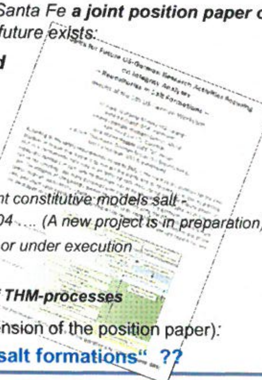
Geomechanical integrity analysis of the geological and geotechnical barriers is an imperative part of PA for repositories in salt

As outcome of the 5th US-German workshop in Santa Fe ***a joint position paper of 8 institutions*** *on necessary research work in the future exists:*

- ***3 main research topics were identified***
  - *The minimum stress criterion*
  - *Consolidation of crushed salt*
  - *How deforms the salt in the long term?*
- ***Key ongoing activities***
  - *BMWi – Joint Project III: Comparison of current constitutive models salt - ongoing research and cooperation since 2004 …. (A new project is in preparation)*
  - *Several working tasks are already in planning or under execution*
  - *Progress on US/German collaborations*

  but some deficits are identified, ***i.e. modeling of THM-processes***
- ***Deliverable product for Salt Club*** (Extension of the position paper):

  „Actual state of integrity analysis in salt formations" ??



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Integrity of saliferous barriers for heat generating radioactive waste – natural analogues and geomechanical requirements

Wolfgang Minkley
IfG-Institut für Gebirgsmechanik GmbH, Leipzig

6[th] US/German Workshop on Salt Repository Research, Design, and Operation

Dresden *September 7 – 9, 2015*

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Natural analogue: Long term storage capacity of high pressure fluids in salt

2003 - salt mine "Unterbreizbach" CO_2-glacier after an underground blow- out (CO_2 becomes solid below -70°C)

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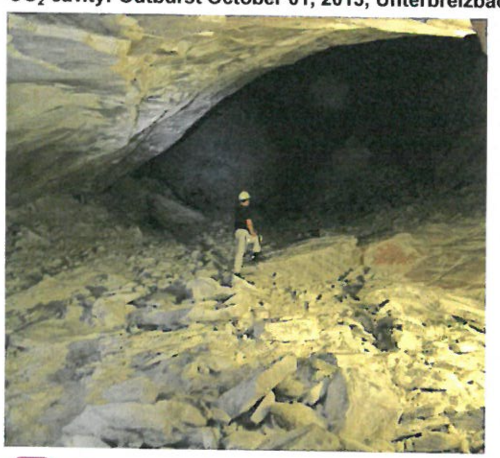
CO_2 cavity: Outburst October 01, 2013, Unterbreizbach



- Largest gas release in salt worldwide
- Gas outburst after blast in carnallitite seam Thuringia
- Depth 900 m
  p = 22 MPa,
  T = 31°C
  - CO_2 supercritical state
- V_{cav} = 100.000 m³
- Cavity presumably created by carnallitite ->sylvinite conversion
- Three miners killed 7 km from burst point

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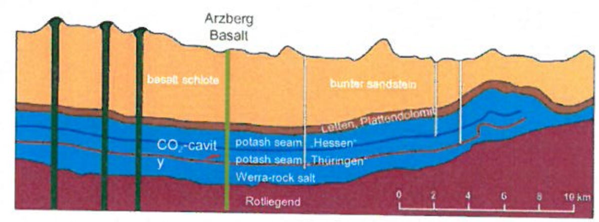
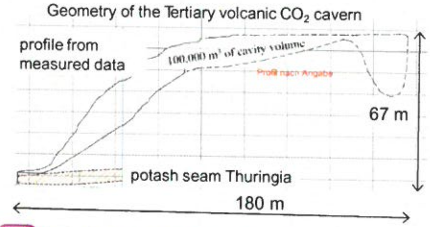


Geometry of the Tertiary volcanic CO_2 cavern



- Tertiary volcanism about 20 Ma ago
- basaltic intrusions transformation carnallitite → sylvinite
- Large volumes of CO_2 trapped in cavities or on grain boundaries
- Frequent gas outbursts triggered by potash mining

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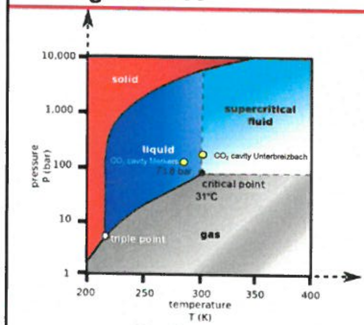
Significance



Phase diagram of CO_2

- Free gas in cavity reaches lithostatic pressure and temperature
- Conditions at outburst location imply liquid or supercritical state
- Pressure drop to atmospheric pressure leads to volume expansion by factor of 500
- Estimated gas volume at standard conditions up to $V_{CO2} = 40 * 10^6$ m³

- **Enormous amounts of gas trapped under high pressure in liquid or supercritical state, for geological timescales!**
- **Natural demonstration of complete containment in salt rocks!**

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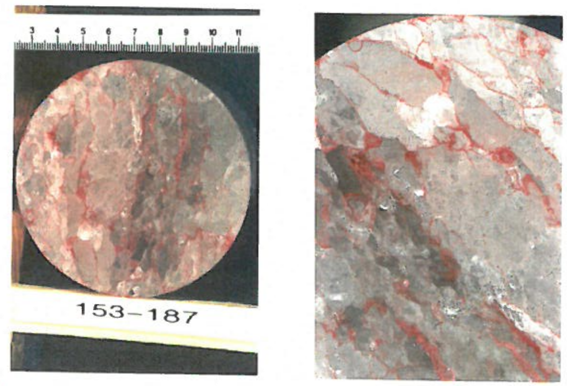
pressure-driven percolation on grain boundaries after exceeding the percolation threshold (minimal stress criterion)



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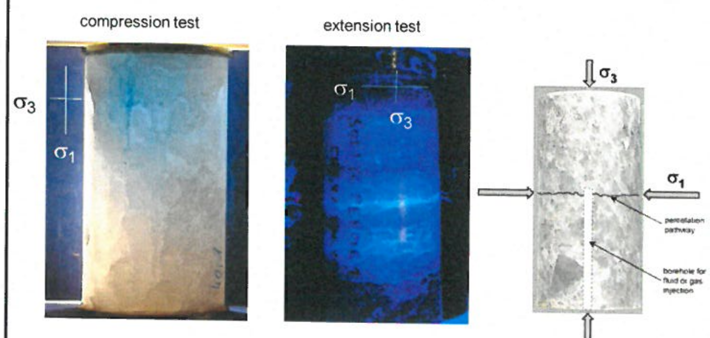
Directed pressure-driven generation of hydraulic flow paths in an anisotropic stress field



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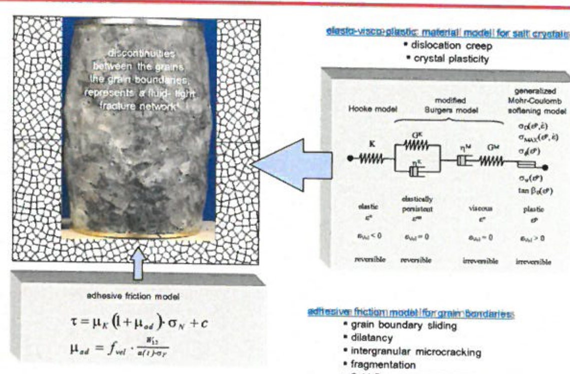
Discontinuum-mechanical model of polycristalline salt rocks

Constitutive models for salt crystls and grain boundaries



$$\tau = \mu_K (1 + \mu_{ad}) \cdot \sigma_N + c$$

$$V = \frac{W_{hydr}^3}{12\,\nu} \cdot b \cdot \frac{\Delta p}{L}$$

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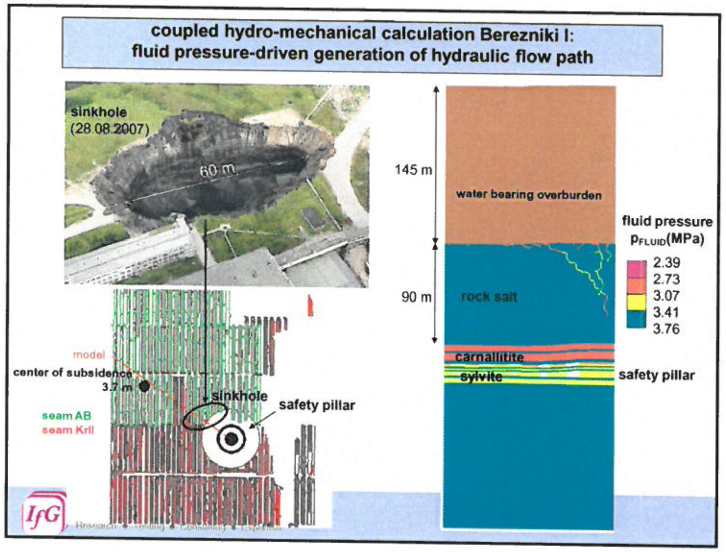
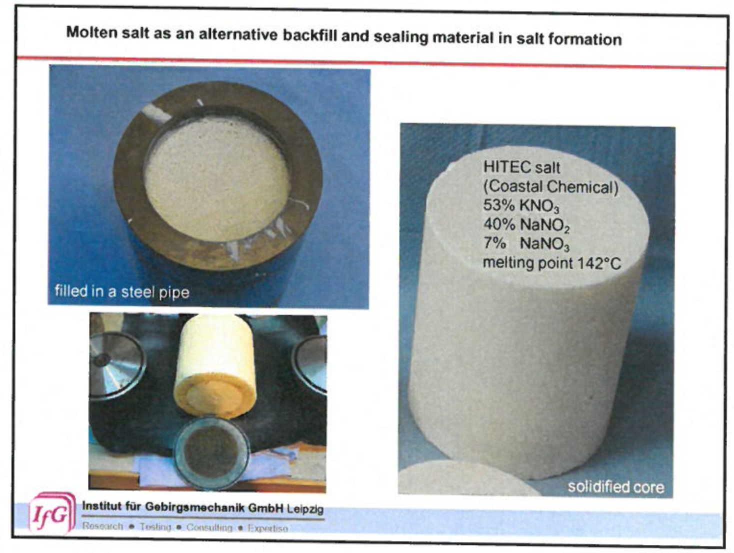

coupled hydro-mechanical calculation Berezniki I:
fluid pressure-driven generation of hydraulic flow path
sinkhole
(28.08.2007)
60 m
145 m
90 m
water bearing overburden
rock salt
carnallitite
sylvite
fluid pressure
pFLUID(MPa)
2.39
2.73
3.07
3.41
3.76
safety pillar
model
center of subsidence
3.7 m
sinkhole
safety pillar
seam AB
seam KrII
IfG


Molten salt as an alternative backfill and sealing material in salt formation
filled in a steel pipe
HITEC salt
(Coastal Chemical)
53% KNO3
40% NaNO2
7% NaNO3
melting point 142°C
solidified core
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eutectic molten salt with low viscosity and high density
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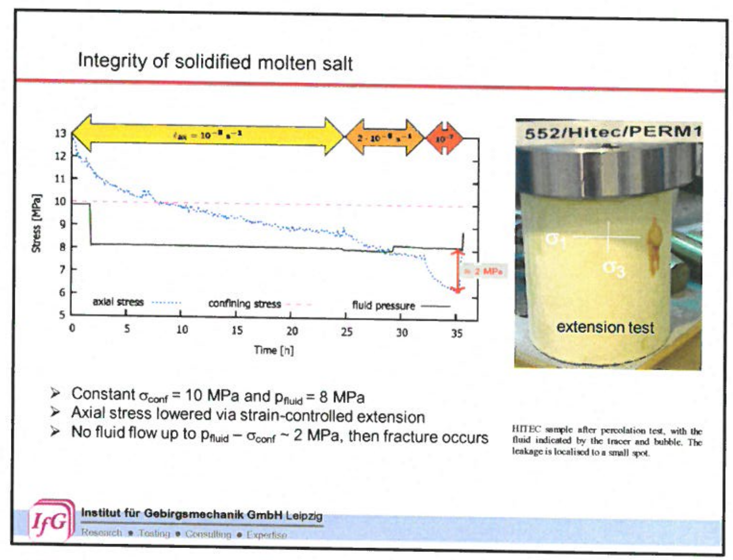
Integrity of solidified molten salt
Stress [MPa]
Time [h]
axial stress
confining stress
fluid pressure
≈ 2 MPa
552/Hitec/PERM1
σ1
σ3
extension test
Constant σconf = 10 MPa and pfluid = 8 MPa
Axial stress lowered via strain-controlled extension
No fluid flow up to pfluid – σconf ~ 2 MPa, then fracture occurs
HITEC sample after percolation test, with the fluid indicated by the tracer and bubble. The leakage is localised to a small spot.
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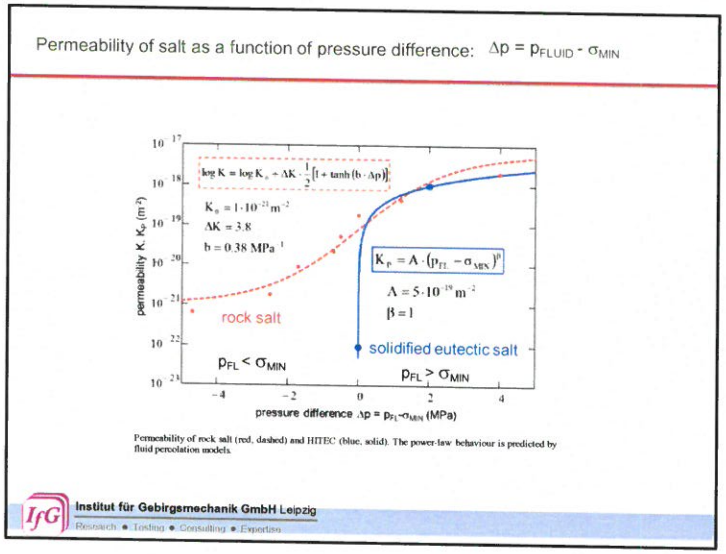
Permeability of salt as a function of pressure difference: Δp = pFLUID - σMIN
log K = log K0 + ΔK · ½ [1 + tanh (b · Δp)]
K0 = 1·10⁻²¹ m⁻²
ΔK = 3.8
b = 0.38 MPa⁻¹
KP = A · (pFL − σMIN)^β
A = 5·10⁻¹⁹ m⁻²
β = 1
rock salt
solidified eutectic salt
pFL < σMIN
pFL > σMIN
permeability K, KP (m²)
pressure difference Δp = pFL-σMIN (MPa)
Permeability of rock salt (red, dashed) and HITEC (blue, solid). The power-law behaviour is predicted by fluid percolation models.
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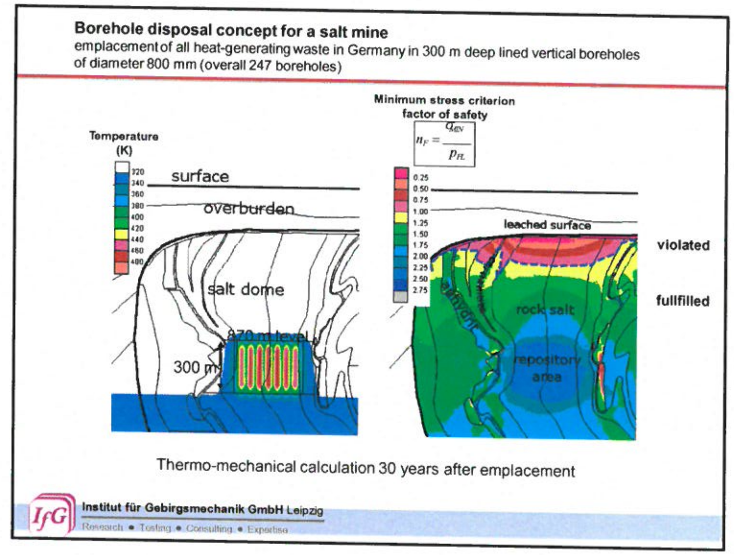
Borehole disposal concept for a salt mine
emplacement of all heat-generating waste in Germany in 300 m deep lined vertical boreholes of diameter 800 mm (overall 247 boreholes)
Temperature (K)
Minimum stress criterion factor of safety
surface
overburden
salt dome
870 m level
300 m
leached surface
rock salt
repository area
violated
fullfilled
Thermo-mechanical calculation 30 years after emplacement
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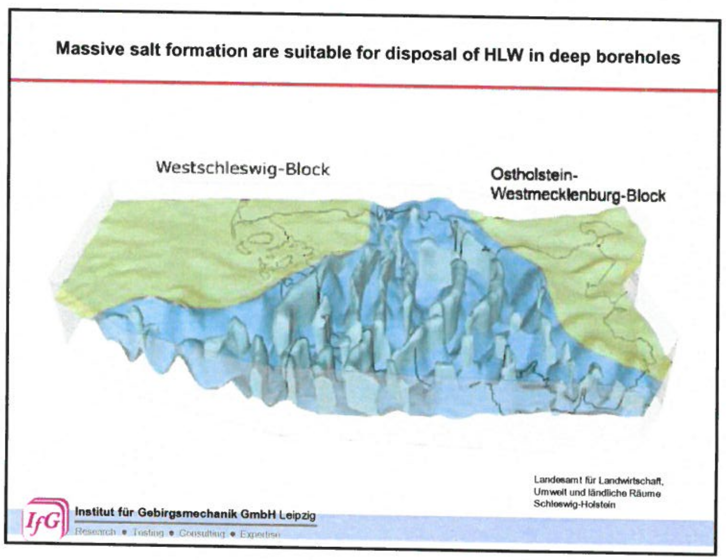
Massive salt formation are suitable for disposal of HLW in deep boreholes
Westschleswig-Block
Ostholstein-Westmecklenburg-Block
Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein
Institut für Gebirgsmechanik GmbH Leipzig
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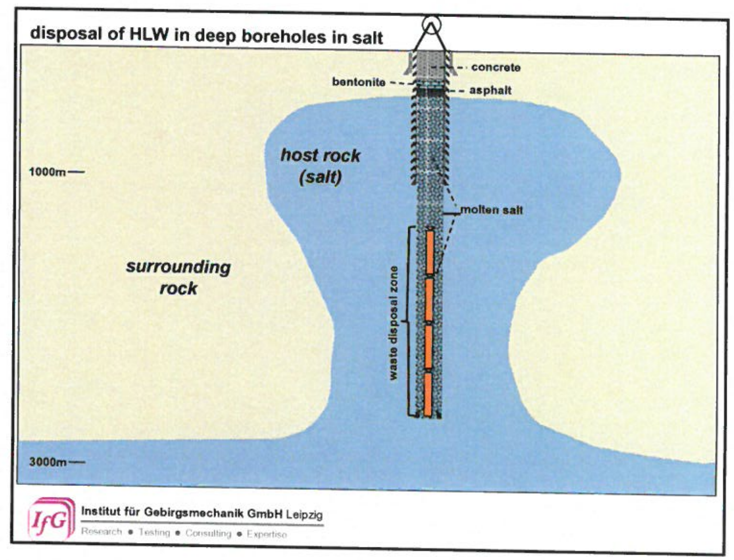
disposal of HLW in deep boreholes in salt
concrete
bentonite
asphalt
host rock (salt)
1000m
molten salt
surrounding rock
waste disposal zone
3000m
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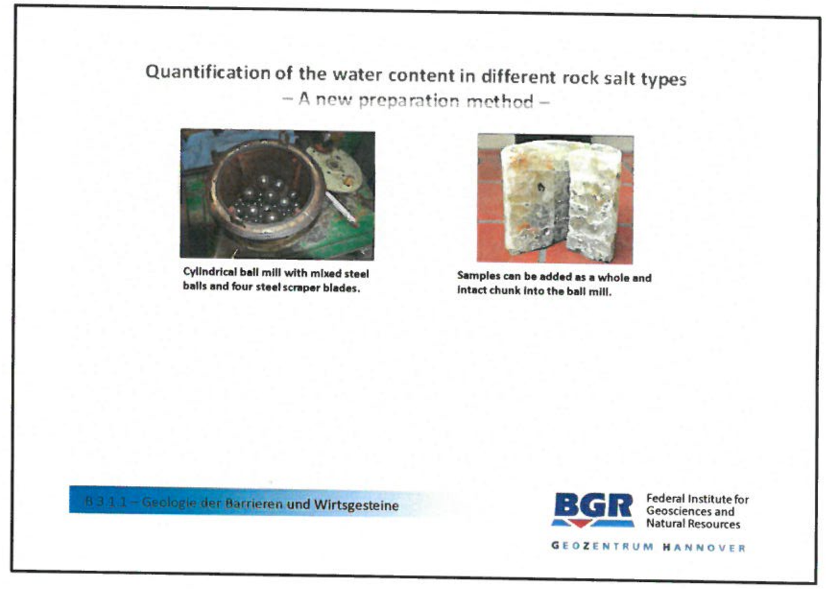
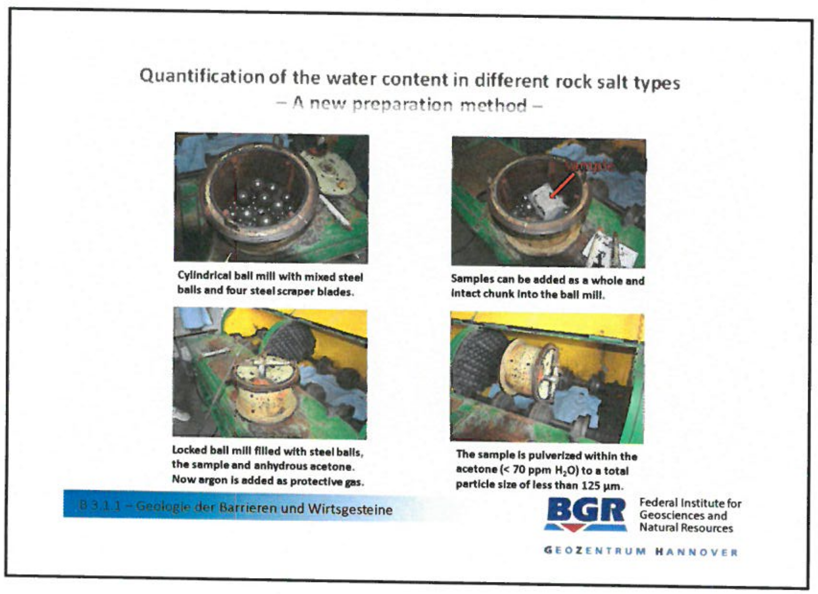
BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER
Content and distribution of fluids in domal and bedded salt: influence on the geomechanical behaviour of rocks
Pusch M., Hammer J., Plischke I.
Federal Institute for Geosciences and Natural Resources – GEOZENTRUM HANNOVER
6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015
Sandia National Laboratories
DBE TEC
PTKA
NWSA
ENERGY


Quantification of the water content in different rock salt types
– A new preparation method –
Cylindrical ball mill with mixed steel balls and four steel scraper blades.
Samples can be added as a whole and intact chunk into the ball mill.
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
BGR Federal Institute for Geosciences and Natural Resources
GEOZENTRUM HANNOVER


Quantification of the water content in different rock salt types
– A new preparation method –
Cylindrical ball mill with mixed steel balls and four steel scraper blades.
Samples can be added as a whole and intact chunk into the ball mill.
Locked ball mill filled with steel balls, the sample and anhydrous acetone. Now argon is added as protective gas.
The sample is pulverized within the acetone (< 70 ppm H2O) to a total particle size of less than 125 µm.
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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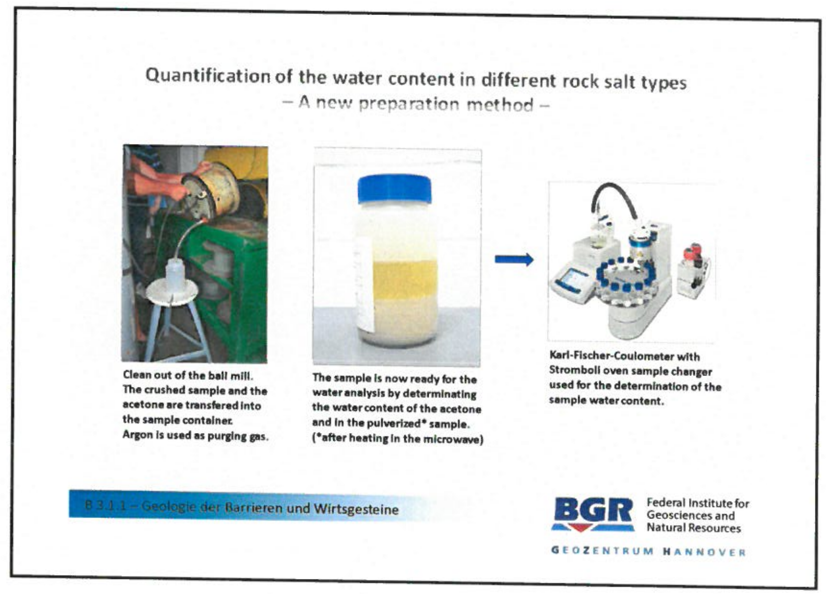
Quantification of the water content in different rock salt types
– A new preparation method –
Clean out of the ball mill. The crushed sample and the acetone are transfered into the sample container. Argon is used as purging gas.
The sample is now ready for the water analysis by determinating the water content of the acetone and in the pulverized* sample. (*after heating in the microwave)
Karl-Fischer-Coulometer with Stromboli oven sample changer used for the determination of the sample water content.
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Water content (BGR 2015) in comparison with water content of WIPP rock salt (IfG 2015)

Samples analyzed with the new preparation method and Karl-Fischer-Titration (KFT)

- **Sample 1:** MB139 (Halite) from WIPP drilling SNLCV301 at drilling meter 2.0 to 2.04 ft
- **Sample 2:** „Hauptsalz" from Gorleben at drilling station 3 from 840 m level

Comparative measurements on crushed salt with Differential Thermal Analysis (DTA)
(analyses are still in progress)

- **Sample 1:** MB139 (Halite) from WIPP drilling SNLCV301 at drilling meter 2.0 to 2.04 ft
- **Sample 2:** „Hauptsalz" from Gorleben at drilling station 3 from 840 m level

Argillaceous (WIPP)	–	–	0.4 wt.-%
Clean salt (WIPP)	0.99 wt.-%	in progress	0.15 wt.-%
Hauptsalz (Gorleben)	0.29 wt.-%	in progress	–

B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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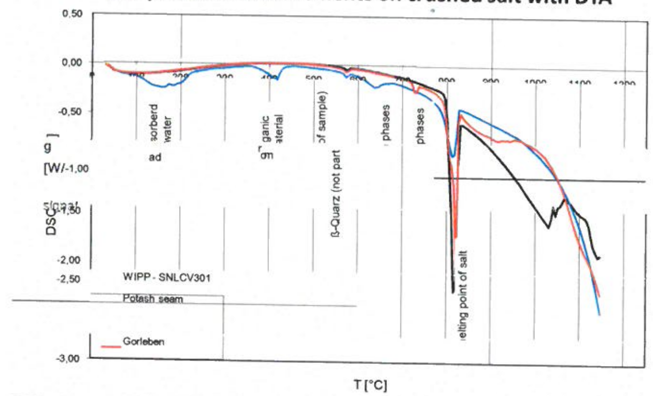
Comparative measurements on crushed salt with DTA



B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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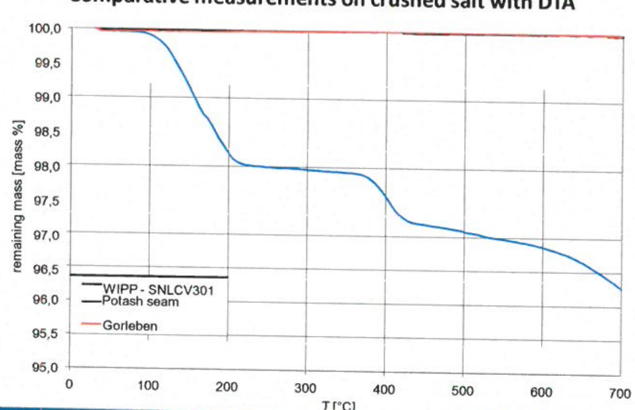
Comparative measurements on crushed salt with DTA



B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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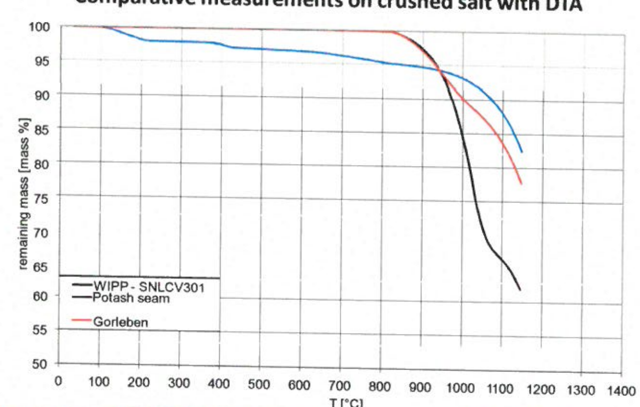
Comparative measurements on crushed salt with DTA



B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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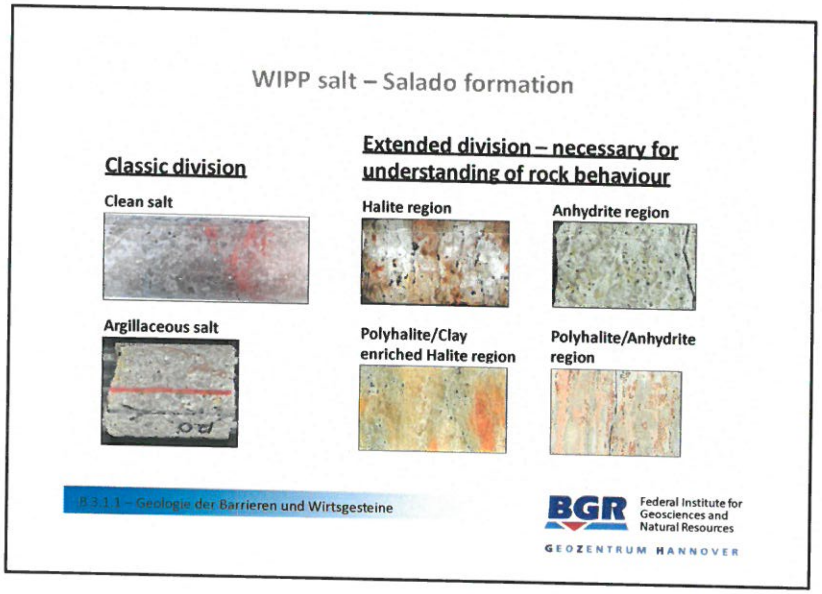
GEOZENTRUM HANNOVER


WIPP salt – Salado formation
Classic division
Clean salt
Argillaceous salt
Extended division – necessary for understanding of rock behaviour
Halite region
Anhydrite region
Polyhalite/Clay enriched Halite region
Polyhalite/Anhydrite region
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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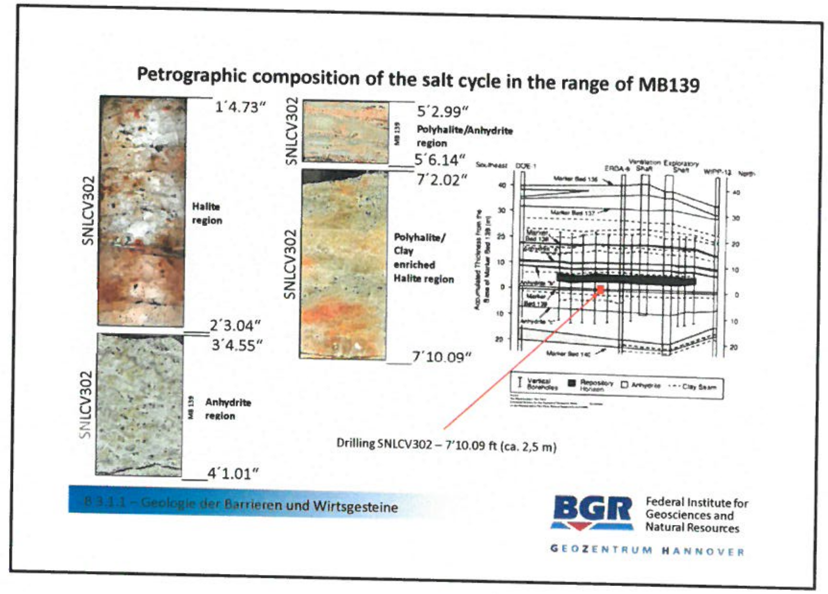
Petrographic composition of the salt cycle in the range of MB139
SNLCV302
1´4.73"
Halite region
2´3.04"
3´4.55"
Anhydrite region
4´1.01"
5´2.99"
Polyhalite/Anhydrite region
5´6.14"
7´2.02"
Polyhalite/Clay enriched Halite region
7´10.09"
Drilling SNLCV302 – 7´10.09 ft (ca. 2,5 m)
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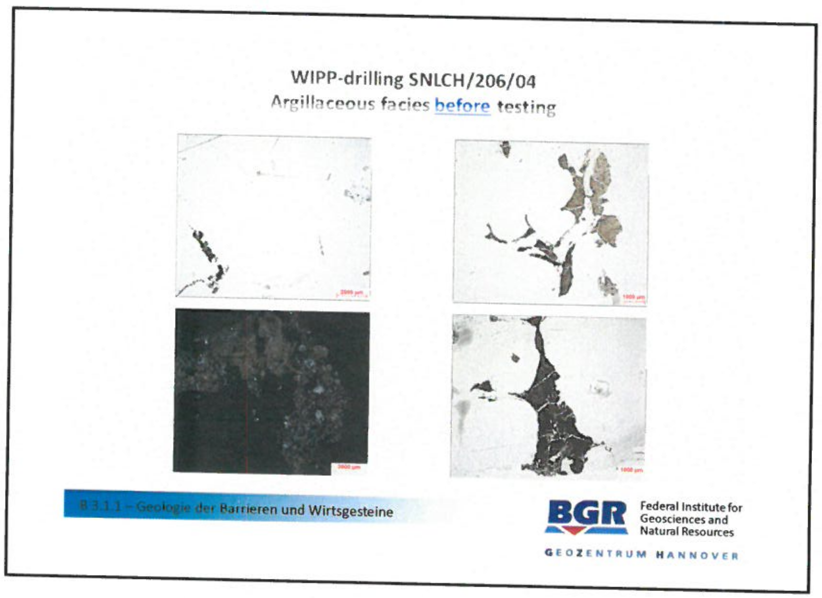
WIPP-drilling SNLCH/206/04
Argillaceous facies before testing
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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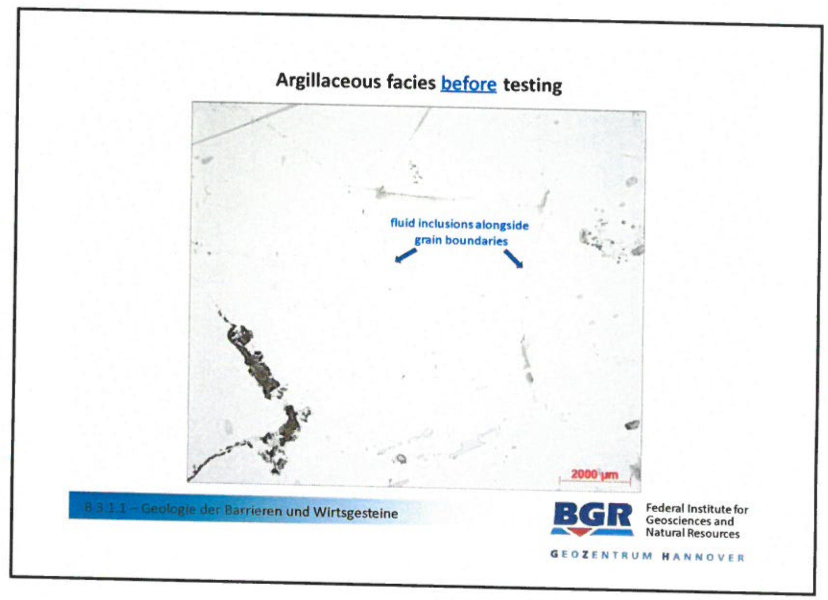
GEOZENTRUM HANNOVER


Argillaceous facies before testing
fluid inclusions alongside grain boundaries
2000 µm
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Argillaceous facies before testing
fractured clay at grain boundary mixed with halite
1000 µm
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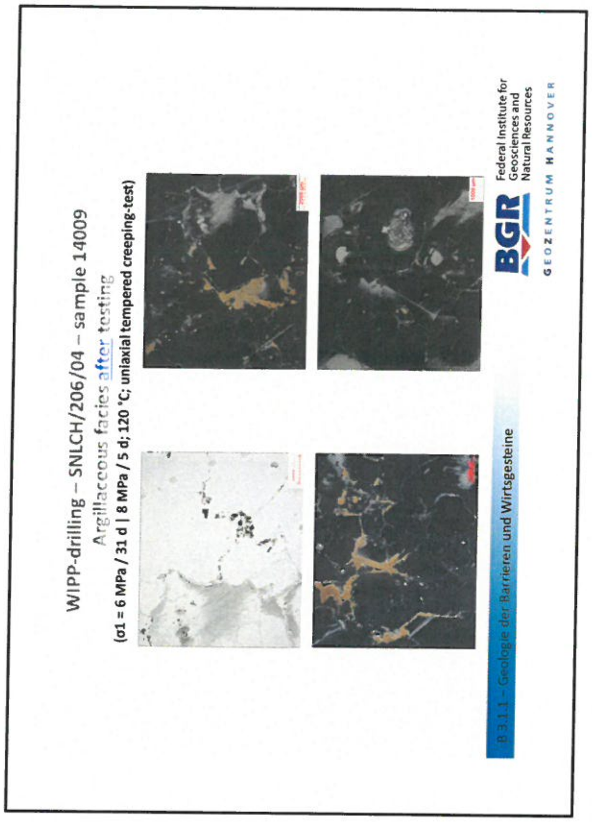
WIPP-drilling – SNLCH/206/04 – sample 14009
Argillaceous facies after testing
(σ1 = 6 MPa / 31 d | 8 MPa / 5 d; 120 °C; uniaxial tempered creeping-test)
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Argillaceous facies after testing – sample 14009
surface contamination due to water release
dislocation in clay at grain boundary
2000 µm
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Argillaceous facies after testing – sample 14009
surface contamination due to water release
collapsed matrix around a fluid inclusion
disruption of halite
fluid filled cleavage face
disruption of clay
1000 µm
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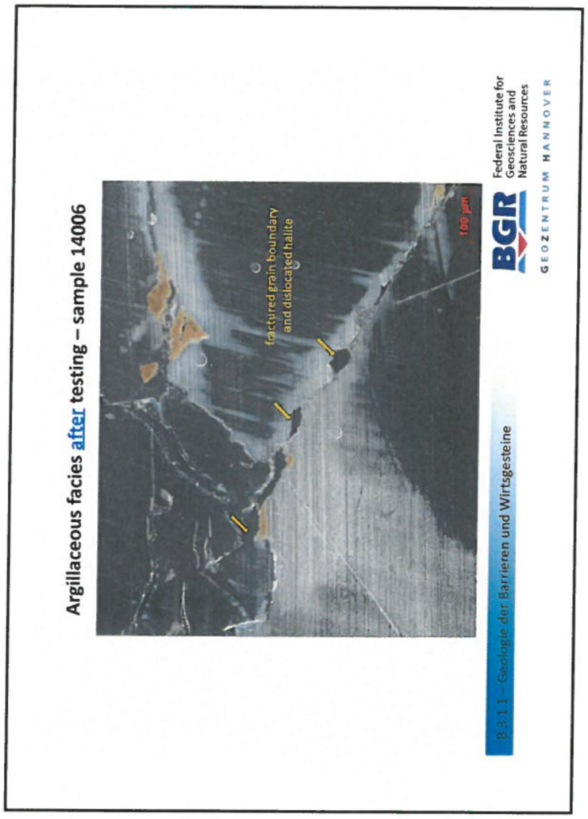
Argillaceous facies after testing – sample 14006
fractured grain boundary and dislocated halite
100 µm
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Argillaceous facies after testing – sample 14006
crack alongside halite grain boundary through polyhalite and clay
1000 µm
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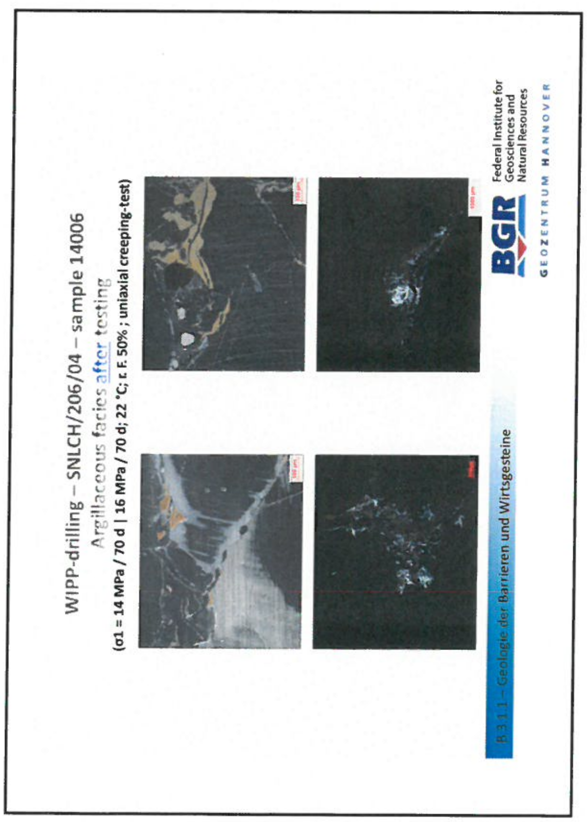
WIPP-drilling – SNLCH/206/04 – sample 14006
Argillaceous facies after testing
(σ1 = 14 MPa / 70 d | 16 MPa / 70 d; 22 °C; r. F. 50% ; uniaxial creeping-test)
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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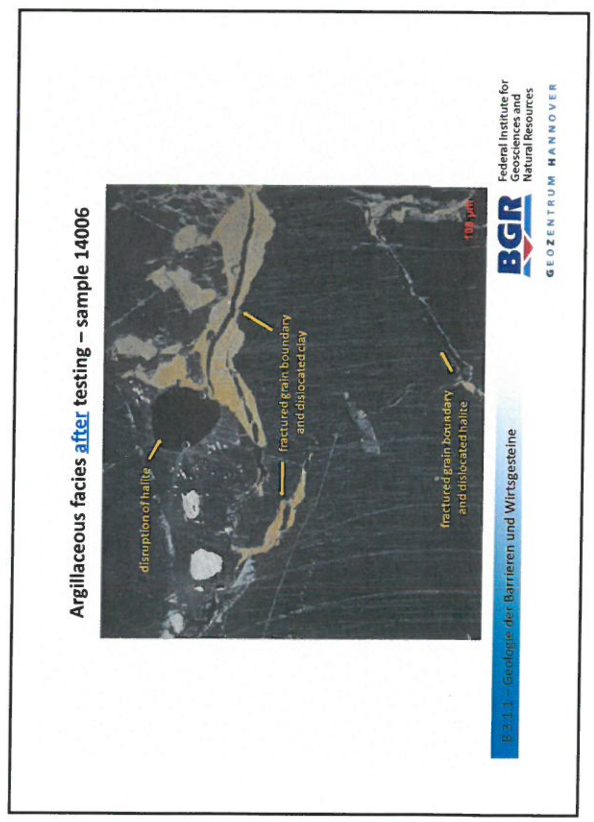
Argillaceous facies after testing – sample 14006
disruption of halite
fractured grain boundary and dislocated clay
fractured grain boundary and dislocated halite
100 µm
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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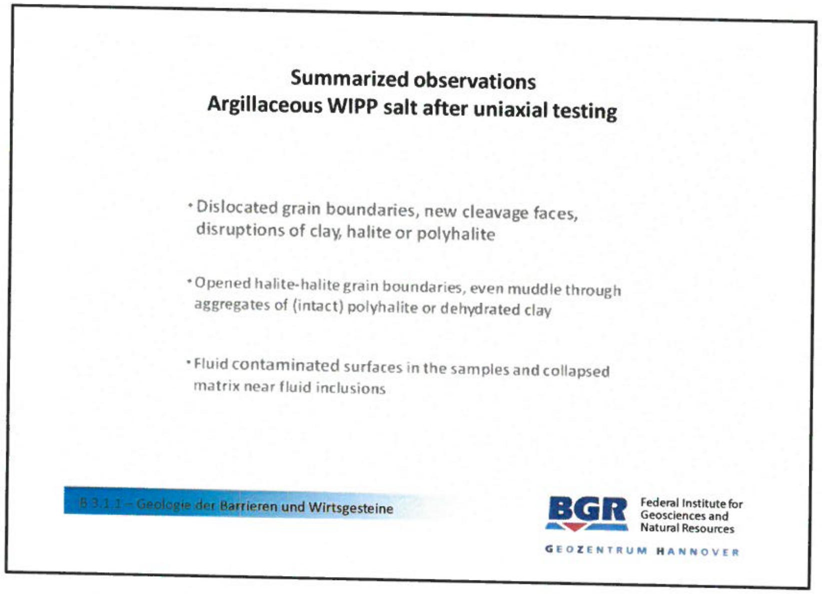
Summarized observations
Argillaceous WIPP salt after uniaxial testing
• Dislocated grain boundaries, new cleavage faces, disruptions of clay, halite or polyhalite
• Opened halite-halite grain boundaries, even muddle through aggregates of (intact) polyhalite or dehydrated clay
• Fluid contaminated surfaces in the samples and collapsed matrix near fluid inclusions
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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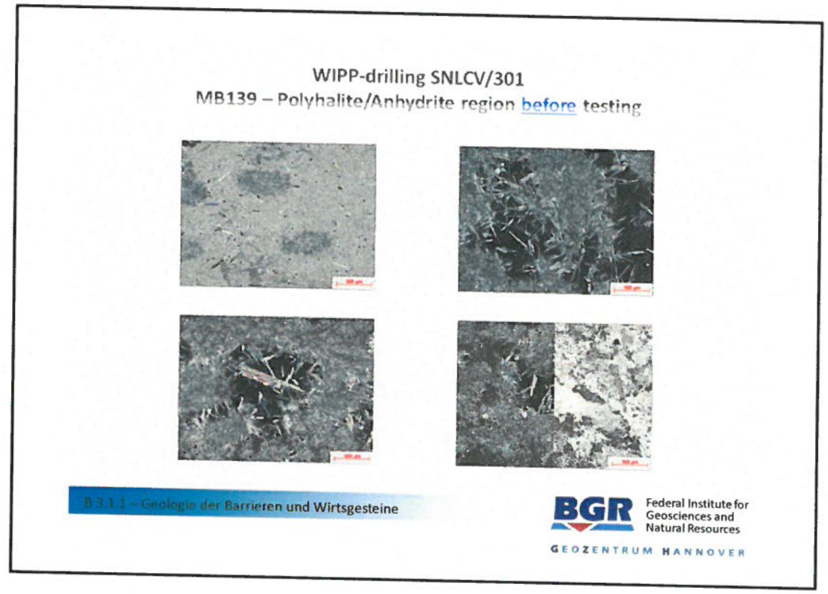
WIPP-drilling SNLCV/301
MB139 – Polyhalite/Anhydrite region before testing
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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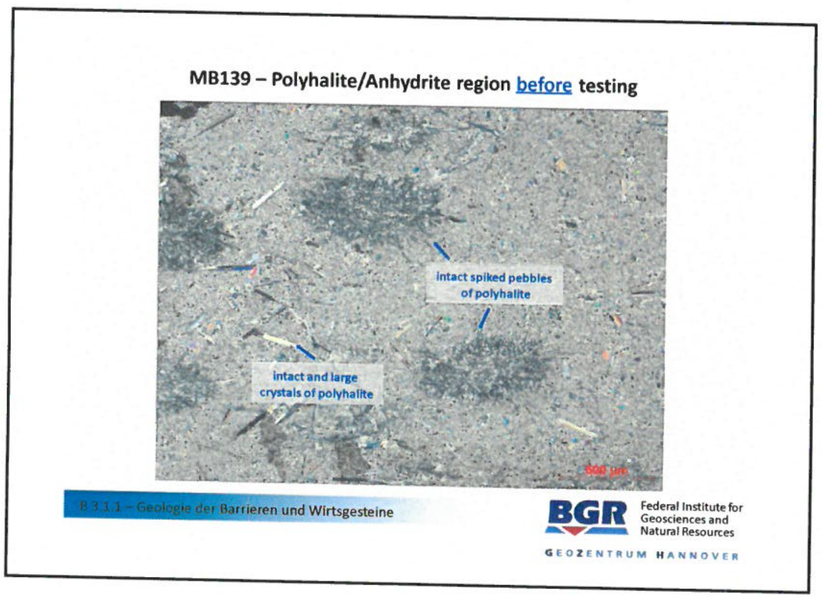
GEOZENTRUM HANNOVER


MB139 – Polyhalite/Anhydrite region before testing
intact spiked pebbles of polyhalite
intact and large crystals of polyhalite
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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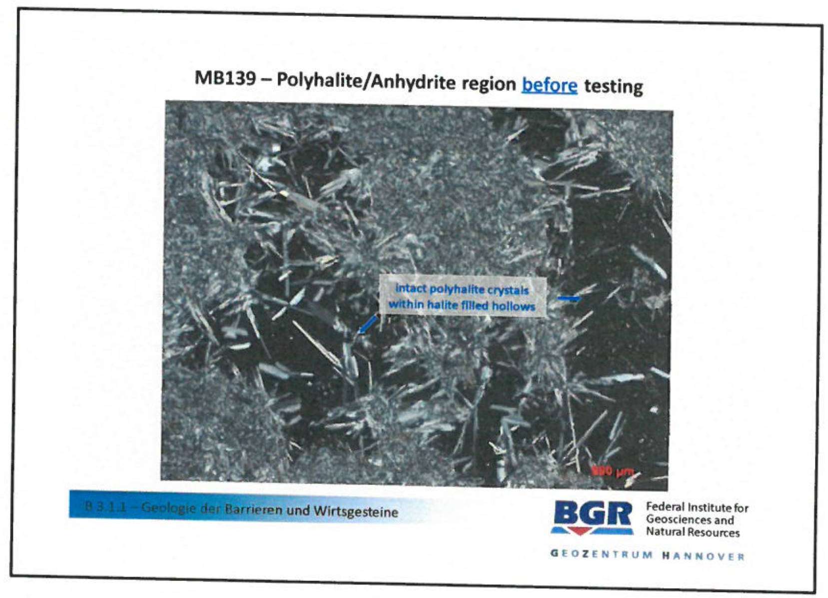
GEOZENTRUM HANNOVER


MB139 – Polyhalite/Anhydrite region before testing
intact polyhalite crystals within halite filled hollows
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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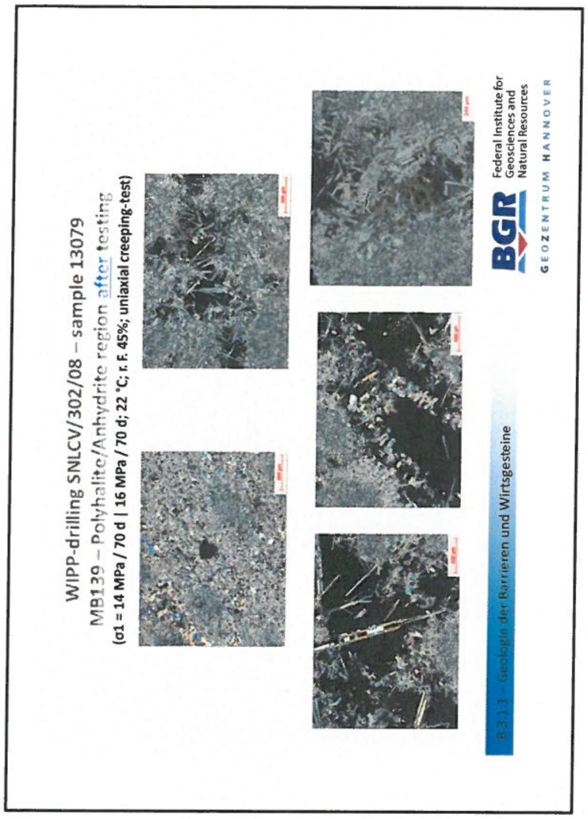
GEOZENTRUM HANNOVER


WIPP-drilling SNLCV/302/08 – sample 13079
MB139 – Polyhalite/Anhydrite region after testing
(σ1 = 14 MPa / 70 d | 16 MPa / 70 d; 22 °C; r. F. 45%; uniaxial creeping-test)
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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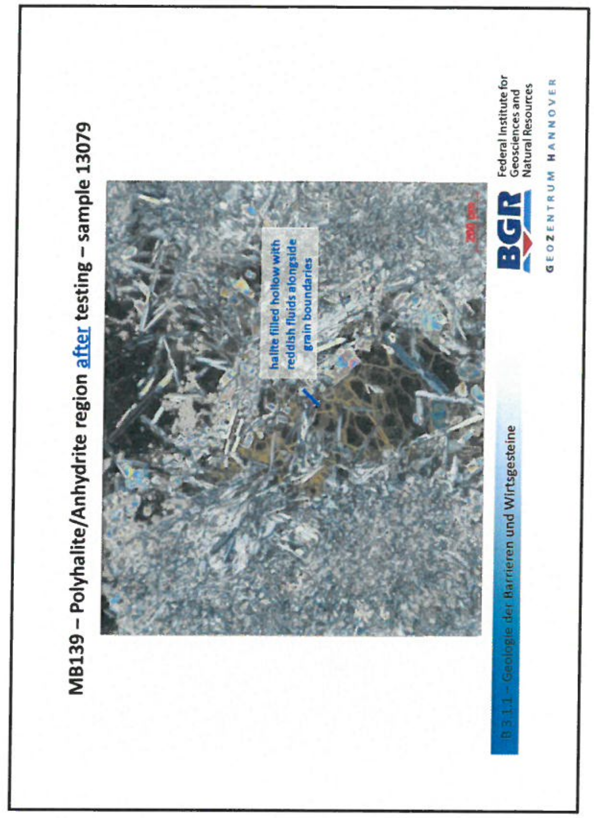
GEOZENTRUM HANNOVER


MB139 – Polyhalite/Anhydrite region after testing – sample 13079
halite filled hollow with reddish fluids alongside grain boundaries
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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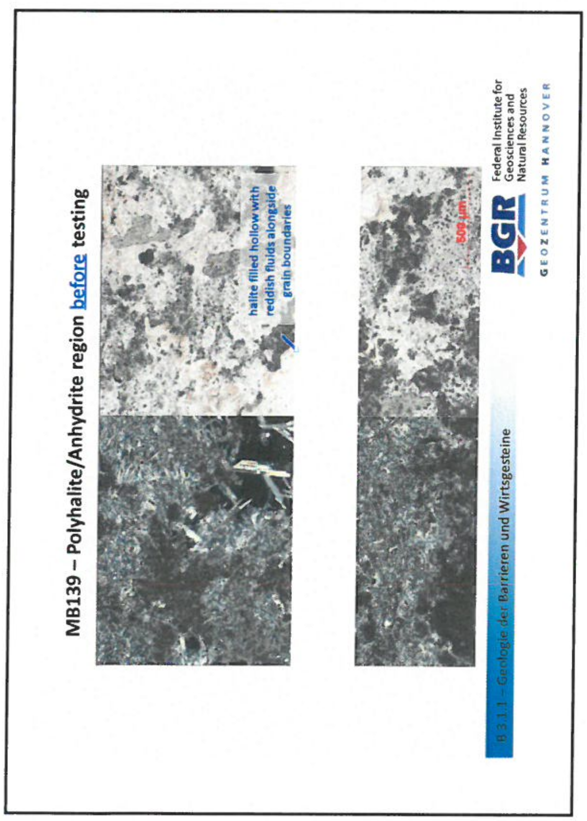
MB139 – Polyhalite/Anhydrite region before testing
halite filled hollow with reddish fluids alongside grain boundaries
500 µm
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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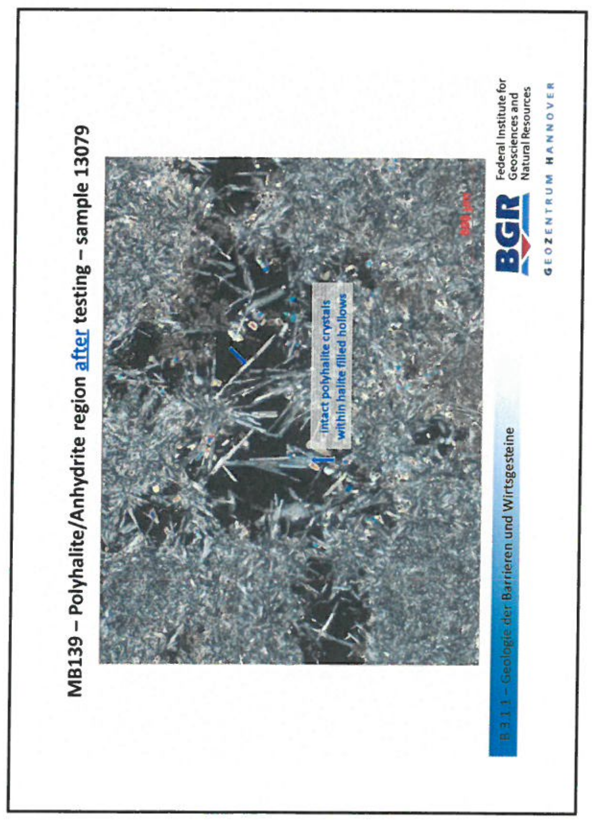
MB139 – Polyhalite/Anhydrite region after testing – sample 13079
intact polyhalite crystals within halite filled hollows
500 µm
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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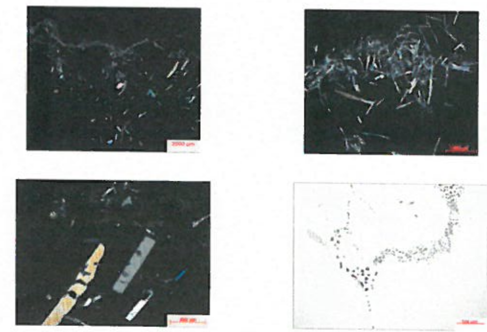
WIPP-drilling SNLCV/301

MB139 – Polyhalite/Clay enriched Halite region before testing



B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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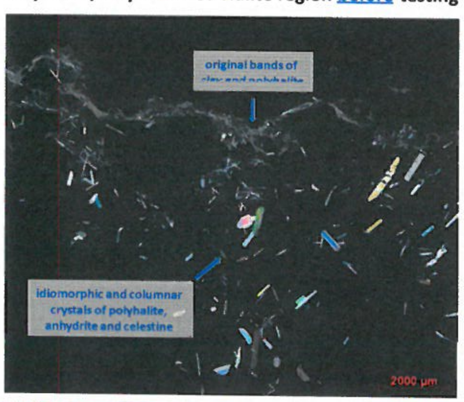
Polyhalite/Clay enriched Halite region before testing



B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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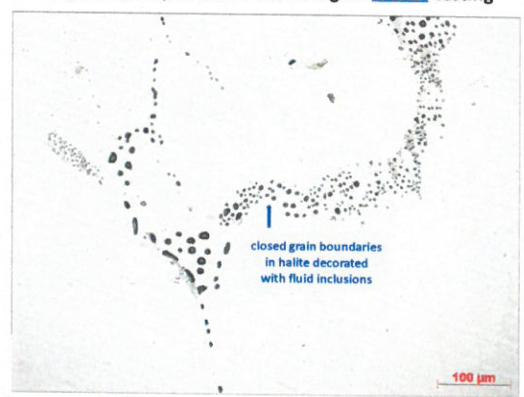
Polyhalite/Clay enriched Halite region before testing



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Summarized observations

Polyhalite/Anhydrite dominated WIPP salt after uniaxial testing

- Large and intact crystals and aggregates of polyhalite or anhydrite, even in halite filled hollows
- Reddish-brownish colored halite-grain boundaries in polyhalite pockets
- No visible increase of cracks; only a few disruptions of anhydrite and polyhalite aggreates occur

B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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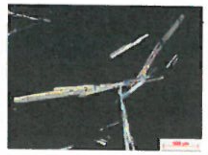
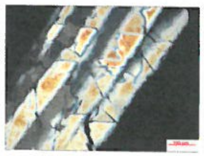
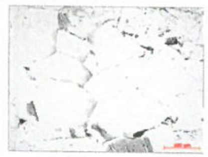
WIPP-drilling SNLCV/302/08 (sample 13080)
MB139 – Polyhalite/Clay enriched Halite region after testing
(σ1 = 14 MPa / 70 d | 16 MPa / 70 d; 22 °C; r. F. 45%; uniaxial creeping-test)

B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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Polyhalite/Clay enriched Halite region after testing – sample 13080

B 3.1.1 – Geologie der Barrieren und Wirtsgesteine

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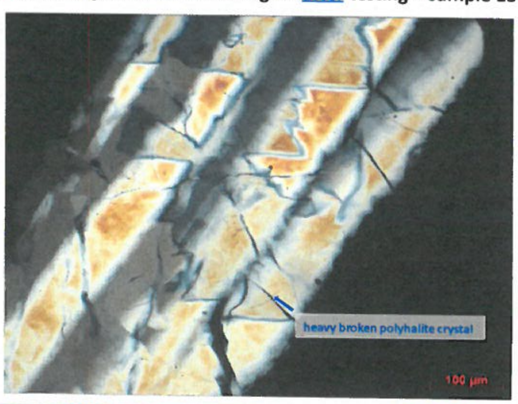
Polyhalite/Clay enriched Halite region after testing – sample 13080



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Summarized observations
Polyhalite and clay/anhydrite enriched WIPP-halite after uniaxial testing

- Opened halite-halite grain boundaries
- No significant increase in broken or deformed crystals of polyhalite/anhydrite
- Intact bands of anhydrite/polyhalite/clay or cluster of polyhalite aggregates are still visible

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Halite region before testing
intact and closed halite-halite grain boundaries
500 µm
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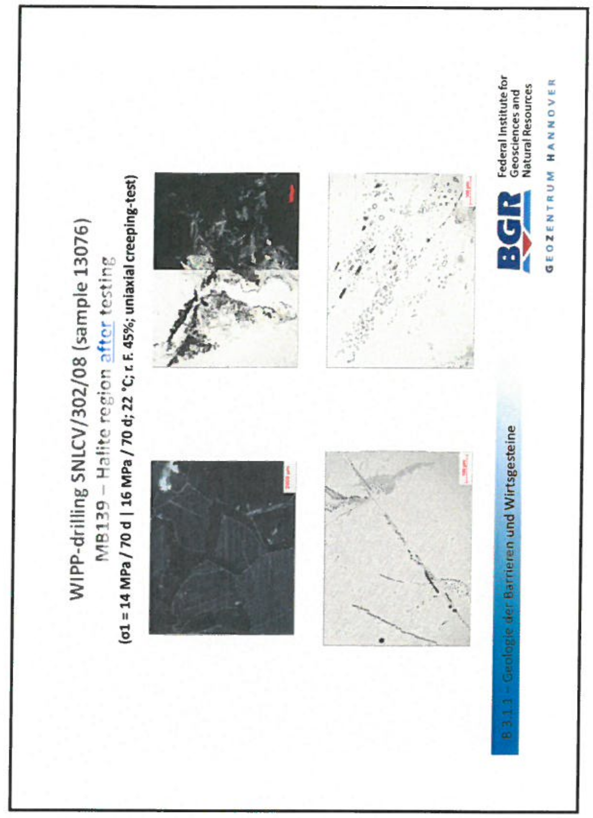
WIPP-drilling SNLCV/302/08 (sample 13076)
MB139 – Halite region after testing
(σ1 = 14 MPa / 70 d | 16 MPa / 70 d; 22 °C; r. F. 45%; uniaxial creeping-test)
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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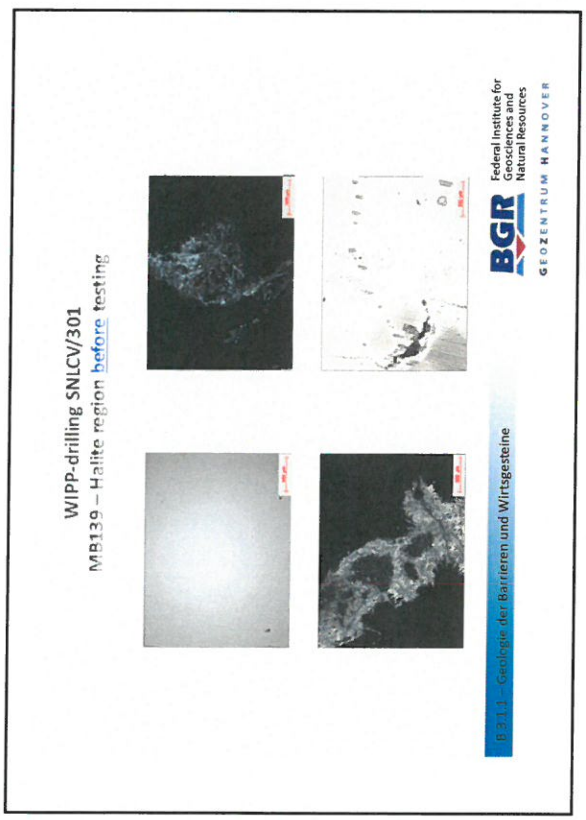
WIPP-drilling SNLCV/301
MB139 – Halite region before testing
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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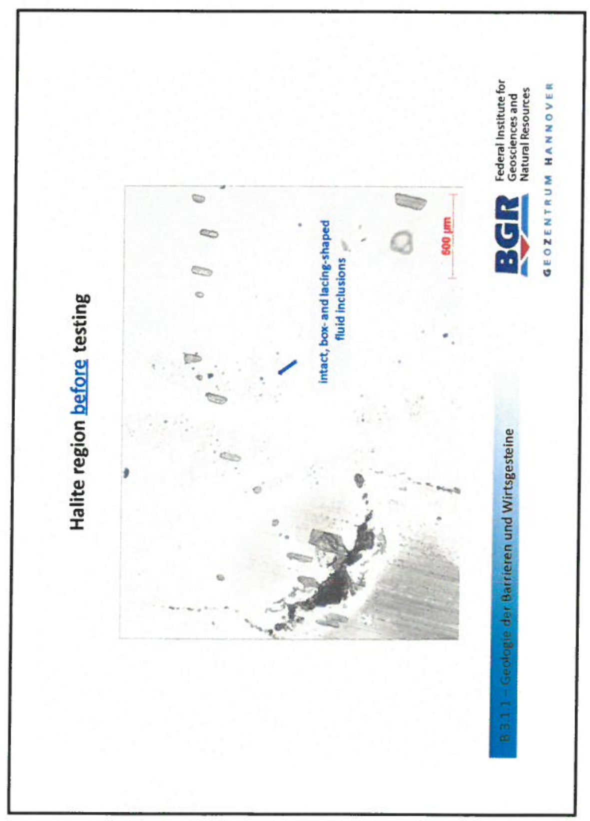
Halite region before testing
intact, box- and lacing-shaped fluid inclusions
500 µm
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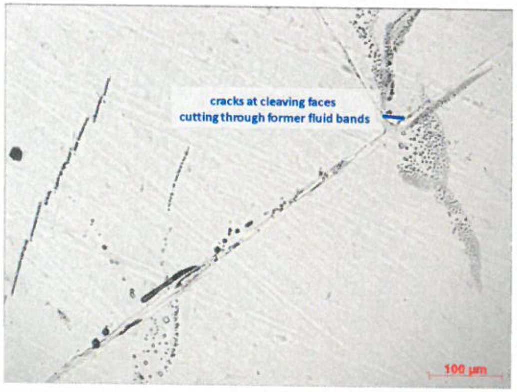
Halite region after testing – sample 13076



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Summarized observations WIPP
halite region after uniaxial testing

- Heavy cracked and wide opened halite-halite grain boundaries, even through polyhalite aggregates
- Cracks and cleavage faces are crossing intact fluid bands with box-shaped (incl. gas-phases) fluid inclusions

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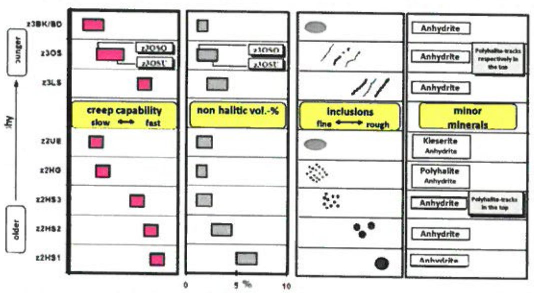
Geomechanical investigations



Correlation of creep behaviour and several texture properties of different types of rock salt from Gorleben salt dome (HUNSCHE et al. 2003).

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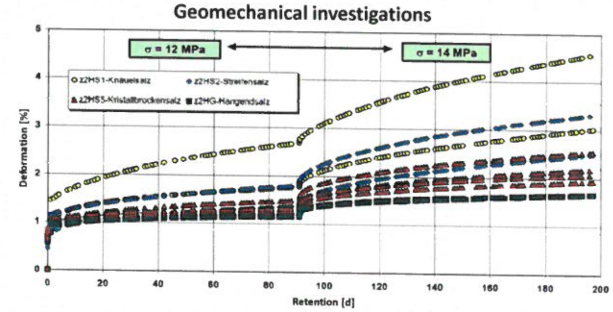
Geomechanical investigations



Results of uniaxial creeping tests (T = 22 °C) on rock salt samples of the Staßfurt-Formation (z2) from drilling Go 1002 (salt dome Gorleben). The stationary creeping rates of Knäuelsalz (z2HS1) differ about more than one dimension as the creeping rates of Hangendsalz (z2HG; HUNSCHE et al. 2003)

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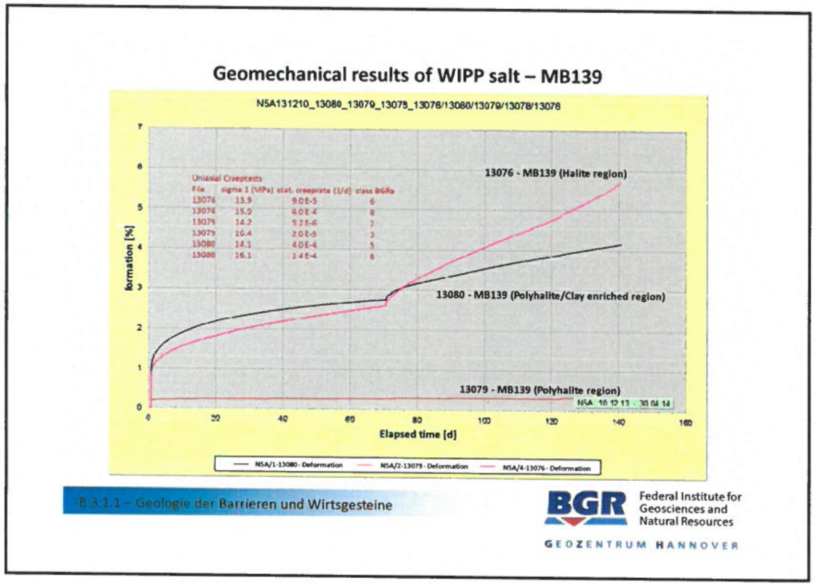
Geomechanical results of WIPP salt – MB139
N5A131210_13080_13079_13075_13076/13080/13079/13078/13076
13076 - MB139 (Halite region)
13080 - MB139 (Polyhalite/Clay enriched region)
13079 - MB139 (Polyhalite region)
Elapsed time [d]
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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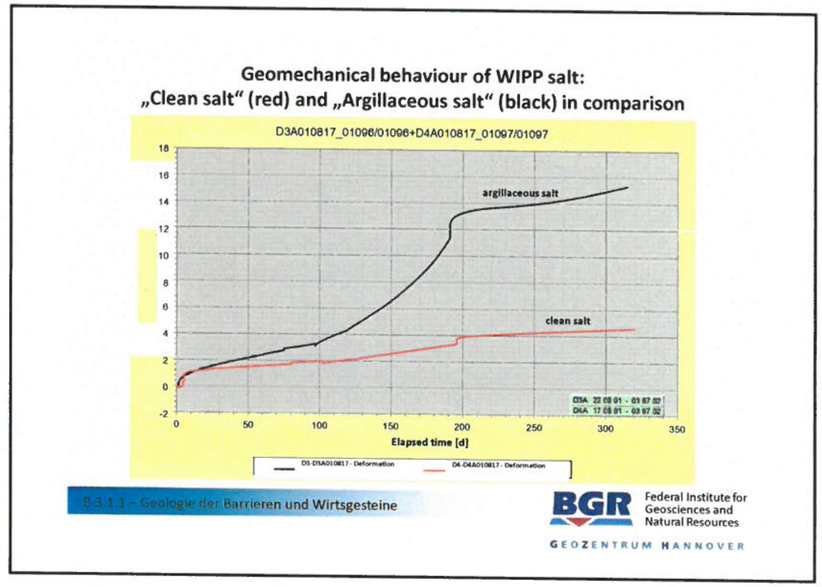
Geomechanical behaviour of WIPP salt:
„Clean salt" (red) and „Argillaceous salt" (black) in comparison
D3A010817_01096/01096+D4A010817_01097/01097
argillaceous salt
clean salt
Elapsed time [d]
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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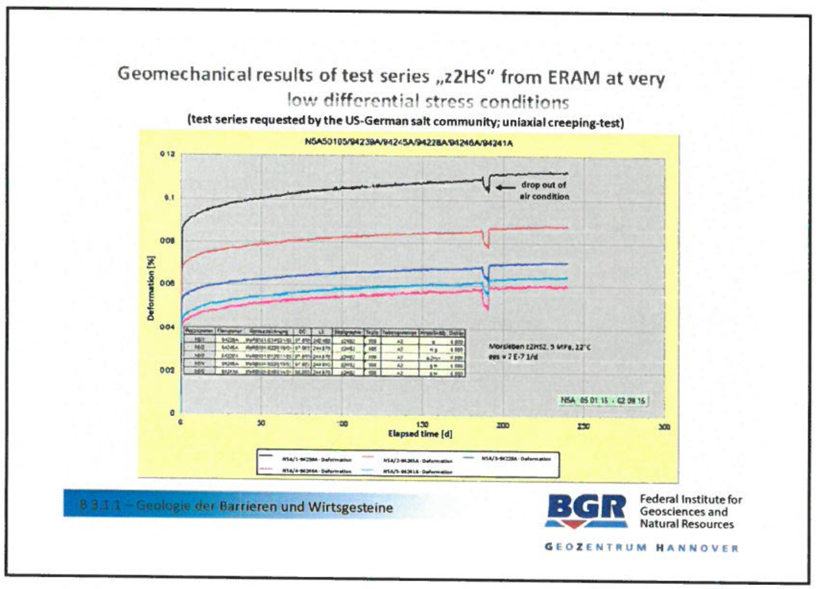
Geomechanical results of test series „z2HS" from ERAM at very low differential stress conditions
(test series requested by the US-German salt community; uniaxial creeping-test)
N5A50105/94239A/94245A/94228A/94246A/94241A
drop out of air condition
Deformation [%]
Elapsed time [d]
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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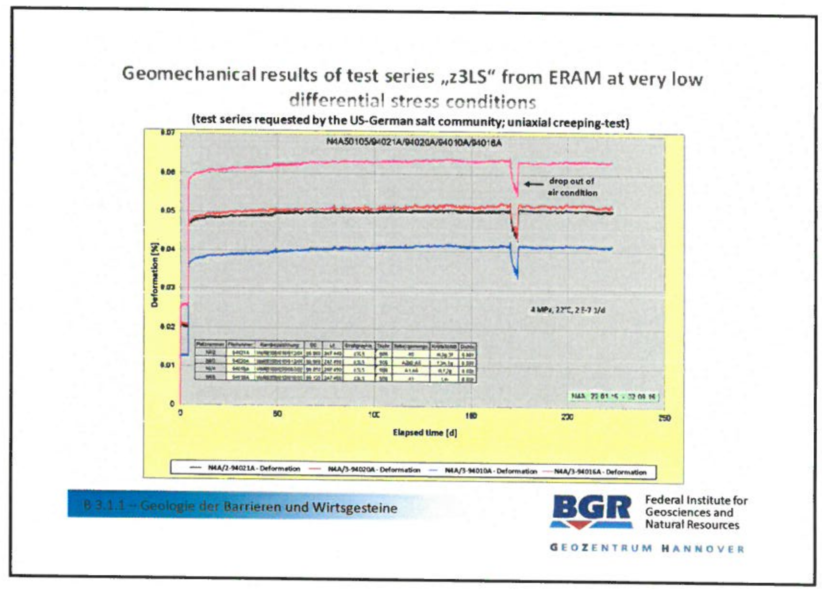
Geomechanical results of test series „z3LS" from ERAM at very low differential stress conditions
(test series requested by the US-German salt community; uniaxial creeping-test)
N4A50105/94021A/94020A/94010A/94016A
drop out of air condition
Deformation [%]
Elapsed time [d]
B 3.1.1 – Geologie der Barrieren und Wirtsgesteine
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Exceptional service in the national interest

Sandia National Laboratories

Comparison of Confined Constant Strain Rate Strength Tests Performed on WIPP "Clean" Salt

Stuart A. Buchholz
RESPEC

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories | DBE TEC | PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology | NNSA | U.S. Department of Energy

Introduction

- Scope of Work
  - Perform a subset of confined triaxial, constant-strain-rate strength tests on intact WIPP "clean" salt

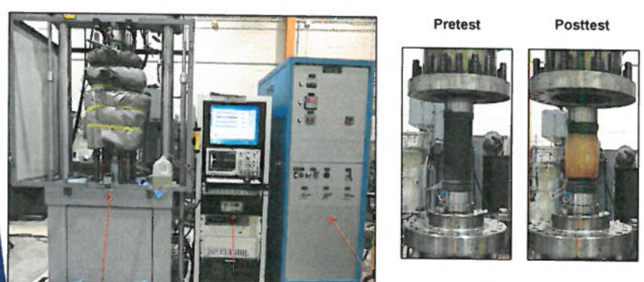
Test Conditions

Confining Pressure (MPa)	Strain Rate (1/s)	Temperature (°C)
0.2, 1.0, 3.0, 20.0	1x10[illegible]	25.0
0.2, 1.0, 3.0, 20.0	1x10[illegible]	100.0

  - Compare results to the much larger test matrix conducted by German laboratories
- Importance to the International Salt Repository Research
  - If the results substantially agree with the German results, the overall database will be considered more robust
  - When combined, the total database of laboratory results will be used to develop input parameters for models to predict material behavior

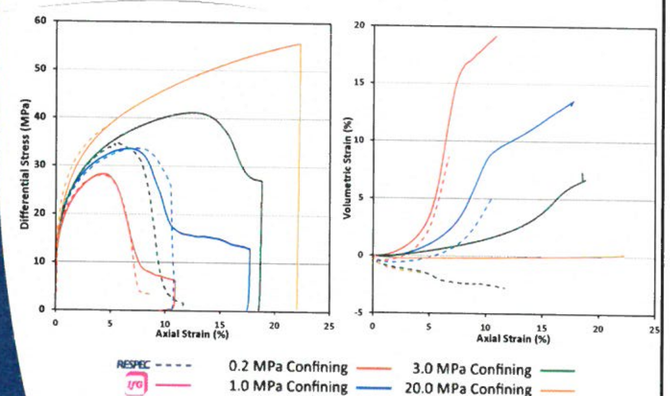
RESPEC

Testing Photographs



RESPEC

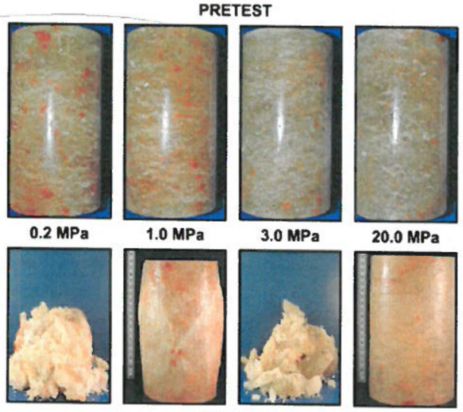
Triaxial Strength Tests (10^{-5} /s, 25°C)



- Axial strains match well at lower confining pressures
- RESPEC data shows considerably more compaction

RESPEC

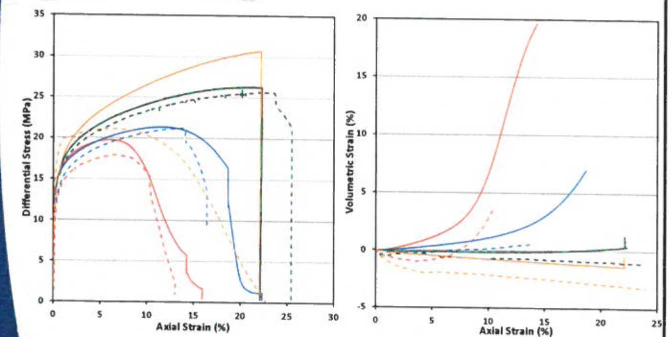
Photographs, 25°C Tests



RESPEC

- 3.0 MPa test failed prematurely
- Axial strain of 20.0 MPa test was limited by the axial force capacity of the test frame

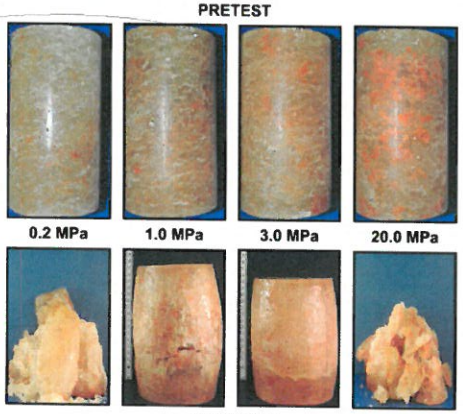
Triaxial Strength Tests (10^{-5} /s, 100°C)



RESPEC

- Axial strains match well at lower confining pressures
- RESPEC data shows considerably more compaction

Photographs, 100°C Tests



RESPEC

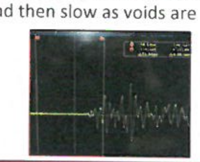
- Brittle to ductile behavior
- 20.0 MPa test failed prematurely

Dilation Determination Methods

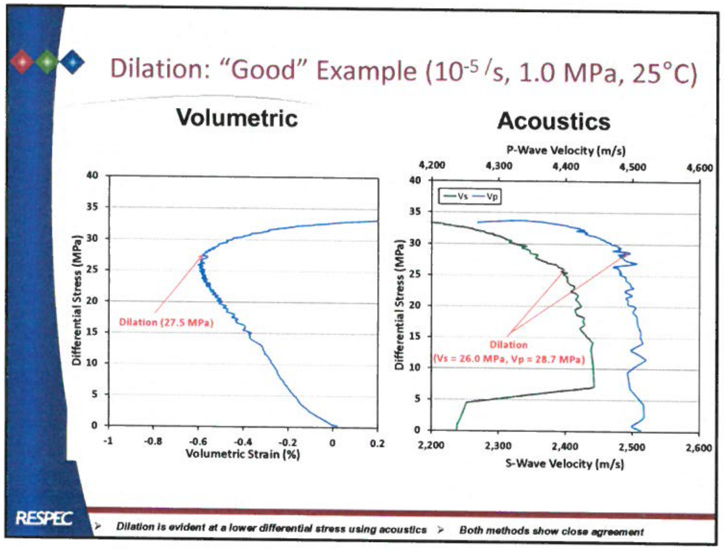
- **Volumetric Strain Measurement**

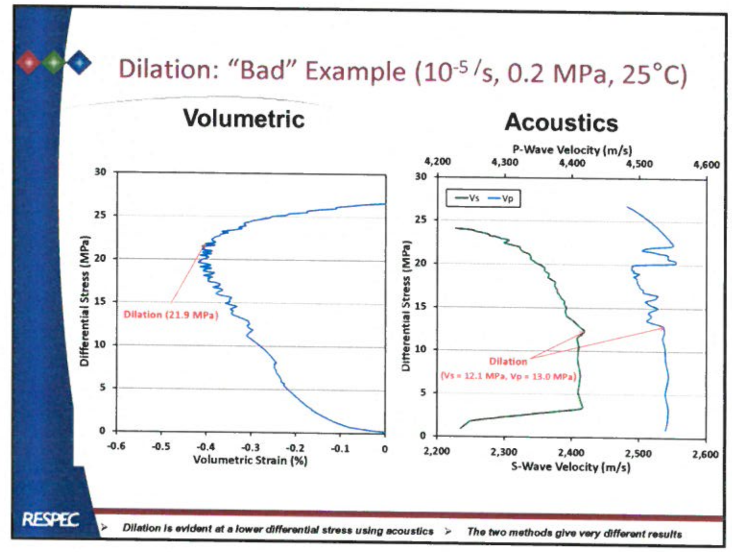
  "Change in slope of volumetric strain curve from compaction to volume expansion, indicating microfracturing (creation of voids) or dilation"
  - Limitations
    - Uses oil displacement for measurement (large volume of oil with regard to volumetric strain, system leaks, corrections)
    - Data interpretation
- **Acoustic Measurement**

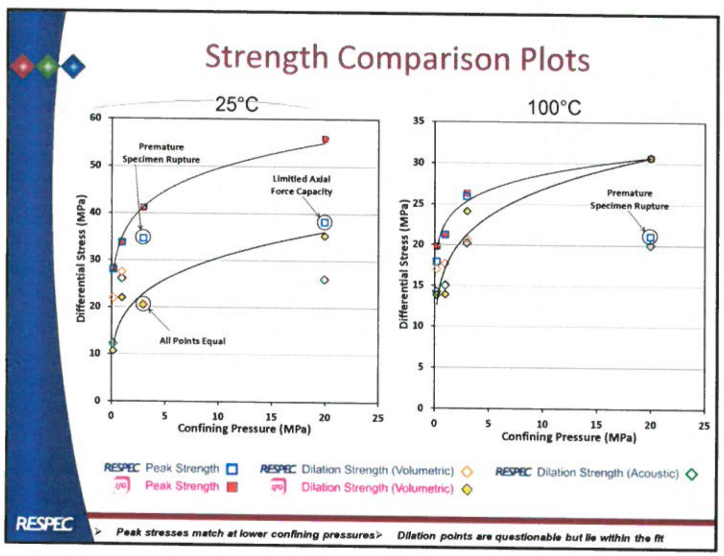
  "Change in slope of shear and compressional wave velocities, wave speeds increase as specimen compacts and then slow as voids are created, indicating dilation"
  - Limitations
    - Signal quality
    - Data Interpretation

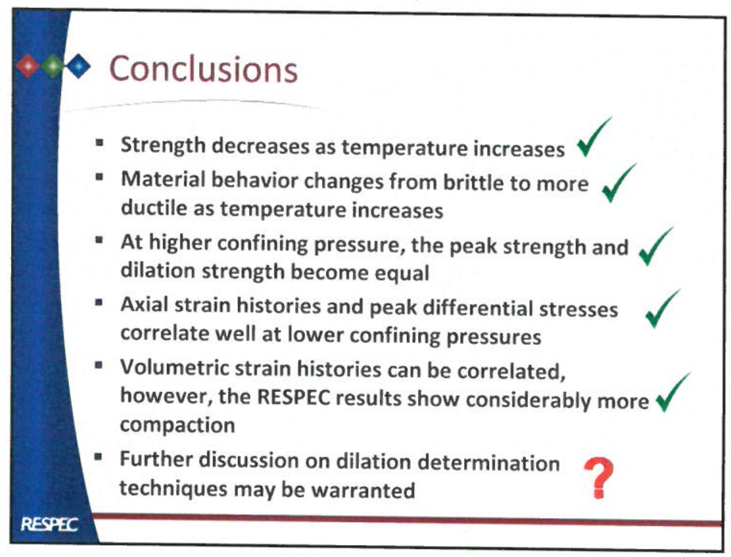


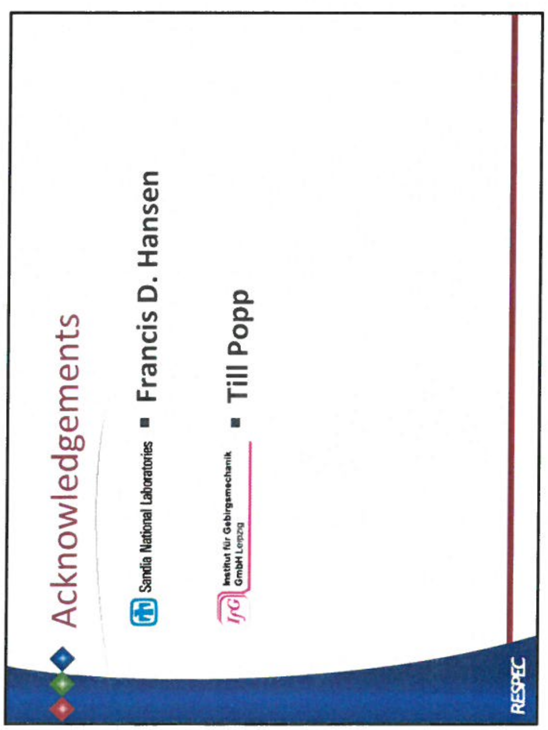
RESPEC

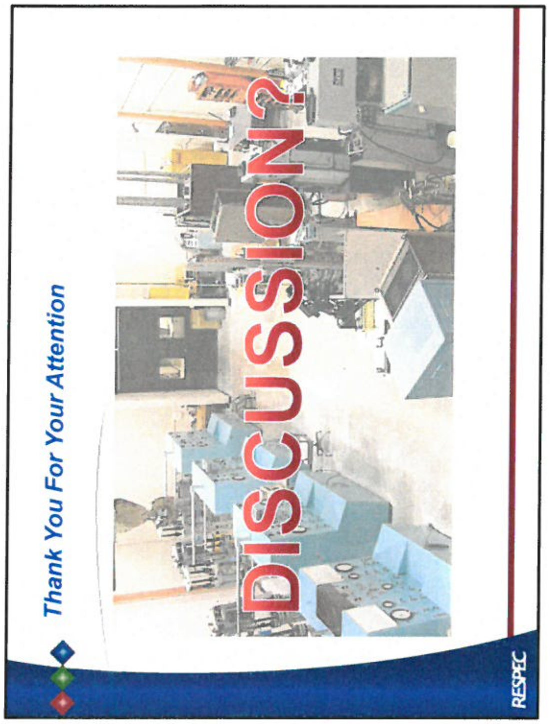

Dilation: "Good" Example (10-5/s, 1.0 MPa, 25°C)
Volumetric
Acoustics
Differential Stress (MPa)
Volumetric Strain (%)
Dilation (27.5 MPa)
P-Wave Velocity (m/s)
S-Wave Velocity (m/s)
Vs
Vp
Dilation
(Vs = 26.0 MPa, Vp = 28.7 MPa)
RESPEC
Dilation is evident at a lower differential stress using acoustics
Both methods show close agreement


Dilation: "Bad" Example (10-5/s, 0.2 MPa, 25°C)
Volumetric
Acoustics
Differential Stress (MPa)
Volumetric Strain (%)
Dilation (21.9 MPa)
P-Wave Velocity (m/s)
S-Wave Velocity (m/s)
Vs
Vp
Dilation
(Vs = 12.1 MPa, Vp = 13.0 MPa)
RESPEC
Dilation is evident at a lower differential stress using acoustics
The two methods give very different results


Strength Comparison Plots
25°C
100°C
Differential Stress (MPa)
Confining Pressure (MPa)
Premature Specimen Rupture
Limited Axial Force Capacity
All Points Equal
Premature Specimen Rupture
RESPEC Peak Strength
Peak Strength
RESPEC Dilation Strength (Volumetric)
Dilation Strength (Volumetric)
RESPEC Dilation Strength (Acoustic)
RESPEC
Peak stresses match at lower confining pressures
Dilation points are questionable but lie within the fit


Conclusions
Strength decreases as temperature increases
Material behavior changes from brittle to more ductile as temperature increases
At higher confining pressure, the peak strength and dilation strength become equal
Axial strain histories and peak differential stresses correlate well at lower confining pressures
Volumetric strain histories can be correlated, however, the RESPEC results show considerably more compaction
Further discussion on dilation determination techniques may be warranted
RESPEC


Acknowledgements
Sandia National Laboratories
Francis D. Hansen
Institut für Gebirgsmechanik GmbH Leipzig
Till Popp
RESPEC


Thank You For Your Attention
DISCUSSION?
RESPEC

Compilation of salt dilation test data for assessment for variability

Lance A. Roberts, Ph.D., P.E.
South Dakota School of Mines and Technology

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

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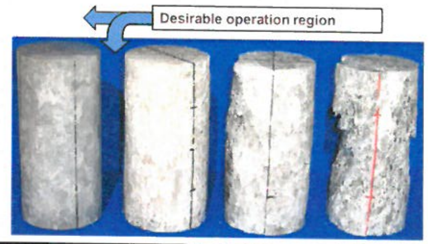
Introduction

Three geomechanical criteria govern salt cavern designs:

- Time-dependent behavior (creep)
- Tensile stresses
- Dilation

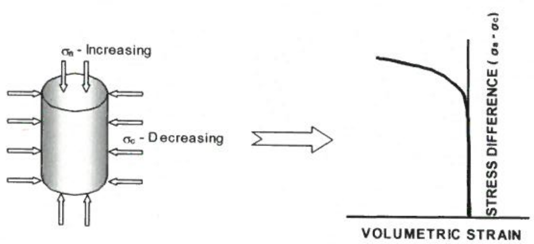
With respect to dilation:

- Must maintain stress conditions below the dilation threshold
- Dilation threshold is determined from laboratory testing

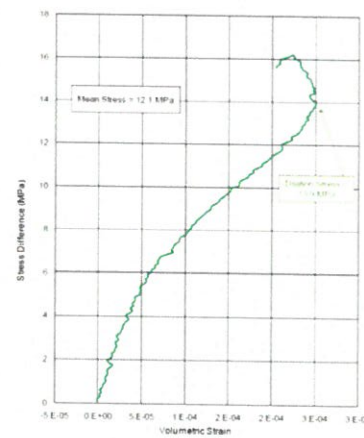


Constant Mean Stress Test

- Specimen subjected to hydrostatic confinement
- Deviatoric stress on specimen is increased while the confining pressure is decreased such that the mean stress on the specimen remains constant
- Volumetric strain is computed and monitored during the test



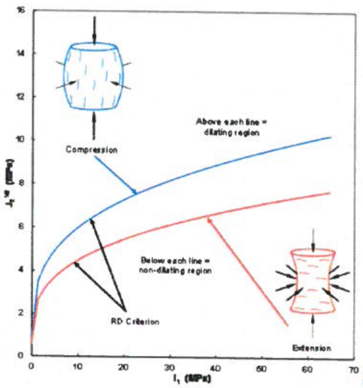
Constant Mean Stress Test



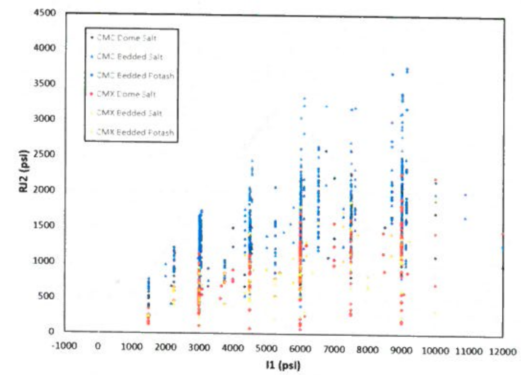
Dilation Limit

- CMS tests conducted in both compression and extension
- Dilation limit from each test plotted with respect to stress invariants
- Various criteria used to fit the data
- Ideally, limit stresses within cavern to levels below the dilation criteria line

$$\sqrt{J_{2,dil}} = \left(D_1 (I_1/\sigma_0)^n + T_0\right) / \left(\sqrt{3}\cos\psi - D_2 \sin\psi\right)$$

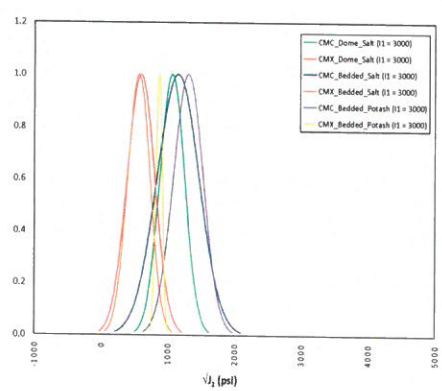


Variability in Dilation Test Data



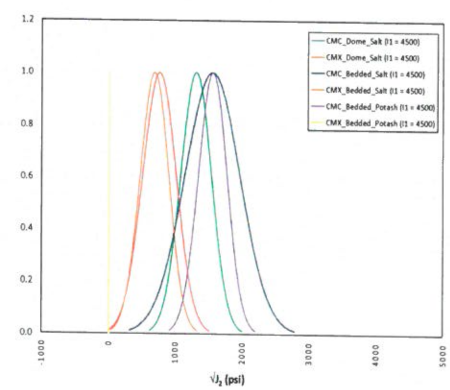
Measured dilational stresses for several subsets of data.

Variability in Dilation Test Data

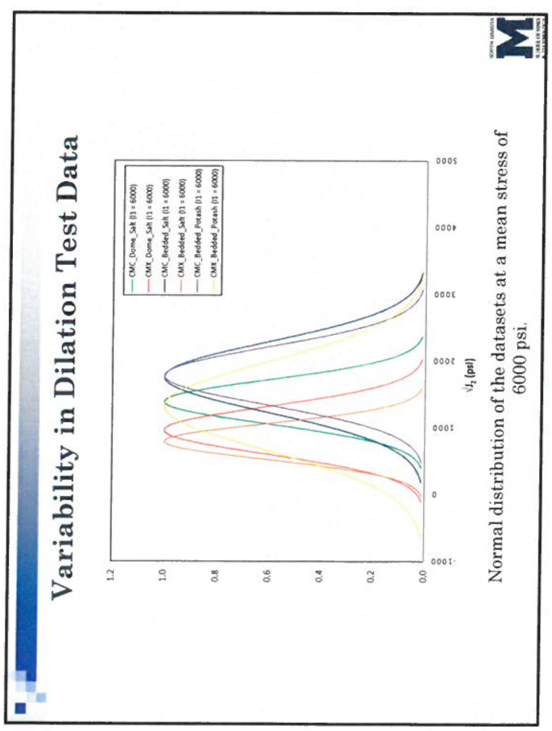


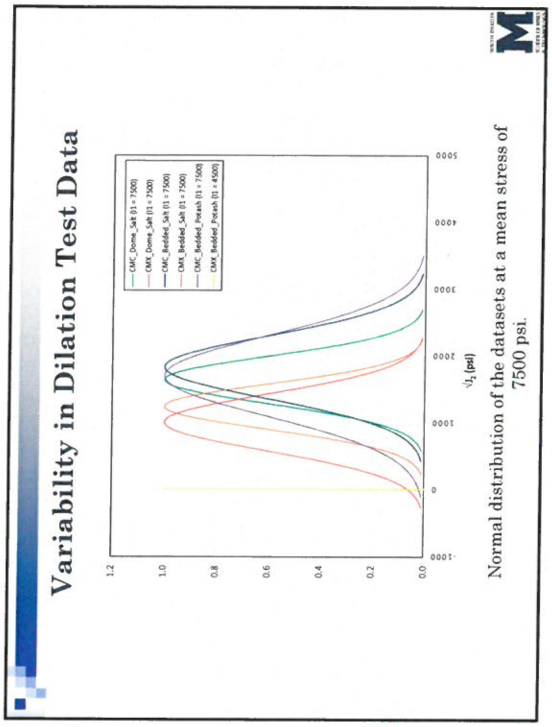
Normal distribution of the datasets at a mean stress of 3000 psi.

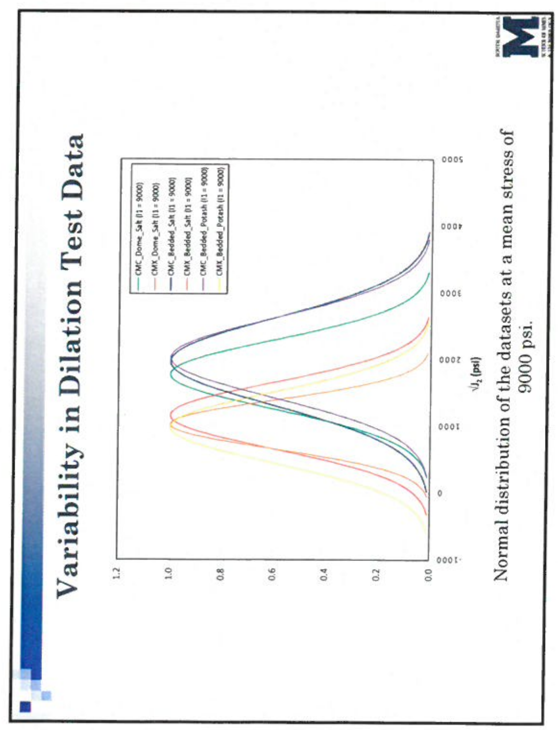
Variability in Dilation Test Data

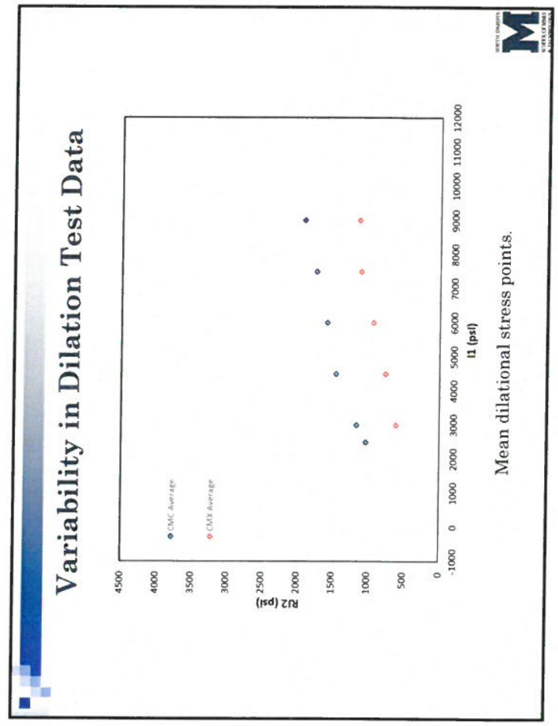


Normal distribution of the datasets at a mean stress of 4500 psi.

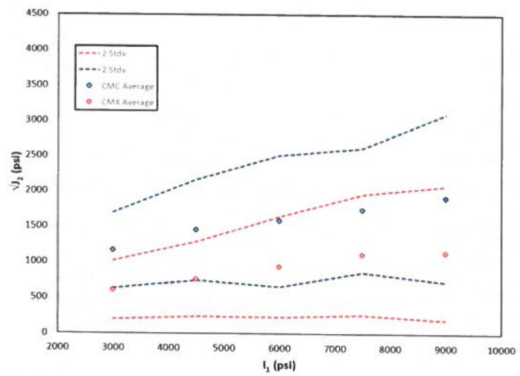

Variability in Dilation Test Data
√J2 (psi)
Normal distribution of the datasets at a mean stress of 6000 psi.


Variability in Dilation Test Data
√J2 (psi)
Normal distribution of the datasets at a mean stress of 7500 psi.


Variability in Dilation Test Data
√J2 (psi)
Normal distribution of the datasets at a mean stress of 9000 psi.


Variability in Dilation Test Data
CMC Average
CMX Average
I1 (psi)
RJ2 (psi)
Mean dilational stress points.

Variability in Dilation Test Data



Mean dilational stress points with standard deviation.

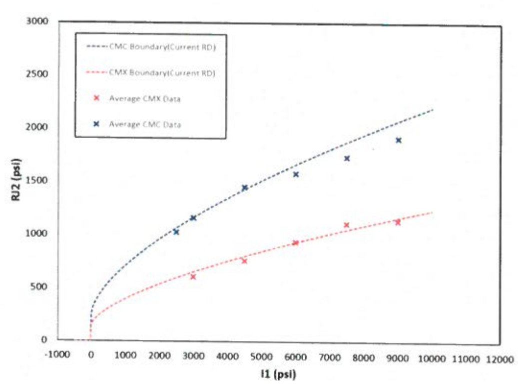
Methodology

- The RESPEC Dilation (RD) criterion contains three fitting variables: D_1, D_2, and n.

$$\sqrt{J_{2,\text{dil}}} = \left(D_1\left(I_1/\sigma_0\right)^n + T_0\right) / \left(\sqrt{3}\cos\psi - D_2\sin\psi\right)$$

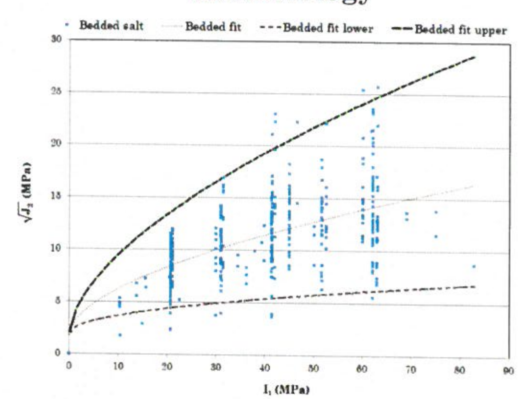
- Examine range in variability of dilation strength by fitting RD criterion to maximum, minimum, and average within laboratory data.
- This can be accomplished by changing the fitting variables.

Methodology



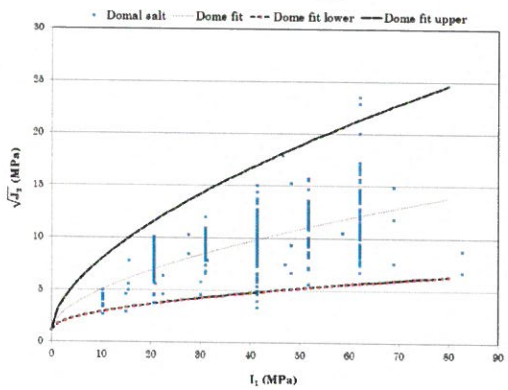
Fit to the mean dilational stress points (CMC and CMX data)

Methodology



Variability in dilation strength for bedded salt (CMC data).

Methodology



Variability in dilation strength for domal salt (CMC data).

Methodology

		D_1 (MPa)	D_2	n	T_o (MPa)
	Minimum	0.66	0.90	0.47	–
Bedded	Mean	1.19	0.96	0.57	1.92
	Maximum	1.90	1.00	0.60	–
	Minimum	0.66	0.55	0.52	–
Domal	Mean	1.23	0.61	0.57	1.40
	Maximum	1.90	0.75	0.60	–

Coefficient of variation (COV) for fitting variables for bedded salt:

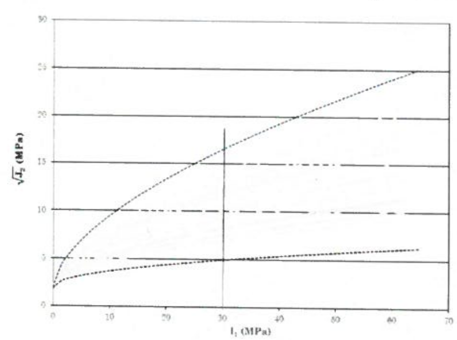
D_1 = 20%

D_2 = 3%

n = 5%

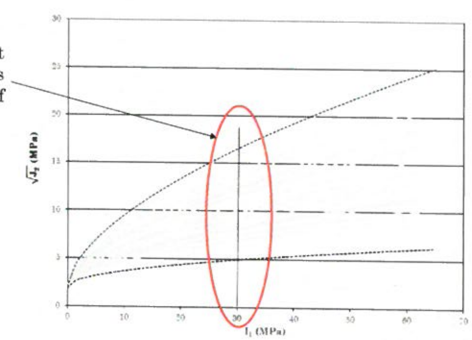
Latin Hypercube

- Now, conduct a Latin Hypercube simulation using the RD criterion and COV of the fitting variables. This will result in the generation of thousands of dilation strength curves:



Analysis of RD Criterion Curves

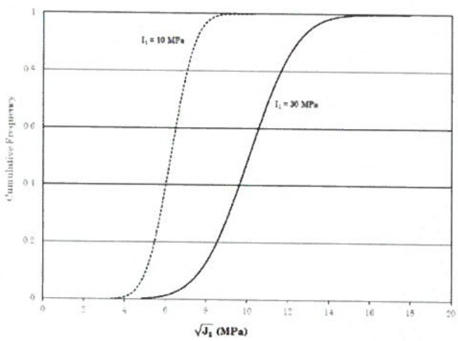
- Once the curves are generated, it is possible to "cut" the curves at a value of I_1 (mean stress):



Analysis of RD Criterion Curves

- The range of values for $\sqrt{J_2}$ can be visualized as a cumulative distribution function and the statistics can be computed:

Statistics (30 MPa)
μ = 10.08 MPa
σ = 1.84 MPa

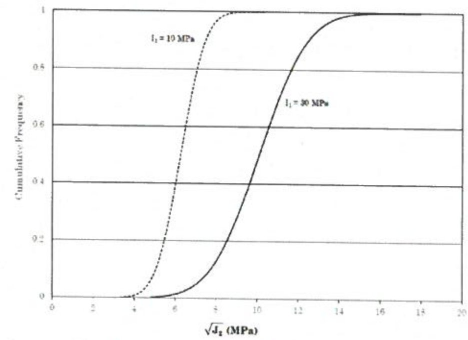


Analysis of RD Criterion Curves

- The last step is to determine a "probability of exceedance" given a value of $\sqrt{J_2}$ within an element of interest:

Example
$\sqrt{J_2}$ = 8.25 MPa
Exceedance = 16%

$\sqrt{J_2}$ = 6.05 MPa
Exceedance = 2%



Probability of exceedance = likelihood of exceeding the dilation criterion.

Probability of Exceedance

- The probability of exceedance, p_f, can be related to a target reliability index, β_T, or expectation of performance:

β_T	p_f	Expected Performance
0	0.500	-
0.5	0.309	-
1.0	0.159	Hazardous
1.5	0.067	Unsatisfactory
2.0	0.023	Poor
2.5	0.006	Below average
3.0	0.001	Above average
3.5	0.0002	-
4.0	0.00003	Good
4.5	0.000003	-
5.0	0.0000003	High

Typical range: 2.0 – 3.5

Adapted from U.S. Army Corps of Engineers 1997, Table B-1

Conclusions / Discussion

- Variability within data for the dilational strength of salt exists.
- Although the database is large, variability is often realized on a project specific basis as well.
- Using a factor of safety approach, variability cannot be directly accounted for in the design.
- A probabilistic method can replace the traditional factor of safety approach and can incorporate variability into the design.
- Probabilistic design methods have long been implemented in structural engineering design, but have only recently been incorporated in geotechnical engineering.

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PTKA

Dilatancy of rock salt – load path effects

Jan-Martin Hertzsch, Otto Schulze, Werner Gräsle
BGR, Hannover

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

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Deformation effects and phases in rock salt

Elastic deformation
↓
transient and stationary creep at constant volume
↙ above dilatancy boundary, microcracks develop
↘ below dilatancy boundary, cracks heal

above dilatancy boundary, microcracks develop:
- increasing permeability ↔ dilatancy & damage
- increasing permeability → permeation
- dilatancy & damage → humidity-induced creep
- dilatancy & damage → loss of load-bearing capacity
- dilatancy & damage → tertiary creep
- dilatancy & damage → creep fracture → post-fracture behavior

σ_{eff} increasing

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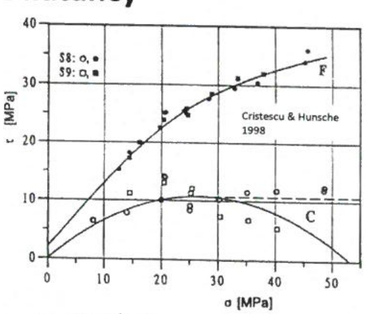
Dilatancy

Signs of dilatancy:
- volume increase under stress
- decrease of seismic wave velocities
- increasing permeability
- increasing acoustic emissions
- increased influence of humidity on creep

Dilatancy boundary = important long-term safety boundary



σ ... mean stress
τ ... shear stress
C ... dilatancy boundary
F ... failure surface

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Dilatancy boundary (rock salt)

In octahedral (invariant) representation:

$\sigma_o = (\sigma_1 + \sigma_2 + \sigma_3)/3$ $\tau_o = ((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)^{0.5}/3$

Cristescu & Hunsche (1998) *(C&H 1998)*:

$$\tau_{o,Dil(2)} = -0.01697 \cdot \sigma_o^2 + 0.8996 \cdot \sigma_o$$

conservative formulation → lower limit: onset of microfractures

Hunsche et al. (2003) *(Go 2003)*:

σ < 50 MPa, samples from several locations, compression tests

$$\tau_{eff,Dil(1)} = 2.61 \cdot \sigma_o^{0.78}$$

with $\tau_{eff,Dil(1)} = \tau_{o,Dil(1)} \cdot \sqrt{3}$

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Dilatancy boundary (rock salt)

Considerable scatter due to:

- variety of effects used to determine boundary
- slow onset of dilatancy and damage
- natural variability of samples

→ Dilatancy boundary is more a band than a clear-cut line.

Load path effects:

What happens if results for compression tests (m=-1) are extrapolated to extension (m=+1)?

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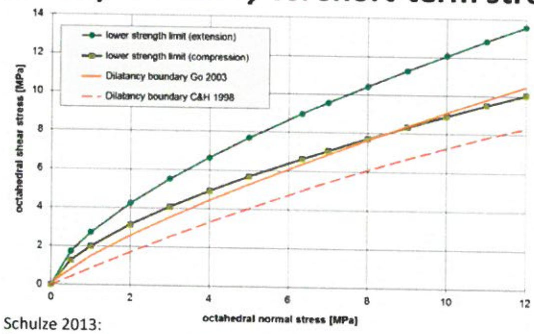
Dilatancy boundary vs. short-term strength



Schulze 2013:
"Go 2003" dilatancy boundary exceeds short-term strength in extension for high stresses
Still below strength limit for stresses relevant for short-term safety case

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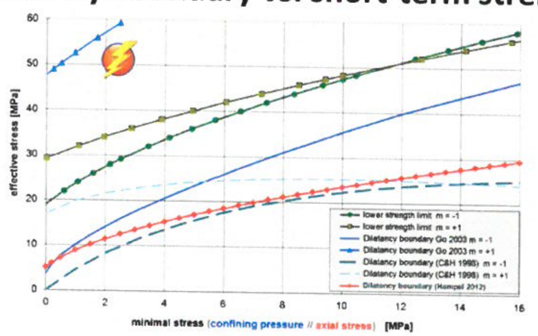
Dilatancy boundary vs. short-term strength



Schulze 2013: Transformation into "laboratory system"
→ OK for compression and for conservative (C&H) dilatancy boundary,
but: **Go 2003 boundary totally implausible for extension**!

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Dilatancy boundary vs. short-term strength

IfG 2011: C&H 1998: underprediction
Go 2003: overprediction → new formulation?

Hampel 2010 (AH):

- lower limit for onset of dilatancy in experiments

$$\sigma_{eff,Dil}(\sigma_{min}) = (a_{Dil} \cdot (\sigma_{min} + b_{Dil}))^{1/2}$$

- depends on minimal stress component
  → expected to be valid for arbitrary load paths
- non-zero for $\sigma_{min} = 0$
- C&H 1998 < AH < Go 2003
- agrees well with experimental results for other salt types

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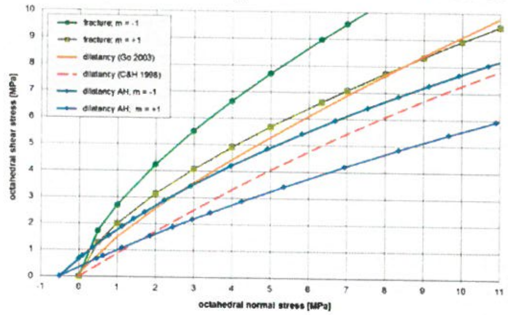
Dilatancy boundary vs. short-term strength



Schulze 2013: back-transformation to invariant formulation.
AH dilatancy boundary (extended CDM) is a suitable criterion.
Further experiments needed to supply data for studies of damage (support of r_v concept), and to investigate effects of texture.

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Further experiments (planned)

Salt Club:

- Various formulations exist for dilatancy boundary.
- Only few experiments have been performed for non-compressive load paths.
- Further investigations are necessary.

→ True triaxial tests are in preparation.

Study of various load paths:

compression: m = -1

$\sigma_1 > \sigma_2 = \sigma_3$

intermediate: m = 0

$\sigma_1 > \sigma_2 = \sigma_0 > \sigma_3$

extension: m = +1

$\sigma_1 < \sigma_2 = \sigma_3$

$\sigma_0 = (\sigma_1 + \sigma_2 + \sigma_3)/3$

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Further experiments (planned)

A true triaxial test rig is available in BGR's outpost in Grubenhagen.

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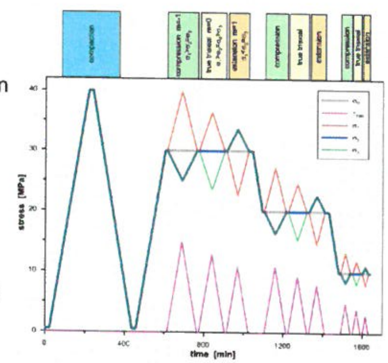
Further experiments (planned)

Test design:

- pre-compaction
- several stages of mean stress σ_0
- at each stage three load paths (compression, true triaxial, extension) until dilatancy starts (minimum of volume)
- maximizes use of sample material



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The concept of SN fuel and HLW disposal in salt rock in Poland

Leszek Lankof
The Mineral and Energy Economy Reserch Innstitute
Jarosław Ślizowski
Karolina Serbin
AGH University of Science and Technology

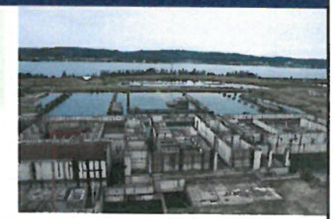
6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA Project Management Agency Karlsruhe · NNSA · U.S. Department of Energy

The plans of SNF & HLW repository siting in Poland

Governmental Research Program on siting Underground Repository of Radioactive Waste (the 80's of XX century) was developed in connection with the construction of the nuclear power plant Żarnowiec


Minister Gospodarki
Program polskiej energetyki jądrowej



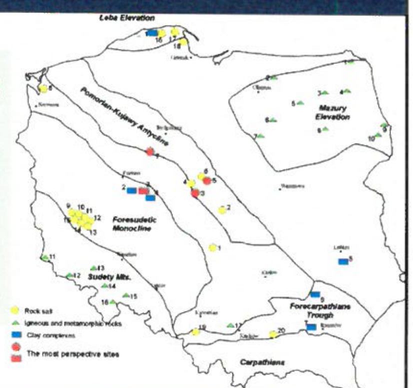
Governmental Research Program on Management of SN fuel and radioactive waste (1997-99)

Polish Nuclear Energy Program 2014 r. - The Ministry of Economy plans to provide the funds for research that will allow for siting of Polish Underground Research Laboratory.

Site selection - the most perspective sites

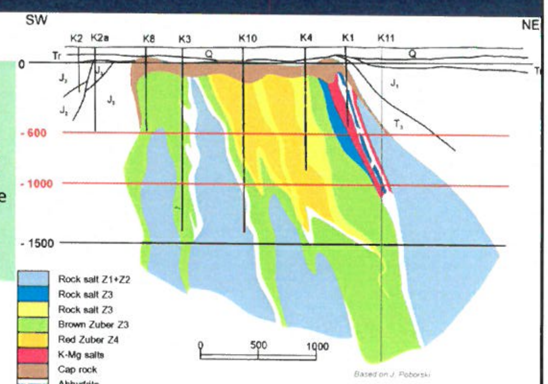
Salt domes in the Central Poland
- Kłodawa
- Damasławek,
- Łanięta,

Clay deposit
- Jarocin-Pogorzela region at the foresudetic monocline

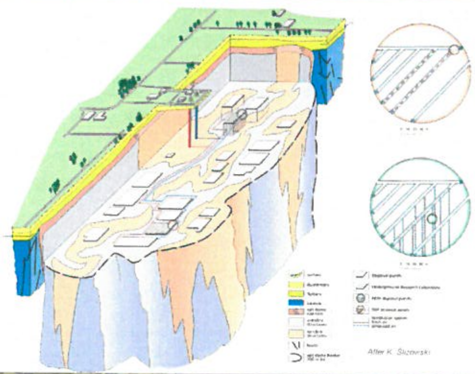


Kłodawa salt dome

Special attention was put on clayey salts (local name "zuber") occurring in Polish Zechstein formation in a large quantity at the depth suitable for repository siting.



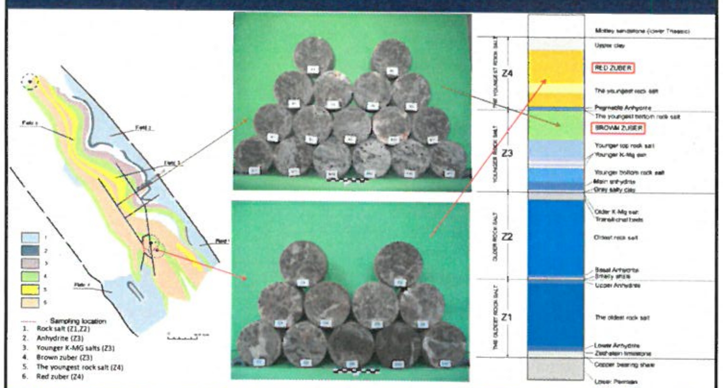
Conceptual model of SNF and HLW repository



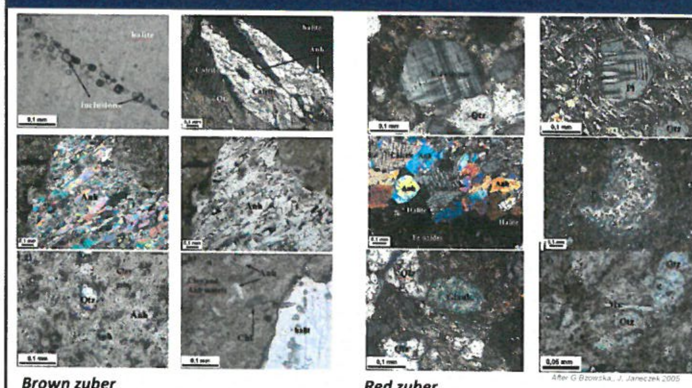
The scope of zubers investigations

- mineralogical and petrogrological properties
  - microscope observation
  - X-ray powder diffraction analysis
  - standard chemical analysis
  - energy dispersive X-ray analysis (EDX)
  - scanning electron microscope analysis (SEM)
- physical properties
  - permeability
  - porosity
  - content of water
- geomechanical properties of zubers
  - triaxial short-term compression tests in the constant load and the strain rate
  - long term creep tests in room temperature, in 60° C and in 90° C and in different effective stress conditions (7.5 – 20 MPa)
  - relaxation tests in different initial effective stress (20 MPa i 25 MPa) in in 60° C and in 90° C
- radionuclide immobilization tests
  - rate, kinetics, temperature dependence

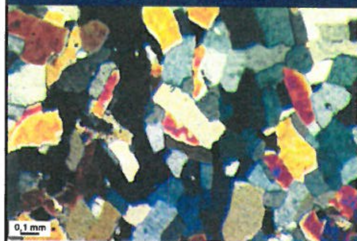
Sampling location



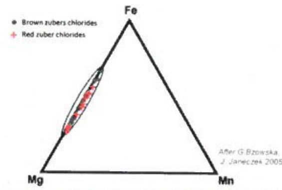
Mineral composition of zubers



Mineral composition of zubers



- The content of clay minerals ranges from 8 to 25%.
- Clay minerals consist mainly of illite, muscovite and Mg-Fe chlorides.



- The predominant mineral in insoluble parts is anhydrite (up to ~45%).

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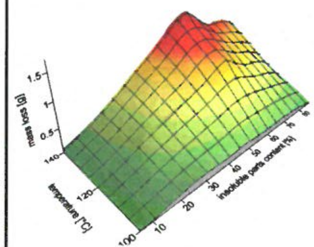
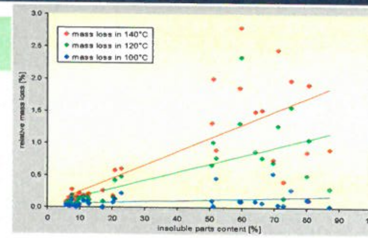
Brine content

To the temperature of 100°C the mass changes didn't exceed 0.7%.





The maximum changes of weight during the heating were noticed in temperature of 140°C in case of samples containing about 60% of insoluble parts.

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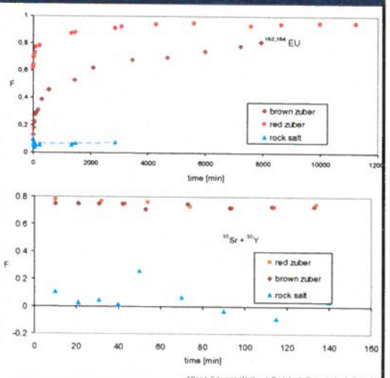
Radionuclide immobilization tests

- Sorption experiments with the radioactive isotopes of ^{90}Sr + ^{90}Y and $^{152,154}Eu$ have shown that in case of zubers capacity of sorption and retention for radionuclides is relatively high in comparison to rock salt.
- Zubers can be considered as the additional geological barrier preventing migration of radionuclides in a far field.



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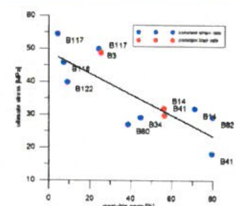
Short term compression tests

- Triaxial short-term compression tests show wide variety of strength parameter values.
- Mean values of effective stress and strain in destroying point were similar for brown and red zubers but they are lower than for rock salt.

	Effective stress constant load rate [MPa]	Effective stress constant strain rate [MPa]	Effective strain [%]
brown zuber	36,7	36,6	3,2
red zuber	46,6	37,7	3,8
Rock salt		71,0	11,3



- The strength values depend on content of insoluble parts (the higher content of insoluble parts the lower is effective stress and strain in destroying point).

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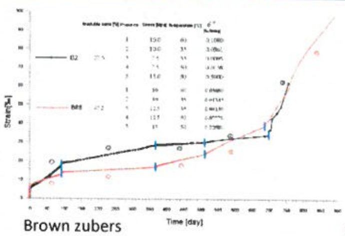
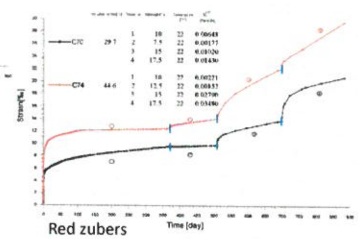
Long term creep tests



Long term creep tests in room temperature, in 60°C and in 90°C and in different effective stress conditions (7.5 – 20 MPa)



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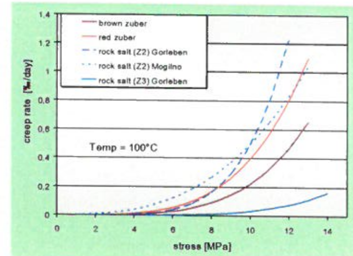
Stationary creep rate

The values of stationary creep for zubers are relatively high in comparison with different types of rock salts.

It means that zubers may be classified as rocks with high creep rate.



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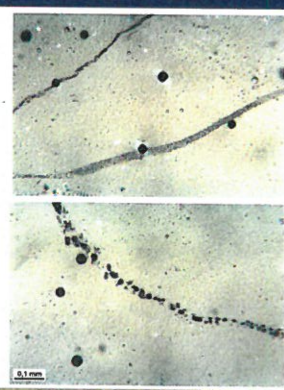
Stationary creep rate

- Investigation on the influence of mineral composition on the stationary creep rate revealed that creep rate may depend on:
  - presence of different type of inclusions (containing gas, brines and hydrocarbons)
  - content of clay minerals.



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Conclusions

- The researches carried out allowed to choose the most perspective sites for underground repository of SNF and HLW
- Special attention was put on zubers which occur in large quantities at depths suitable for siting underground repositories
- The aim of zubers research program was to determine:
  - mineralogical and petrogrological properties
  - physical properties
  - geomechanical properties of zubers
  - radionuclide immobilization tests
- The preliminary results of carried out research does not excluded zubers as a host rock for siting underground repositories.
- Although the preliminary concept of the Uderground Research Laboratory was elaborated, no in-situ demonstration tests on rock salt and zubers were carried out so far.

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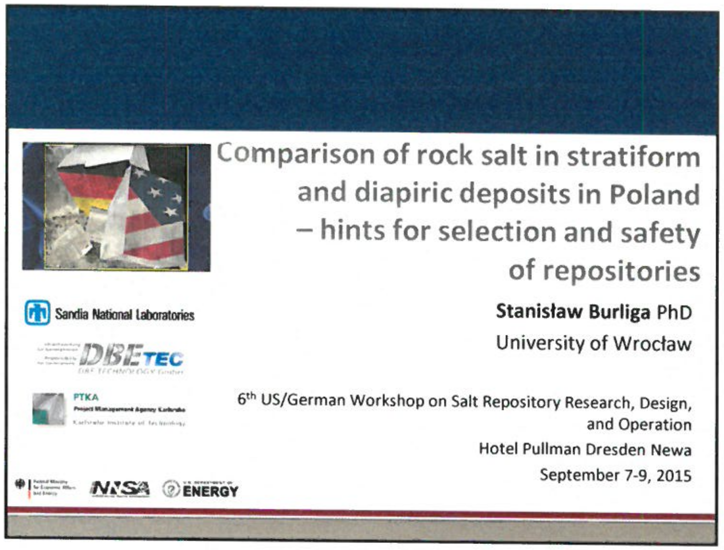
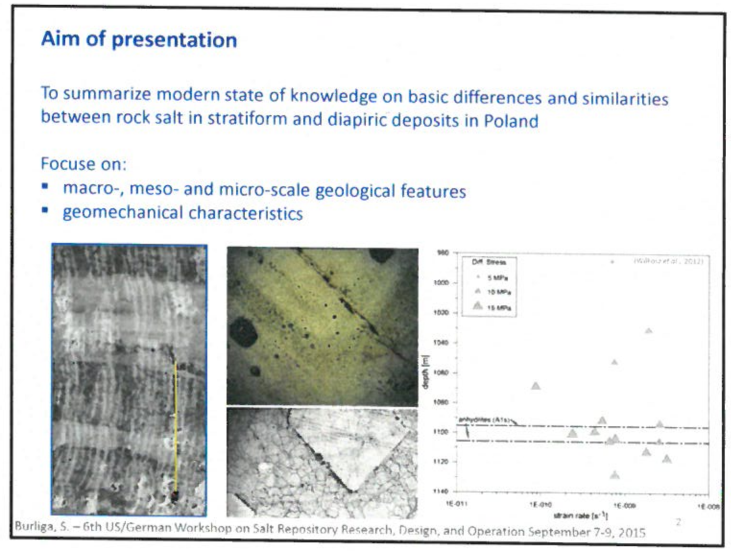
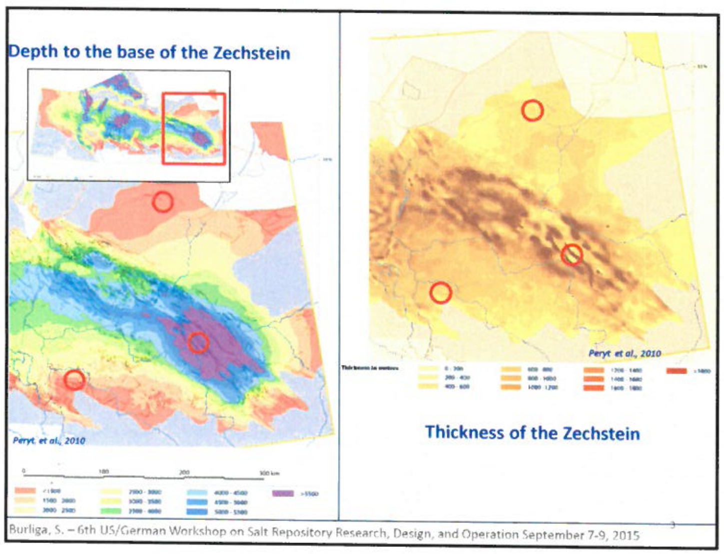

Comparison of rock salt in stratiform and diapiric deposits in Poland – hints for selection and safety of repositories
Stanisław Burliga PhD
University of Wrocław
6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015
Sandia National Laboratories
DBETEC
PTKA
NWSA
ENERGY


Aim of presentation
To summarize modern state of knowledge on basic differences and similarities between rock salt in stratiform and diapiric deposits in Poland
Focuse on:
macro-, meso- and micro-scale geological features
geomechanical characteristics
Burliga, S. – 6th US/German Workshop on Salt Repository Research, Design, and Operation September 7-9, 2015
2


Depth to the base of the Zechstein
Peryt et al., 2010
Thickness of the Zechstein
Peryt et al., 2010
Burliga, S. – 6th US/German Workshop on Salt Repository Research, Design, and Operation September 7-9, 2015
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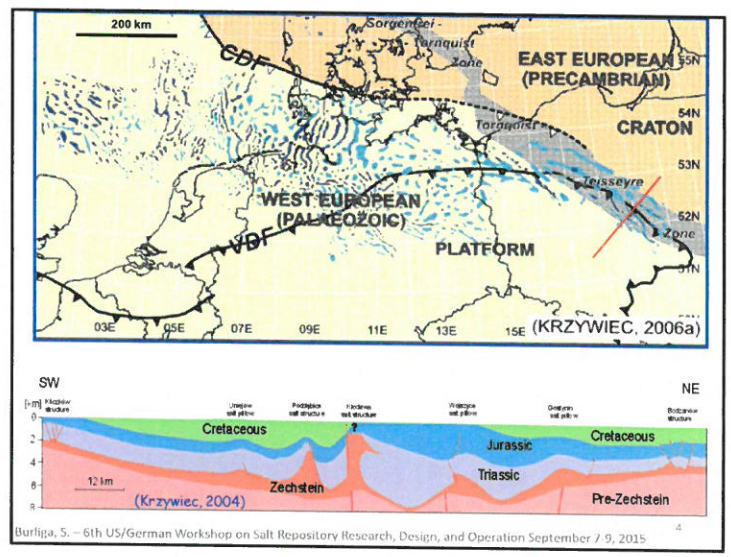
200 km
Sorgenfrei - Tornquist Zone
CDF
EAST EUROPEAN (PRECAMBRIAN)
CRATON
Tornquist
Teisseyre Zone
WEST EUROPEAN (PALAEOZOIC)
VDF
PLATFORM
55N
54N
53N
52N
51N
03E
05E
07E
09E
11E
13E
15E
(KRZYWIEC, 2006a)
SW
NE
Cretaceous
Jurassic
Triassic
Zechstein
Pre-Zechstein
12 km
(Krzywiec, 2004)
Burliga, S. – 6th US/German Workshop on Salt Repository Research, Design, and Operation September 7-9, 2015
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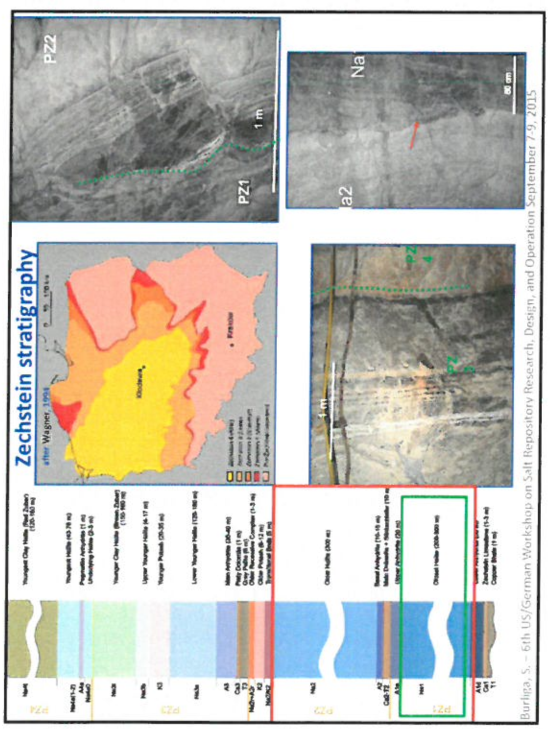
Zechstein stratigraphy
after Wagner, 1994
PZ2
PZ1
1 m
Na
a2
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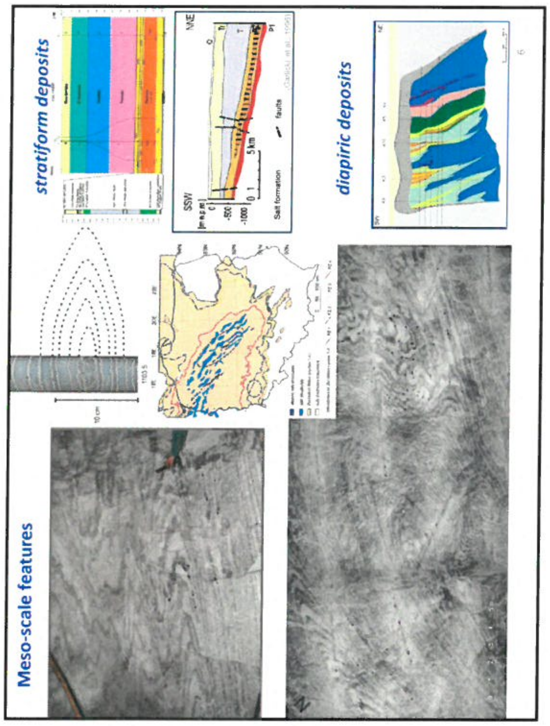
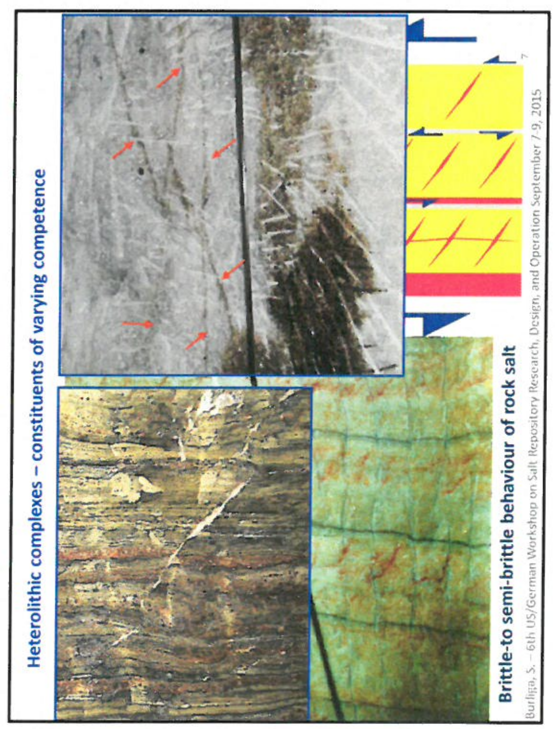
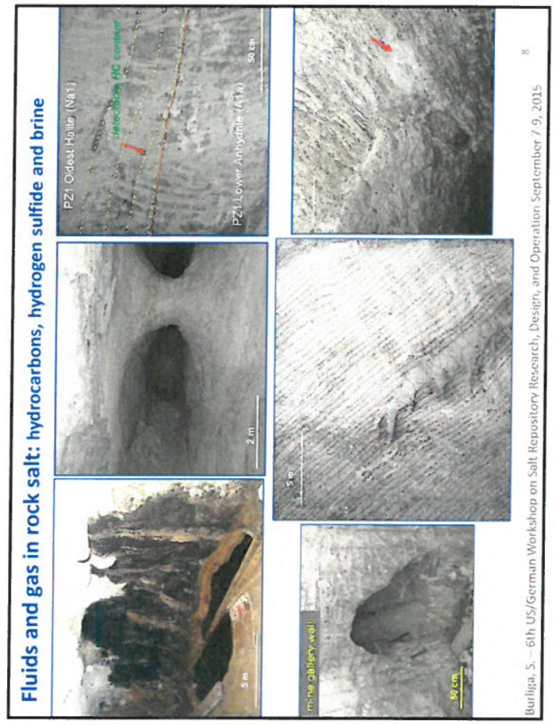

Meso-scale features
stratiform deposits
diapiric deposits
SSW
NE
5 km
faults
Salt formation
6


Heterolithic complexes – constituents of varying competence
Brittle-to semi-brittle behaviour of rock salt
Burliga, S. – 6th US/German Workshop on Salt Repository Research, Design, and Operation September 7-9, 2015
7


Fluids and gas in rock salt: hydrocarbons, hydrogen sulfide and brine
PZ1 Oldest Halite (Na1)
PZ1 Lower Anhydrite (A1s)
2 m
5 m
50 cm
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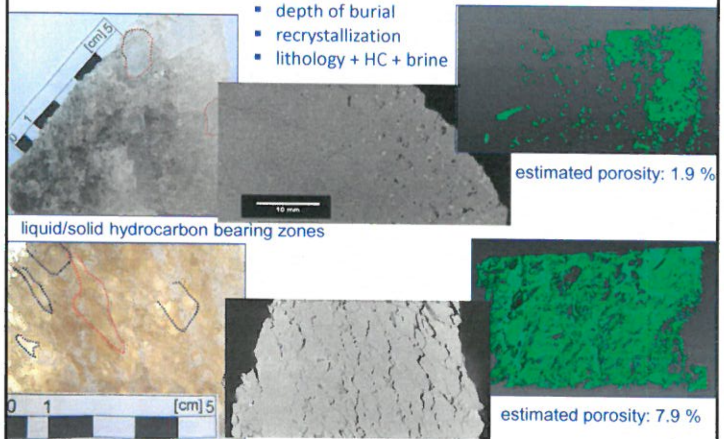
8

Porosity of rock salt

gas bearing zones

Function of:
- depth of burial
- recrystallization
- lithology + HC + brine

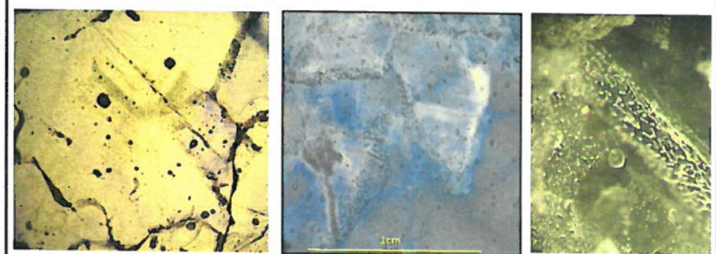


Source of brine

Internal
- fluid inclusions in minerals
- mineral phase changes during diagenesis and alteration
- formation water

External
- hardly predictable

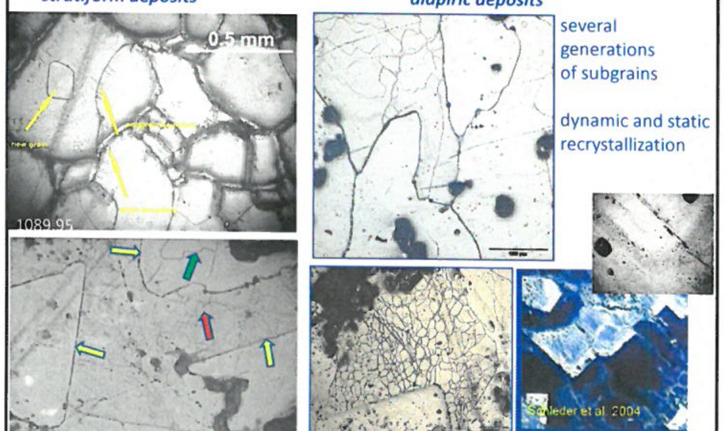
expulsion of fluids from inclusion during recrystallization



Internal structure of rock salt beds – microstructures

stratiform deposits

diapiric deposits



- several generations of subgrains
- dynamic and static recrystallization

(Wilkosz *et al.*, 2012)

Subgrains – plalaeopiezometry

location in the Na1 salt bed	differential stress /MPa/
10 cm below top	1.19
middle portion (highest values)	3.22
620 cm above base	2.58
550 cm above base	3.47
430 cm above base	2.88
340 cm above base	2.39
260 cm above base	1.45
120 cm above base	1.83
10 cm above base	0.99

(Burliga, 2007)

$\sigma = 107\, D^{-0.87}$

- the highest values in the central part of the salt bed, above the intra-salt anhydrite beds
- lower sections of the salt bed dominated by new grains; subgrains are scarce
- lower sections rich in subgrains and recrystallized halite
- upper sections contain relics of primary structures

depth below surface /m/	differential stress /MPa/
979.05	1.6
986.40	1.3
1008.45	1.6
1038.35	2.0
1063.2	3.6
1072.75	1.9
1089.95*	0.8
1141.18*	1.0

(Wilkosz et al., 2012)

Paleostress distribution in major lithostratigraphic units in a diapiric structure (Kłodawa Salt Structure)

Stratigraphic unit	Differential stress range σ [Mpa]	Average differential stress σ [Mpa]
Oldest Halite and Older Halite (Na1-Na2)	0.4-1.63	1.03
Younger Halite (Na3)	1.54-3.99	2.95
Younger Potash K3	1.45-3.78	3.04
Brown Clayey Salt Na3t	1.71-2.68	2.20
Youngest Halite Na4	1.59-3.23	2.16
Red Clayey Salt Na4t	1.36-3.76	2.15

Deformation characteristics:

stratiform deposits

- solution-precipitation creep
- dislocation creep
- variable recrystallization
- common relics of primary structures in halite
- deviatoric stresses: 0.6-3.6 MPa

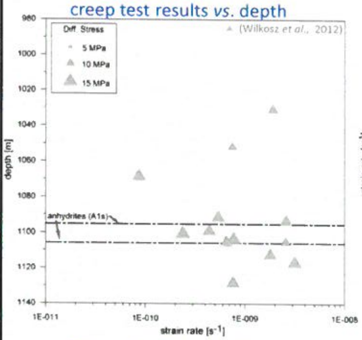
diapiric deposits

- dislocation creep
- solution-precipitation creep locally
- advanced recrystallization
- rare relics of primary structures in halite
- deviatoric stresses: <1– 2 MPa

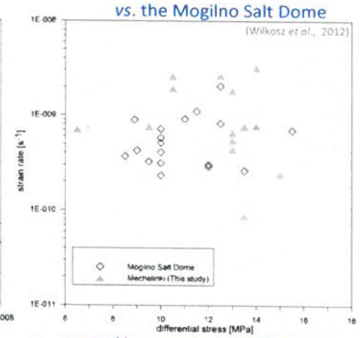
Geomechanical properties of rock salt

Triaxial creep tests

Mechelinki stratiform deposits creep test results *vs.* depth



Mechelinki stratiform deposits *vs.* the Mogilno Salt Dome



- heterogeneity of rheological properties throughout the profile
- basal layers: creep rate >10^{-9} 1/s (at differential stress 10.5–14.0 MPa
- comparable creep rates ranging between 10^{-11} 1/s and 10^{-9} 1/s at differential stress 6.5-15.0 MPa and temperature 30°C
- some samples from the stratiform deposits indicate creep rate of >2.5 ˙ 10^{-9} 1/s

Convergence

in-situ geodetic measurements

stratiform deposits

- early convergence of caverns: 100-600 mm yr $^{-1}$
- after >10 years: 30-100 mm yr $^{-1}$ [7 ‰]
- vertical and lateral convergence may differ

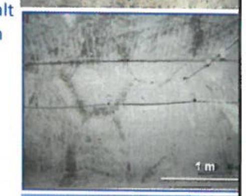
diapiric deposits

- early convergence of caverns: 100-600 mm/yr
- after >10 years: 6-10 mm yr $^{-1}$ [1 ‰]
- vertical and lateral convergence similar

Source: *Bieniasz et al., 2011; Marcola-Sadowska et al., 2009*

Conclusions

- salt deposits targeted for disposal of wastes should be evaluated individually – lithology and properties of a rock salt complex are specific for each salt formation
- the geological and geomechanical characteristics of buried rock salt are functions of the depth of burial, lithological heterogeneity and tectonic evolution of a salt complex; the variability in salt properties occurs both in salt domes and stratiform deposits
- preserved sedimentary structures indicate that salt complexes are compartmentalized and some compartments can be very weakly affected by deformation over millions of years
- conduits in rock salt inherited from early diagenetic and ancient deformational stages of the salt structure development
- relationships between microctructural features of rock salt and geomechanical properties of rock salt are still not well recognized and require further studying



Thank you for your attention

Exceptional service in the national interest

Sandia National Laboratories

Shear Strength and Deformation along Discontinuities in Salt

Steven R. Sobolik
Sandia National Laboratories

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories
DBE TEC
PTKA Project Management Agency Karlsruhe
NNSA
ENERGY

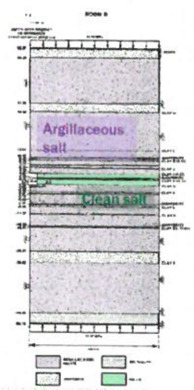
Outline

- Desire to understand shear strength, deformation along salt discontinuities, effects on salt creep, permeability along interface, potential for cracking
- Early tests proposed for WIPP
- Study of oil/NG/potash interaction in SE New Mexico
- Pressurized slot test at Yucca Mountain
- Proposed slot test in salt to create shear along discontinuity, measure displacement, aperture changes
- Other options for shear testing

2

Discontinuities in salt

- Influence of nonhomogeneities in repository performance identified as 1 of 4 key subject areas
- Examples include bedding interfaces, boundary shear planes, joints, and seams of non-halite material such as anhydrite
- Does shear strain cause formation of permeable flow path along an interface, or premature salt failure due to exceeding interface shear strength?
- Little existing in situ data to characterize shear strength of salt interface, resulting effects of shear on interface displacement and permeability



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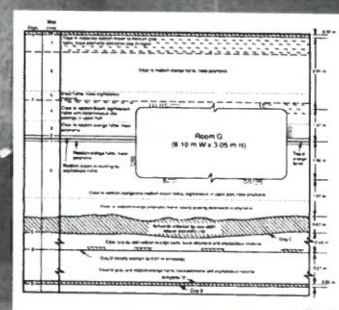
Early test proposed for WIPP

- Munson & Matalucci (1983) proposed in situ test with direct shear across clay seam.
- 1 X 1-m block in wall containing representative clay seam would be isolated by cutting around it in place in one of the drifts.
- Flatjacks installed in slots cut around the block to apply shear and normal stresses.
- Displacements along and across the seam would be measured as function of applied stress.
- This proposed test never occurred.



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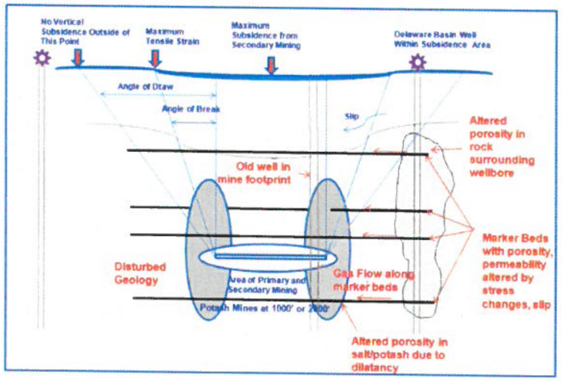
Sandia investigation of interaction of oil, natural gas, potash operations



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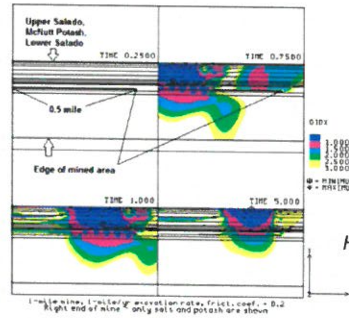
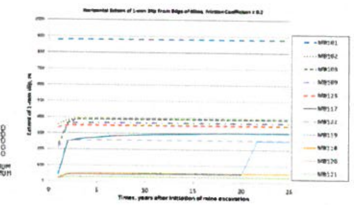
Damage, slip from interaction



Dilatant damage factor for mine 302 m deep, 1 mile/year excavation rate, marker bed friction coefficient = 0.2; factor<1 indicates dilatant damage.

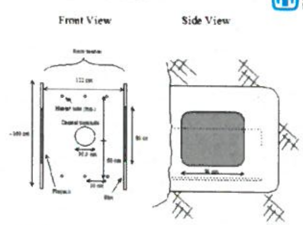


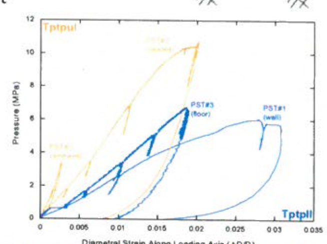
Horizontal extent of 1-mm slip from edge of the mine, friction coefficient=0.2.

6

Pressurized slot test at Yucca Mountain, Nevada

- Four pressurized slot tests performed May-December 2002 in volcanic tuff, during the characterization of Yucca Mountain as a potential radioactive waste repository
- Designed to measure a rock mass modulus and to determine the extent of nonelastic, permanent deformation under high stress loading conditions
- Tests performed with flatjack pressures 6-10 MPa (in situ σ_v=4.3 MPa)
- Tests #1, #3 ambient temperature; Test #2 performed at both ambient and heated (90C) conditions



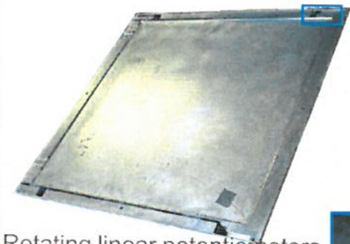
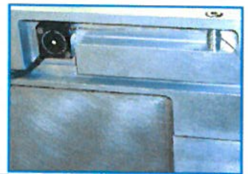


7

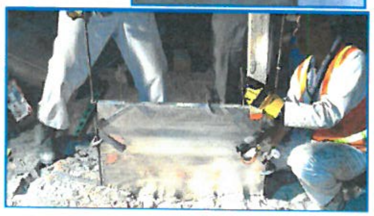
PST Test Procedure

- Site preparation
  - Drill dowel pin holes
  - Mount surface deformation pins
  - Core the central hole and map locations of prominent lithophysae
  - Instrument central hole
- Slot cutting and flat-jack installation
  - Cut slots with Hydraulic Rock Saw
  - Map surface of slots
  - Install flat-jacks and platens along with displacement gages
  - Install instrumentation for remotely measuring pin deformations
- Slot pressurization
  - Pressurize flat-jacks, and increase until null slot displacement is achieved.
  - Cycle flat-jack pressures.
  - Maintain constant pressure in flat-jacks to check the time dependent deformation of the rock mass

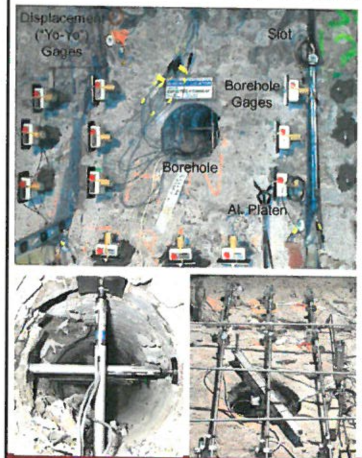
Instrumented Flat-jack

Rotating linear potentiometers gages
(4 per flat-jack, 0-5 cm range) measure displacements between the two load bearing platens.



PST Instrumentation



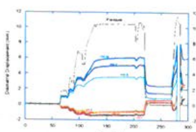
- Total data and video channels recorded 35 (typical):
  - 12 surface displacement gages (9 horizontal + 3 vertical)
  - 6 borehole displacement gages (3 horizontal + 3 vertical)
  - 2 video channels (1 axial + 1 borehole crown)
  - 8 platen displacement gages (4 left + 4 right)
  - 2 pressure transducers in parallel (1 left + 1 right flat-jacks)
  - 5 thermocouples (2 flat-jacks + 1 rib + 1 ambient air + 1 borehole)
- Data from borehole displacement gages were excellent and provided the basis to determine in situ mechanical properties of lithophysal tuff.

Comparison of E and Strength

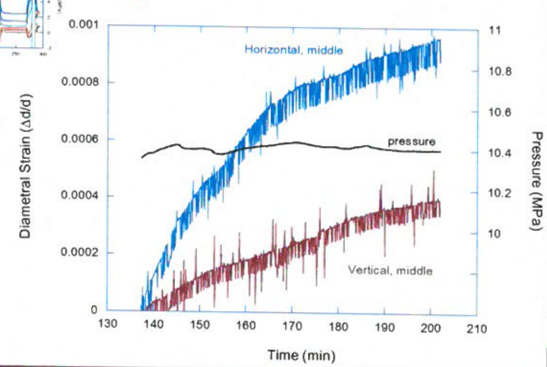
Test	Location	Condition	Tuff Unit	E (GPa)	Strength (MPa)
11.5" diameter core	ESF	Saturated,24°C	Tptpul (3)	5.9 ± 0.9	11.2 ± 1.7
11.5" diameter core	ECRB	Saturated,24°C	Tptpll (1)	5.3	15.7
11.5" diameter core	ESF	Room dry,24°C	Tptpul (7)	13.7 ± 5.3	22.2 ± 6.9
11.5" diameter core	ECRB	Room dry,24°C	Tptpll (3)	7.6 ± 2.3	21.2 ± 7.7
11.5" diameter core	ESF	Dry, 190-200°C	Tptpul (3)	10.3 ± 3.2	30.5 ± 9.5
11.5" diameter core	ECRB	Dry, 190-200°C	TPtpll (2)	6.8 ± 0.4	31.7 ± 0.8
Goodman Jack	TTF	Ambient / Heated	Tptpmn	3.3 / 5.9	NA
Plate Loading Test	TTF	Ambient	Tptpmn	17	NA
Plate Loading Test	TTF	43°C	Tptpmn	43	NA
PST#1	ESF	Ambient	Tptpll	0.5 ± 0.3	6*
PST#2	ESF	Ambient	Tptpul	3.0 ± 0.5	NA
PST#2	ESF	Heated, >80°C	Tptpul	1.5 ± 0.5	11*
PST#3	ECRB	Ambient	Tptpll	1.0 ± 0.3	7*

*-Peak Pressure in the Flat-Jack

"Creep" behavior in fractured tuff (PST#2)

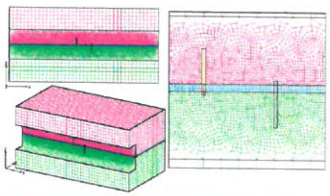


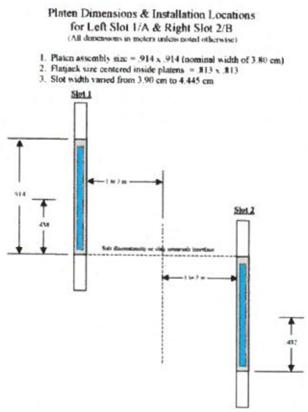
Not actually creep behavior, but inelastic behavior due to compression of lithophysae, existing fractures



Proposed slot test in salt

- Measurements of applied pressure and displacement will capture the evolution of shear-induced characteristics of the inhomogeneity and neighboring salt during the test.
- Changes in permeability may be approximated by measurement of the changes to the interface aperture.
- Pre-test analyses to predict changes to interface





13

Pre-test analyses, compare to data

- Seam/interface may be modeled as contact surface, or as thin layer or one of more materials
- Select material models, parameters for shear stiffness & strength, change in permeability
- Compare predictions of displacement along interface, change in aperture thickness, based on design, actual pressure application to measured values
- Also consider including long-duration constant pressure, to collect measurements for transient, steady-state creep parameters
- Measure permeability or flow in interface (and changes during test), if feasible
- Ambient test required; additional heated test should be considered

14

Other options for in situ shear testing

- **Pressurized borehole test:** Similar to pressurized slot test, but instead drill 10-cm boreholes that can be sealed and pressurized up to 10 MPa
- **Hydraulic fracture borehole test:** Similar to pressurized borehole, hydrofrac holes, inject dye to detect flow through seam (similar test proposed for WIPP)

15

Thank you for your attention!

16

Exceptional service in the national interest — Sandia National Laboratories

SALT UNDERGROUND RESEARCH FACILITY ACTIVITIES

Christi D. Leigh PhD
Sandia National Laboratories

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA Project Management Agency Karlsruhe · NNSA · U.S. Department of Energy

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A consensus of Sandia salt scientists as to the most valuable tests and demonstrations that could be considered if a URL becomes available in salt, either in the USA (say at WIPP or elsewhere) or in Europe.

We would like critical feedback on this list. We believe that the science basis for salt disposal is understood and the next testing can be prioritized regardless of the actual salt URL location. We would be open to collaboration on field tests.

2

Potentially Available Underground Research Space

- Äspö - Hard Rock Laboratory
- Asse Mine
- BfS
- Gorleben
- Grimsel Test Site
- HADES
- Horonobe Underground Research Center
- IRSN
- Konrad
- Korea Underground Research Tunnel (KURT)
- Mizunami Underground Research Laboratory
- Mont Terri Project
- Morsleben
- Olkiluoto Research Tunnel

WIPP?

Commercial Mines?

Underground research space is very expensive to create and maintain, and, as such, that space is precious and needs to be put to the best uses possible.

3

"BEST" work to be done in an underground research laboratory in salt would include at least the following guidelines:

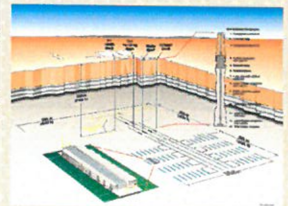
- Engage in technical activities that will have the effect of reducing uncertainties to which assessments of long-term repository performance are sensitive.
- Propose activities that demonstrate the feasibility of operating a salt repository for heat-generating waste.
- Maintain consistency with identified international priorities

4

A test or demonstration might address specific features, events or processes (FEPS) to confirm our understanding and ability to model performance of a deep geologic repository for heat generating radioactive waste in salt. An activity might be proposed to build confidence that the safety functions of a deep geologic repository in salt are understood and can be forecast over regulatory time periods. A URL activity might be identified by consensus of international collaborations. Many test concepts pertain to design and operational practice, which embody model prediction and confirmation at full-scale. These particular objectives align with similar lists put forward by IAEA and NEA

5

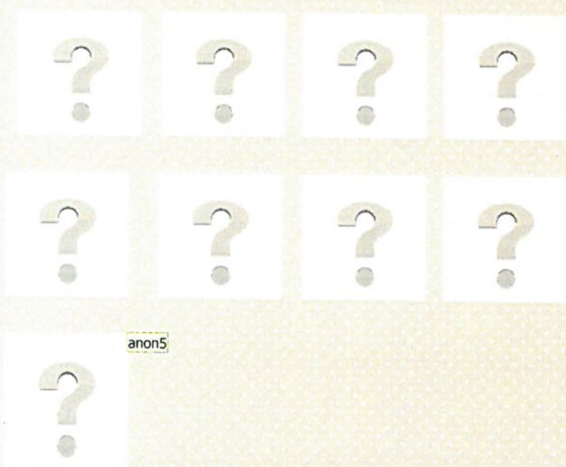
Safety Case Is Solid For Disposal Of Transuranic Waste In Salt



- Site Selection
- Site Characterization
- Pre-Closure Safety Evaluation and Operations
- Post-Closure Safety Evaluation
  - Wastes and Engineered Barriers Features and Issues
  - Natural Barriers Features and Issues
  - Repository System Features and Issues
  - Modeling Issues
- Confidence Building

Materially Advance The Safety Case For Disposal Of Heat-generating Radioactive Waste In Salt.

6



7

CHARACTERIZING EARLY EVOLUTION OF SALT EXCAVATIONS

Capturing early behavior of excavations in salt is a well identified information gap essential to geomechanical constitutive model development and evaluation.

Interactive Session Summary

8

LARGE-SCALE *IN SITU* CONSOLIDATION

For most concepts of salt disposal, reconsolidation of granular salt to low porosity and low permeability at field-scale application is prerequisite to affecting sealing functions.

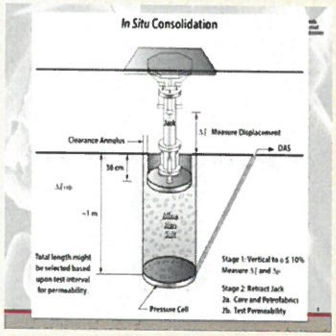


Figure 1. Field-scale reconsolidation of granular salt.

Interactive Session Summary

DRIFT-SCALE SEAL DEMONSTRATION

Geotechnical barriers are the second most vital consideration after the geologic formation itself for long-term isolation of nuclear waste.

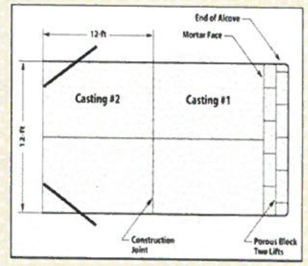


Figure 2. Nominal schematic of drift-scale seal demonstration.

Interactive Session Summary

BOREHOLE SEAL DEMONSTRATION

A salt URL provides opportunity to place, test and forensically examine borehole plugs.

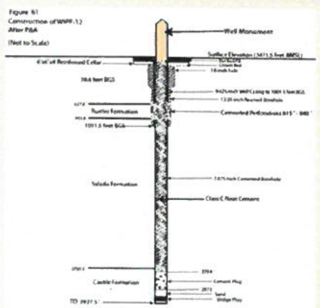


Figure 3. Construction of WIPP-12 after plugging and abandonment (DOE 1996).

Interactive Session Summary

SINGLE HEATER TEST

A single heater test provides a flexible opportunity to predict and measure salt response and establish test protocol.

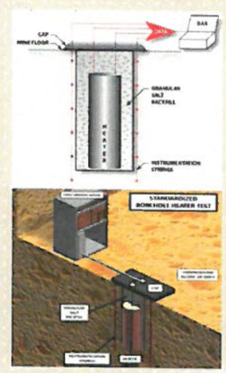


Figure 4. Schematic of single heater test.

Interactive Session Summary

BRINE AVAILABILITY BOREHOLE HEATER TEST

A small, standardized borehole heater test fielded in a range of vertical and horizontal boreholes will address generic open issues from previous tests and provide fundamental data for the local salt system.

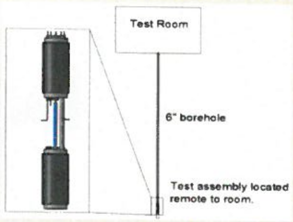
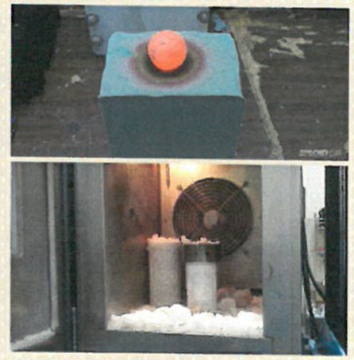


Figure 5. Standardized borehole brine availability test in salt

Interactive Session Summary

SALT DECREPITATION TEST

Salt subject to decrepitation has been observed to shatter or rupture, but the effects this process has on the porosity, permeability, and strength of the salt have not been quantified.



Interactive Session Summary

DIFFUSION TEST

Experimental measurements to characterize diffusion model parameters will be a key support for the safety case

Interactive Session Summary

UNDERGROUND SALT CREEP LABORATORY TO INVESTIGATE LOW-STRAIN-RATE WASTE PACKAGE BUOYANCY EFFECTS

Understanding the potential for large, heavy waste packages to sink over time periods of 10^4 years or longer, is motivated by recently published low-strain-rate creep data, and requires advanced salt creep testing and modeling.

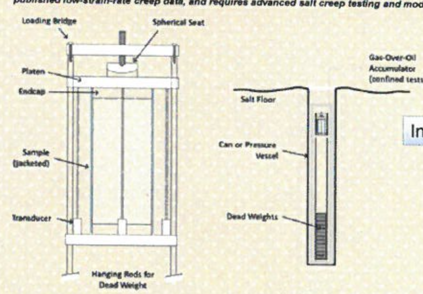


Figure 7. Concept drawing for low-stress (dead loaded) low strain-rate ambient temperature core testing apparatus, for confined and unconfined testing, to be deployed in a URL.

Interactive Session Summary

Modelling of crushed salt compaction – Recent findings

Dr.-Ing. Oliver Czaikowski
GRS, Repository Safety Research Division

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

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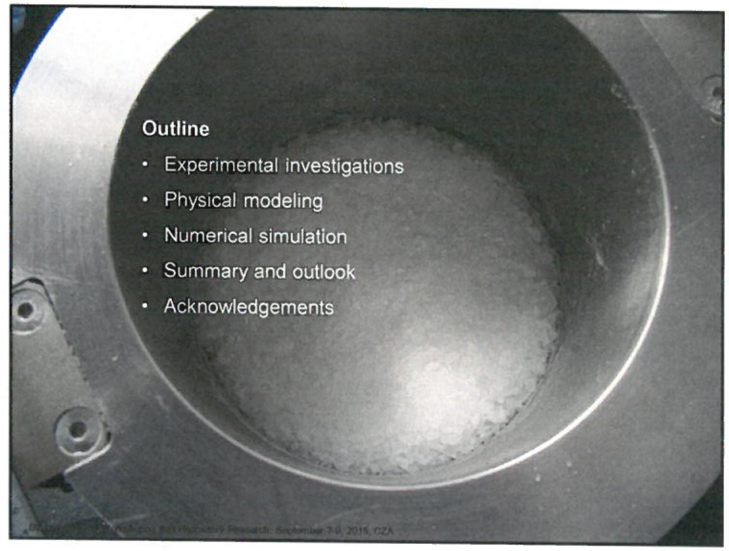
NNSA ENERGY



Motive and origination I

Objectives

- REPOPERM Phase1 (concluded):
  - Review of existing thermal, hydraulic and mechanical data for crushed salt; Evaluation of data based on relevance criteria, Oedometer test → error analysis for porosity determination
    - → very high uncertainty for low porosity values
- REPOPERM Phase2 (ongoing):
  - increasing prediction reliability of compaction models based on a laboratory program and benchmark exercises,
  - investigation of the relevance of the low permeability range during compaction process

Project partners

- BGR, Hannover
- DBE Technology, Peine
- GRS, Braunschweig

Motive and origination II

Research project

- Funded by Federal Ministry for Economic Affairs and Energy (BMWi)
- Duration: 2007 - 2009, second phase started May 2010

Yardstick

- Low porosities <10% (<5%) in laboratory scale

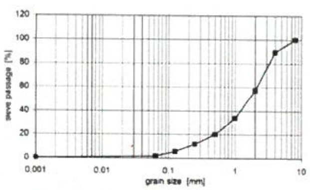
Repository concept

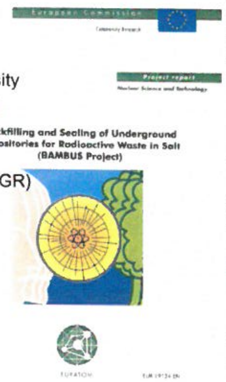
- safe containment within an isolating rock zone (containment providing rock zone)
  - hydraulic properties in buffer and backfill must be known for high degrees of compaction
  - *open question*: is there a cut-off porosity below which there is no advective flow

Backfill material

Crushed salt

- z2HS ASSE Hauptsalz from road header excavation
- Maximum grain size 8mm (BAMBUS Project)
- Manual emplacement and pre-compaction to 30% porosity
- Oven-dried / natural moisture content / artificially wetted
- Compaction rate / stress control
- Temperature control
- Available literature / experiments (oedometric tests by BGR)
- No additives (bentonite / SVV)





Experimental setup & test results

Physical Modeling

CODE_BRIGHT – COupled DEformation of BRIne Gas and Heat Transport

FEM-Code for coupled THM-analysis of multiphase flow in geological media (3D)

- Superposition of deformation mechanism, *Olivella & Gens (2002)* :
  - $\dot{\varepsilon}_{CS} = \dot{\varepsilon}^{EL} + \dot{\varepsilon}^{DC} + \dot{\varepsilon}^{VP} + \dot{\varepsilon}^{FADT}$

Elastic deformation behaviour (EL)

- Elastic stiffness increases with decreasing porosity

Dislocation creep (DC)

- Inelastic viscous deformation of the individual salt grains due to deviatoric stress
- Deformation rate of crushed salt is identical to intact rock salt for min. porosity

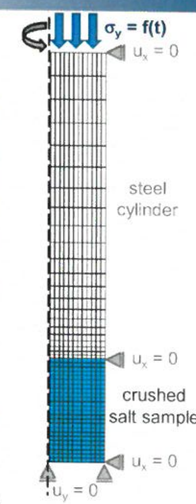
Viscoplastic deformation behaviour (VP)

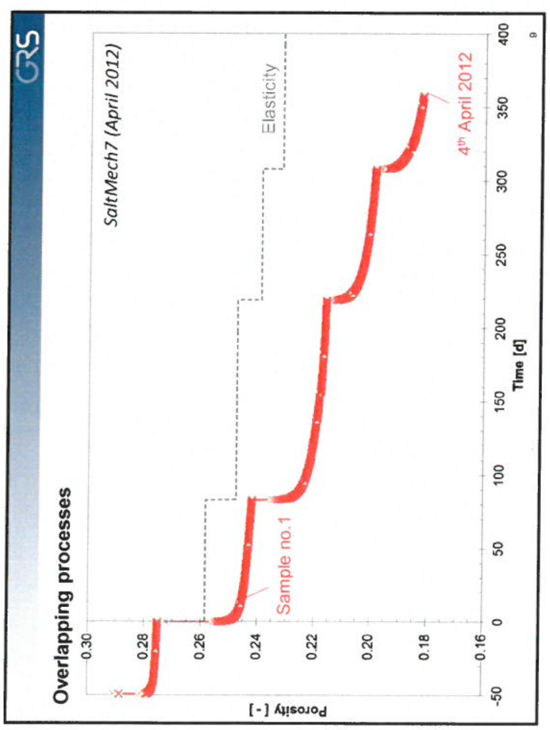
- Viscoplastic deformation of the grain aggregate (grain re-organisation & crushing)

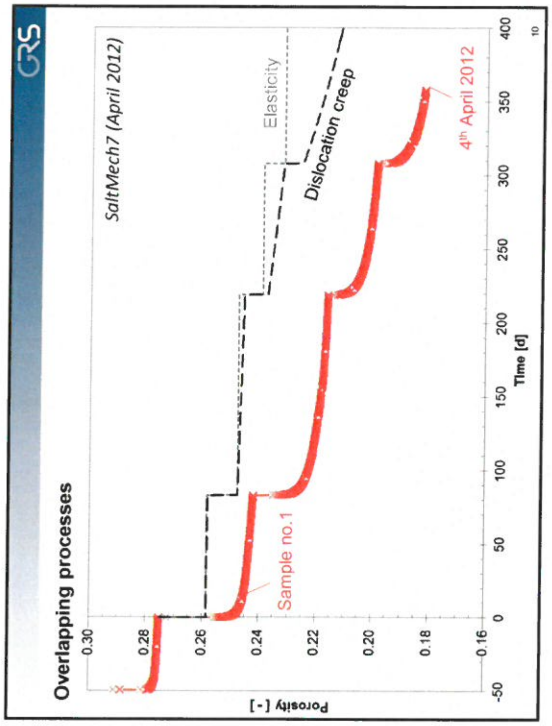
Fluid assistant diffusional creep (FADT)

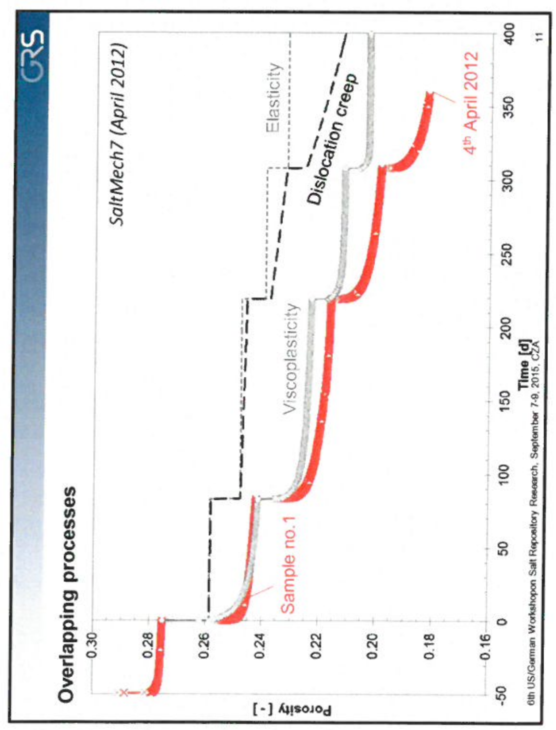
- Material stiffness decreases with amount of moisture/brine
  - The mechanism which is held responsible for this is pressure solution at the contact zones between the grains, where stress concentrations occur, and precipitation in the pores, *Spiers et al. (1986, 1990)*

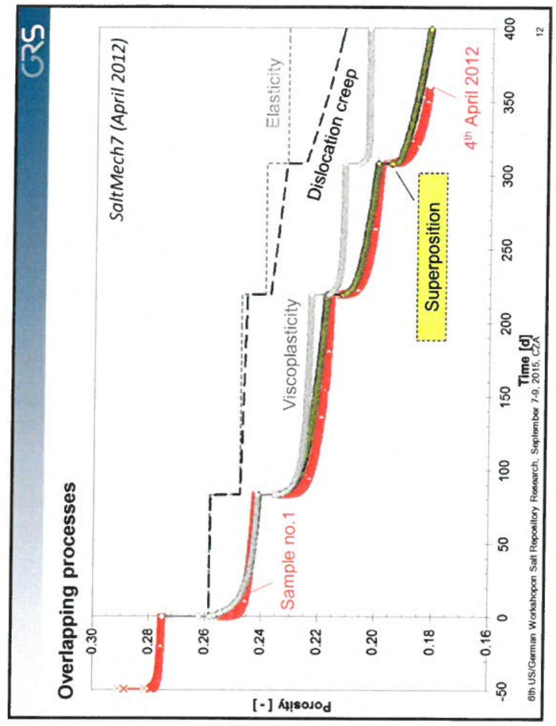
Numerical simulation

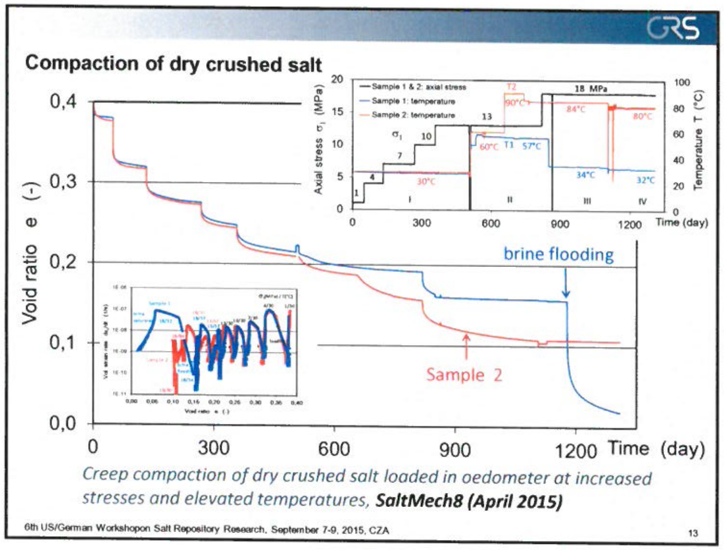



Overlapping processes
SaltMech7 (April 2012)
Elasticity
Sample no.1
4th April 2012
Porosity [-]
Time [d]
9


Overlapping processes
SaltMech7 (April 2012)
Elasticity
Dislocation creep
Sample no.1
4th April 2012
Porosity [-]
Time [d]
10


Overlapping processes
SaltMech7 (April 2012)
Elasticity
Dislocation creep
Viscoplasticity
Sample no.1
4th April 2012
Porosity [-]
Time [d]
6th US/German Workshopon Salt Repository Research, September 7-9, 2015, CZA
11


Overlapping processes
SaltMech7 (April 2012)
Elasticity
Dislocation creep
Viscoplasticity
Superposition
Sample no.1
4th April 2012
Porosity [-]
Time [d]
6th US/German Workshopon Salt Repository Research, September 7-9, 2015, CZA
12


Compaction of dry crushed salt
Void ratio e (-)
Time (day)
brine flooding
Sample 2
Sample 1 & 2: axial stress
Sample 1: temperature
Sample 2: temperature
Axial stress σ1 (MPa)
Temperature T (°C)
18 MPa
Creep compaction of dry crushed salt loaded in oedometer at increased stresses and elevated temperatures, SaltMech8 (April 2015)
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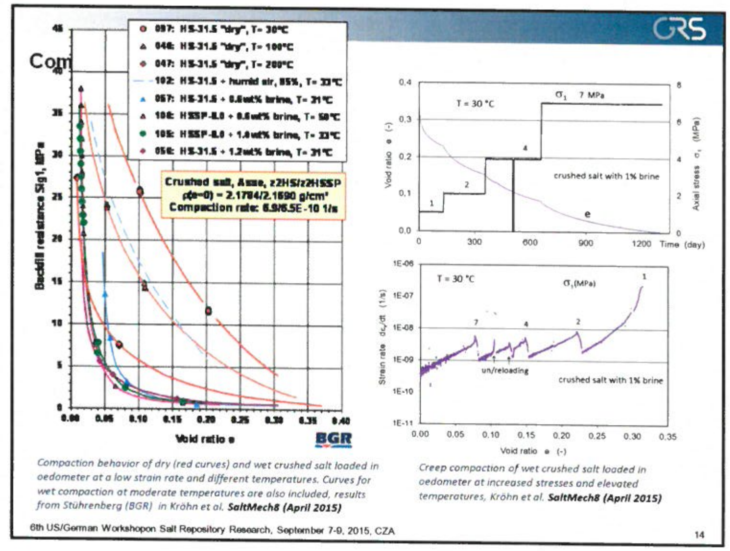
Backfill resistance Sig1, MPa
Void ratio e
Crushed salt, Asse, z2HS/z2HSSP
Compaction rate: 6.9/6.5E-10 1/s
BGR
T = 30 °C
σ1 7 MPa
crushed salt with 1% brine
Void ratio e (-)
Axial stress σ1 (MPa)
Strain rate dε/dt (1/s)
un/reloading
Compaction behavior of dry (red curves) and wet crushed salt loaded in oedometer at a low strain rate and different temperatures. Curves for wet compaction at moderate temperatures are also included, results from Stührenberg (BGR) in Kröhn et al. SaltMech8 (April 2015)
Creep compaction of wet crushed salt loaded in oedometer at increased stresses and elevated temperatures, Kröhn et al. SaltMech8 (April 2015)
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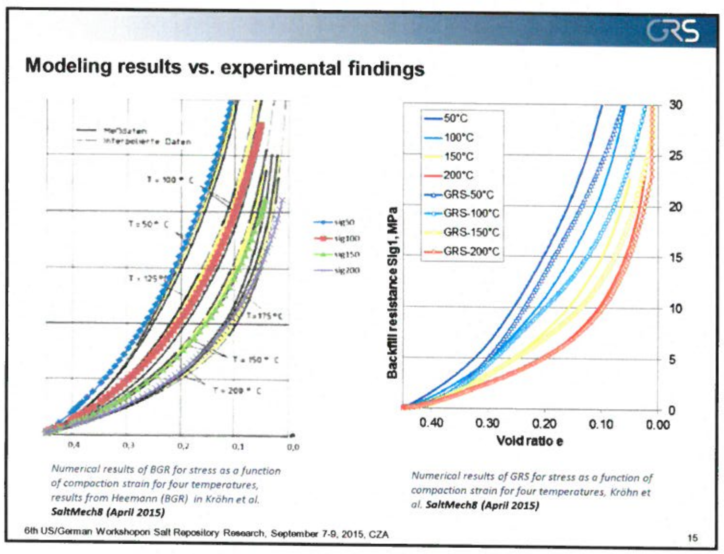
Modeling results vs. experimental findings
50°C
100°C
150°C
200°C
GRS-50°C
GRS-100°C
GRS-150°C
GRS-200°C
Backfill resistance Sig1, MPa
Void ratio e
Numerical results of BGR for stress as a function of compaction strain for four temperatures, results from Heemann (BGR) in Kröhn et al. SaltMech8 (April 2015)
Numerical results of GRS for stress as a function of compaction strain for four temperatures, Kröhn et al. SaltMech8 (April 2015)
6th US/German Workshopon Salt Repository Research, September 7-9, 2015, CZA
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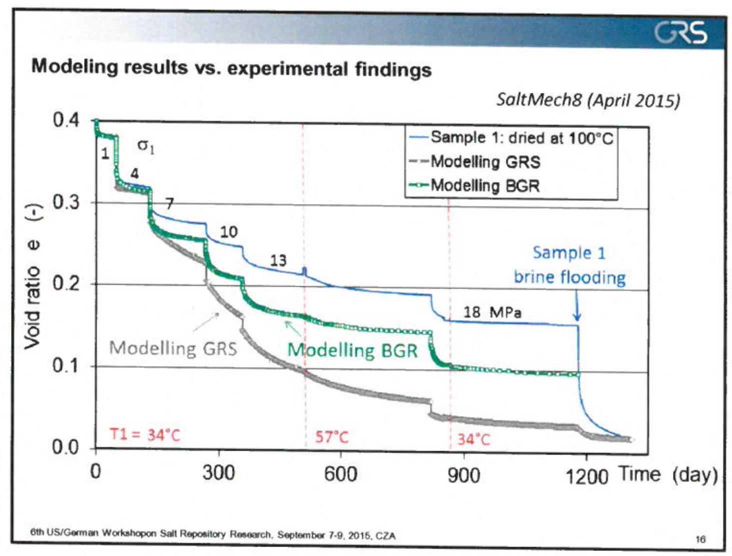
Modeling results vs. experimental findings
SaltMech8 (April 2015)
Sample 1: dried at 100°C
Modelling GRS
Modelling BGR
Void ratio e (-)
Time (day)
Sample 1
brine flooding
18 MPa
Modelling GRS
Modelling BGR
T1 = 34°C
57°C
34°C
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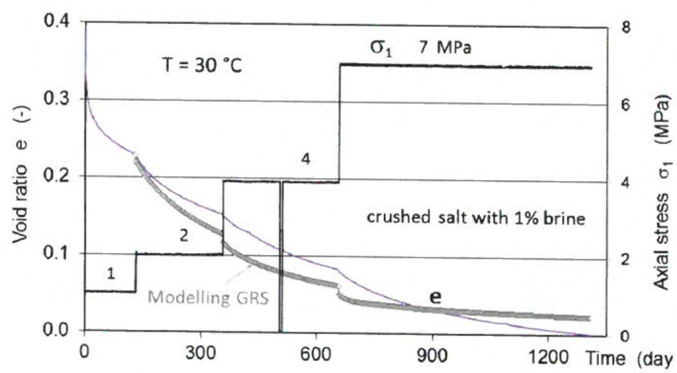
GRS

Modeling results vs. experimental findings

SaltMech8 (April 2015)



GRS

Summary & Outlook

- With respect to theoretical considerations the work presented here aims at the evaluation of numerical modelling capabilities for the long-term deformation behavior of granular salt backfill.
- Several constitutive models are available, and different aspects of material behavior can be modelled separately.
- Up to now there is no evidence whether the implemented constitutive equations are valid for the experimental range especially the compaction behavior at low porosities.
- While it is generally agreed that crushed rock salt backfill will eventually be compacted to low porosity, the experimental data as well as theoretical considerations have shown that **prediction of the temporal evolution of compaction is still imperfect!**

GRS

Acknowledgements

The authors gratefully acknowledge the funding of the various experimental and theoretical investigations within the REPOPERM project phase 2 (FKZ 02E10477) by the German Federal Ministry for Economic Affairs and Energy (BMWi), represented by the Project Management Agency Karlsruhe (PTKA-WTE)

Federal Ministry for Economic Affairs and Energy

PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology

- Dieter Stührenberg & Ulrich Heemann (BGR)
- Klaus-Peter Kröhn, Klaus Wieczorek & Chun-Liang Zhang (GRS)

Development of a generic HLW repository concept in bedded salt incl. safety and safety demonstration concept (KOSINA)

Wilhelm Bollingerfehr
DBE TECHNOLOGY GmbH

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology · NNSA · U.S. Department of Energy

Outline

- ❑ Context
- ❑ Objectives
- ❑ Work Program
- ❑ Schedule
- ❑ Outlook

Context

❑ Stand AG = legal basis for a new site selecting process

- idea: science based selecting process to find the site which provides safety best for one million years
- implementation of a "Repository Commission" (RC)
- main scientific-technical tasks of "RC"
  - ➢ definition of site selecting criteria
  - ➢ development of a methodological approach to compare safety of repository systems in different host rocks

Context

❑ a methodological approach to compare safety of repository systems in different host rocks:

- ➢ requires at least the existence of generic repository concepts and adequate safety - and safety demonstration concepts for all potential host rock formations in Germany (salt, clay and crystalline rock)
- ✓ comprehensive repository concepts, safety concepts, and safety demonstration concepts for domal salt are available
- ✓ repository concepts, safety concepts, and safety demonstration concepts for clay do exist / are in progress
- ✓ at least ideas for repository, safety, and safety demonstration concepts for crystalline rocks are in progress
- ➢ for bedded salt all of this is still missing

KOSINA Project

- BMWi/PTKA launched the R&D-project KOSINA in summer 2015

  (Konzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flach lagernden Salzschichten in Deutschland und Überprüfung des entwickelten Sicherheits- und Nachweiskonzeptes)

  = *development of a concept for a generic repository for heat generating waste in bedded salt in Germany as well as the review (adaptation) of existing safety and safety demonstration concepts*

- Partner: BGR, GRS, IfG, and DBE TEC
- Duration: 32 months

Objectives

- major objective:
  - development of a technical site independent concept for a repository for heat generating waste and spent fuel on basis of generic geologic models for bedded salt including a safety and safety demonstration concept
- detailed objectives:
  - development of a generic geologic model (+ parameters)
  - development of a safety and safety demonstration concept
  - development of technical repository designs
  - demonstration of geomechanical integrity

➢ provide a technical-scientific basis for the safety oriented evaluation of repository systems in different host rocks according to the site selection law.

Work Programme

WP 1: Compilation of basic planning data and requirements (all)

WP2: Development of generic geologic models and derivation of model parameters (BGR and IfG)

WP3: Development of safety / safety demonstration concepts (GRS)

WP4: Analysis of geo-mechanical Integrity (BGR und IfG)

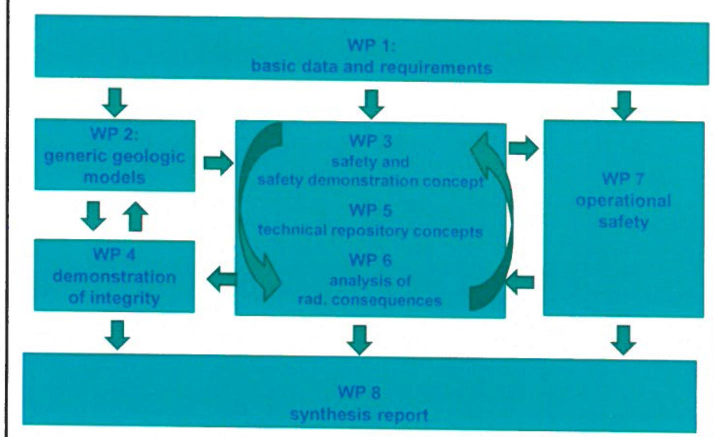
WP5: Development of repository designs for 4 variants (DBE TEC)

WP6: Analysis of radiological consequences (GRS)

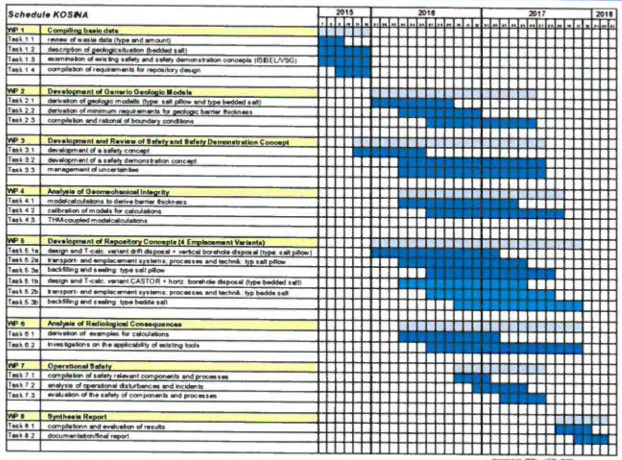
WP7: Evaluation of operational safety (DBE TEC)

WP8: Synthesis report (all)

Interdependencies of Work Packages



Schedule



Wilhelm Bollingerfehr/09/2015
US/German Workshop
Dresden, September 7 – 9, 2015

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Outlook

- ❑ work program was launched in July this year (kick-off meeting)
- ❑ interim report on basic data and design requirements scheduled for end of 2015
- ❑ R&D project KOSINA is going to fill a gap on repository design and safety demonstration concepts
- ❑ KOSINA-project results will not be fully available for the final report of the Repository Commission; however the expected results / interim results will be available when the site selecting process is going to be implemented (2017 or 2018 ?)

Wilhelm Bollingerfehr/09/2015
US/German Workshop
Dresden, September 7 – 9, 2015

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DBE TECHNOLOGY GmbH

Thank you
for your attention.

Wilhelm Bollingerfehr/09/2015
US/German Workshop
Dresden, September 7 – 9, 2015

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Exceptional service in the national interest — Sandia National Laboratories

A comparison of bedded and domal salt regarding heat-generating nuclear waste disposal

Frank D. Hansen PhD PE
Sandia National Laboratories

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories · DBE TEC · PTKA Project Management Agency Karlsruhe · U.S. Department of Energy · NNSA

9/22/2015

Motivation

- Compare and contrast characteristics of bedded and domal salt as they pertain to disposal of heat-generating nuclear waste in salt formations
- Clear and contemporary reasons to pursue comparison of bedded and domal salts
- Workshop discussion:
  - Annotated outline comparing bedded and domal salt
  - Publication options

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Comparison Document(s)

- Expected to be a major deliverable(s) for international salt repository R&D
  - Nuclear waste disposal in the United States has concentrated on bedded salt
  - Similar efforts in Germany emphasized geologic domal salt
- Provide collective understanding of basic salt physical, mechanical, chemical, petrological, hydrological, and thermal behavior
- Relevance of similarities and differences are discussed on the basis of scale from the large-scale (formation), to the mesoscale (meters), and to the microscopic scale

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Venues

Authored collaboratively by US and German scientists

- USA Nuclear Energy Report
- KoSiNa contribution
- Publications - open literature
- NEA Salt Club

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1.0 Introduction

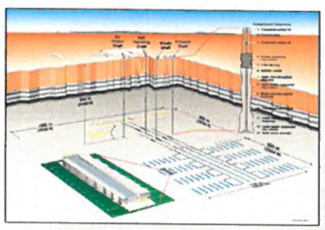
1.1 Salt Characteristics
1.2 Generic Repository Evolution
1.3 Transferability
1.4 Potential Generic vs. Site Specific Issues

2.0 Formation Scale

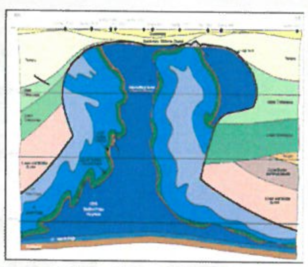
2.1 Structural Geology
2.2 Salt Basins
- 2.2.1 Salt basins in Germany
- 2.2.2 Salt basins in The Netherlands
- 2.2.3 Salt basins in Poland
- 2.2.4 Salt basins in the United States

2.3 Large-scale modeling

Existing Information



WIPP Underground Layout



Preliminary safety analysis of the Gorleben site (VSG)
(Vorläufige Sicherheitsanalyse Gorleben)

3.0 Mesoscale

3.1 Thermal Effects
3.2 Brine Migration
3.3 Mechanical Properties
3.4 Creep
- 3.4.1 Results of the Joint Project Testing
- 3.4.2 Results from the SPR program

3.5 Mesoscale Lithology
3.6 Excavation Damage Zone
3.7 Modeling
3.8 Seal Systems (or separate document?)

4.0 Microscale

4.1 Mineralogical Comparisons
4.2 Microprocesses
4.3 Brine Content

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Goals of Breakout Session

- Discuss differences and similarities as they pertain to the safety case
- Solicit input from 6th Workshop participants
- Create a document that can serve as a guide for development of a compendium
- Provide scientific basis for FEPs evaluations

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U.S. DEPARTMENT OF ENERGY | OFFICE OF ENVIRONMENTAL MANAGEMENT

RECOVERY OF THE WASTE ISOLATION PILOT PLANT FOLLOWING THE FEBRUARY 2014 EVENTS

Casey Gadbury
Manager, Office of Program Management
Carlsbad Field Office

6th US/German Workshop
Salt Repository Research, Design, and Operation
Dresden, Germany
7-9 September 2015

Feb 5, 2014: salt haul truck fire incident

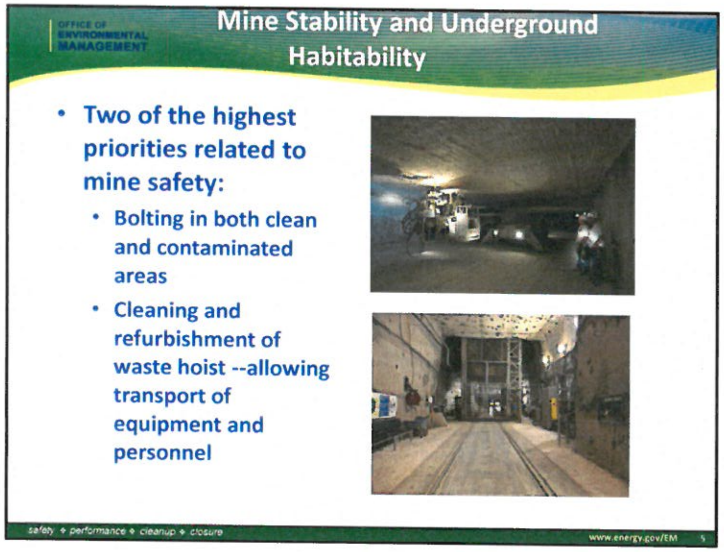
- Underground workers evacuated without injuries except some cases of minor smoke inhalation
- Major soot contamination required cleanup before electrical equipment operation
- Accident Investigation Board (AIB) critically evaluated cause and analyzed response

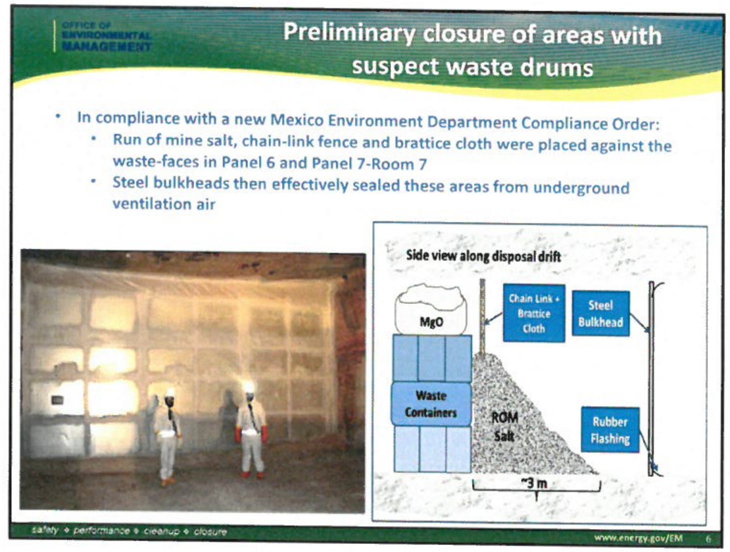
Feb 14, 2014: underground waste drum burst

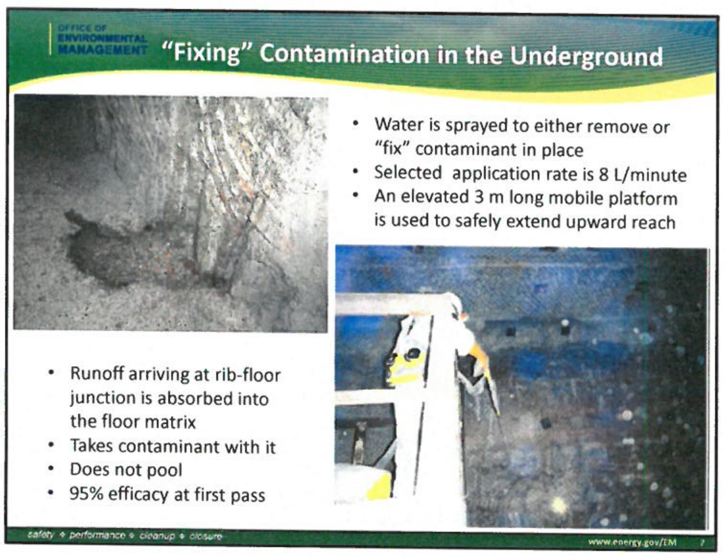
- Single drum burst sent particulate into underground air
- Continuous air monitor detected release and engaged the HEPA filtration system
- Minor amount of radiation bypassed filters, resulting in some offsite release (~2mCi, ~70 MBq)
- About 500 drums in the underground (Panel 6 and Panel 7, Room 7) have similar waste content (nitrate salts and organic neutralizer and absorbent) and have been isolated from underground ventilation air
- An AIB investigated event cause and response

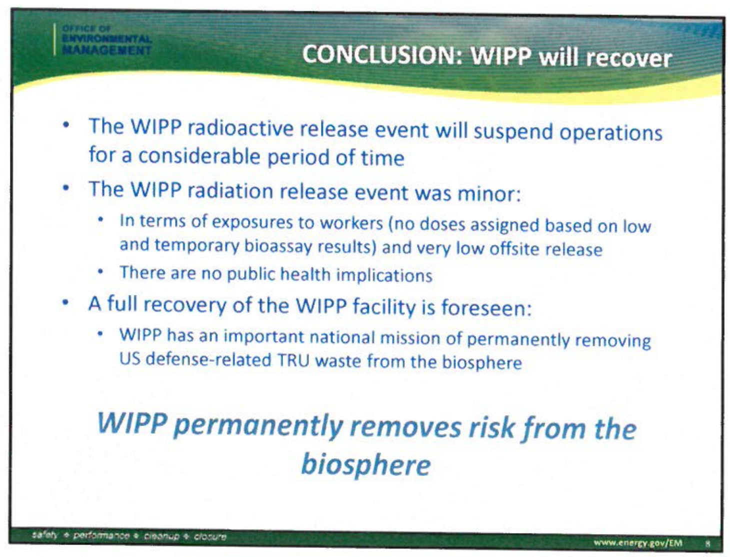
Key Recovery Steps toward Resumption of Operations

- **Nuclear Safety Document Revisions (continuing)**
- **Safety Management Program Revitalization (continuing)**
- **Underground restoration (underway)**
- **Expedite mine stability (bolting, underway)**
- **Initial Panel 6, Panel 7, Room 7 Closure (completed)**
- **Interim Ventilation (underway)**
- **Supplemental Ventilation Modifications (installation underway)**
- **Readiness Activities (planned)**
- **Resume Waste Emplacement Operations (initial emplacements to begin in 2016)**


OFFICE OF ENVIRONMENTAL MANAGEMENT
Mine Stability and Underground Habitability
• Two of the highest priorities related to mine safety:
• Bolting in both clean and contaminated areas
• Cleaning and refurbishment of waste hoist --allowing transport of equipment and personnel
safety ♦ performance ♦ cleanup ♦ closure
www.energy.gov/EM 5


OFFICE OF ENVIRONMENTAL MANAGEMENT
Preliminary closure of areas with suspect waste drums
• In compliance with a new Mexico Environment Department Compliance Order:
• Run of mine salt, chain-link fence and brattice cloth were placed against the waste-faces in Panel 6 and Panel 7-Room 7
• Steel bulkheads then effectively sealed these areas from underground ventilation air
Side view along disposal drift
MgO
Chain Link + Brattice Cloth
Steel Bulkhead
Waste Containers
ROM Salt
Rubber Flashing
~3 m
safety ♦ performance ♦ cleanup ♦ closure
www.energy.gov/EM 6


OFFICE OF ENVIRONMENTAL MANAGEMENT
"Fixing" Contamination in the Underground
• Water is sprayed to either remove or "fix" contaminant in place
• Selected application rate is 8 L/minute
• An elevated 3 m long mobile platform is used to safely extend upward reach
• Runoff arriving at rib-floor junction is absorbed into the floor matrix
• Takes contaminant with it
• Does not pool
• 95% efficacy at first pass
safety ♦ performance ♦ cleanup ♦ closure
www.energy.gov/EM 7


OFFICE OF ENVIRONMENTAL MANAGEMENT
CONCLUSION: WIPP will recover
• The WIPP radioactive release event will suspend operations for a considerable period of time
• The WIPP radiation release event was minor:
• In terms of exposures to workers (no doses assigned based on low and temporary bioassay results) and very low offsite release
• There are no public health implications
• A full recovery of the WIPP facility is foreseen:
• WIPP has an important national mission of permanently removing US defense-related TRU waste from the biosphere
WIPP permanently removes risk from the biosphere
safety ♦ performance ♦ cleanup ♦ closure
www.energy.gov/EM 8

Office of Environmental Management/Carlsbad Field Office

WIPP Panel Closure Using Run-of-Mine (ROM) Salt

Casey Gadbury
Carlsbad Field Office
US Department of Energy

Sandia National Laboratories
DBE TEC
PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology
NWSA
U.S. Department of Energy

6th US/German Workshop on Salt Repository Research, Design, and Operation
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OFFICE OF ENVIRONMENTAL MANAGEMENT

WIPP Panel Closure Using Run-of-Mine (ROM) Salt

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Carlsbad Field Office, US Department of Energy

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Contents

- Topic definition
- Current WIPP repository status
- Panel closure design initially selected by regulators
- Problems with initially selected panel closure design
- Basis for alternative Run of Mine (ROM) salt option proposed to federal regulator
- Technical support for ROM Panel Closure (ROMPC)
- ROMPC Performance Assessment
- Next step: state regulator approval process

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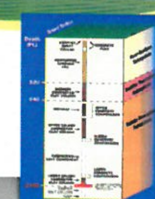
WIPP Repository Closures and Seals

- Shaft seals are not the subject of this presentation
- Room closures to isolate filled rooms from underground ventilation are not the subject of this presentation
- Preliminary panel closures to isolate panels from ventilation are not the topic of this presentation
- Final panel (seven rooms) closures are the topic of this presentation
  - Panel closures serve to isolate disposal units from each other over the very long term

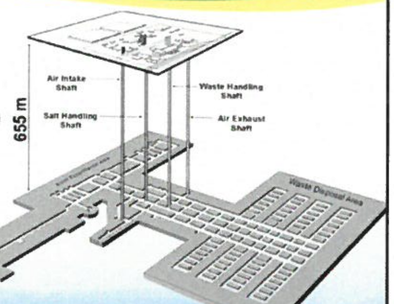


Shaft seal schematic

Preliminary panel closures

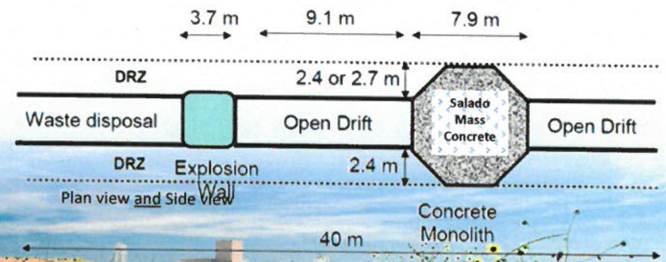
WIPP Disposal Concept

- Deep Geologic Repository in Salt
- Disposal of defense related transuranic (mixed) waste
- 10 panels (8 currently permitted)
- Each panel has seven disposal rooms
- Two access drifts per panel
  - Intake
  - Exhaust
- Five options for final panel closures were originally submitted: the regulator chose the most complex , and conservative option



Final Panel Closure Design Option Selected by Regulators

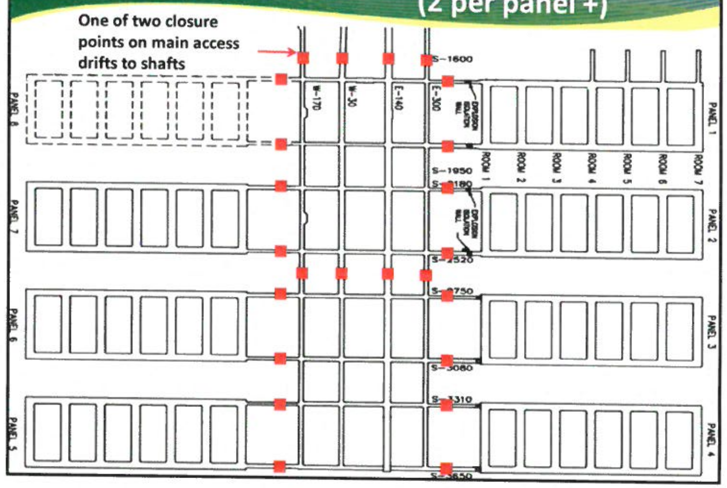
- Federal regulator (US Environmental Protection Agency--EPA) mandated a specific panel closure design (Condition 1 of the WIPP Certification under 40 CFR 194)
- State of New Mexico Environment Department (NMED) regulator adopted the EPA requirement as the disposal unit "closure"

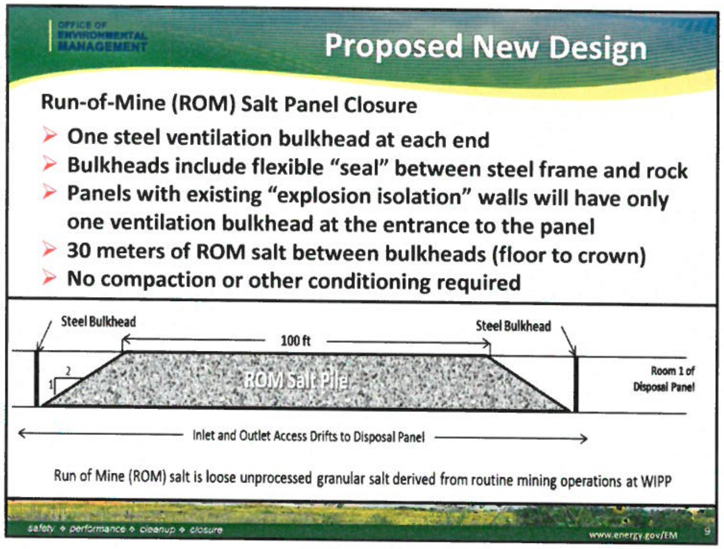


Concerns with Selected Complex Closure Option

- Cannot manufacture and deliver the Salado Mass Concrete to the given specifications while meeting the design requirements
- Hydrogen and methane monitoring data showed there is no need for explosion wall (original concept based on extreme conservatism)
- Design is very complex and expensive to construct
- Construction would impact disposal operations

...and there are many of them (2 per panel +)




OFFICE OF ENVIRONMENTAL MANAGEMENT
Proposed New Design
Run-of-Mine (ROM) Salt Panel Closure
One steel ventilation bulkhead at each end
Bulkheads include flexible "seal" between steel frame and rock
Panels with existing "explosion isolation" walls will have only one ventilation bulkhead at the entrance to the panel
30 meters of ROM salt between bulkheads (floor to crown)
No compaction or other conditioning required
Steel Bulkhead
100 ft
Steel Bulkhead
ROM Salt Pile
Room 1 of Disposal Panel
Inlet and Outlet Access Drifts to Disposal Panel
Run of Mine (ROM) salt is loose unprocessed granular salt derived from routine mining operations at WIPP
safety ♦ performance ♦ cleanup ♦ closure
www.energy.gov/EM
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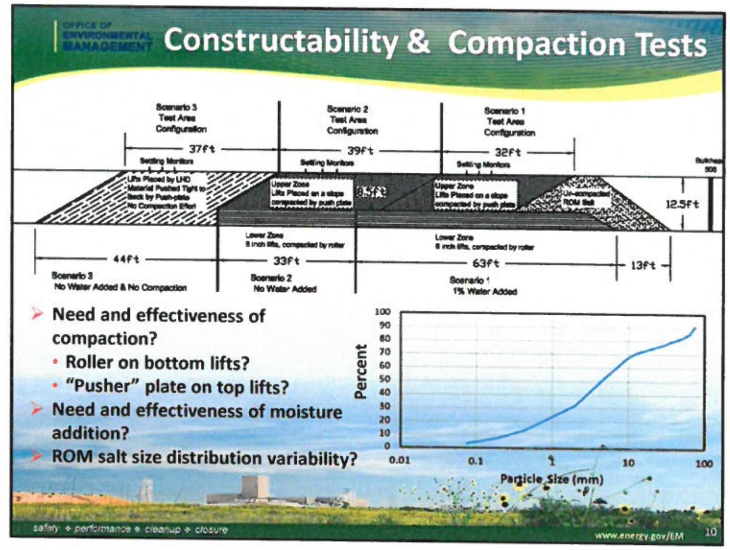
OFFICE OF ENVIRONMENTAL MANAGEMENT
Constructability & Compaction Tests
Scenario 3 Test Area Configuration
Scenario 2 Test Area Configuration
Scenario 1 Test Area Configuration
37ft
39ft
32ft
12.5ft
44ft
33ft
63ft
13ft
Scenario 3 No Water Added & No Compaction
Scenario 2 No Water Added
Scenario 1 1% Water Added
Need and effectiveness of compaction?
Roller on bottom lifts?
"Pusher" plate on top lifts?
Need and effectiveness of moisture addition?
ROM salt size distribution variability?
Percent
Particle Size (mm)
safety ♦ performance ♦ cleanup ♦ closure
www.energy.gov/EM
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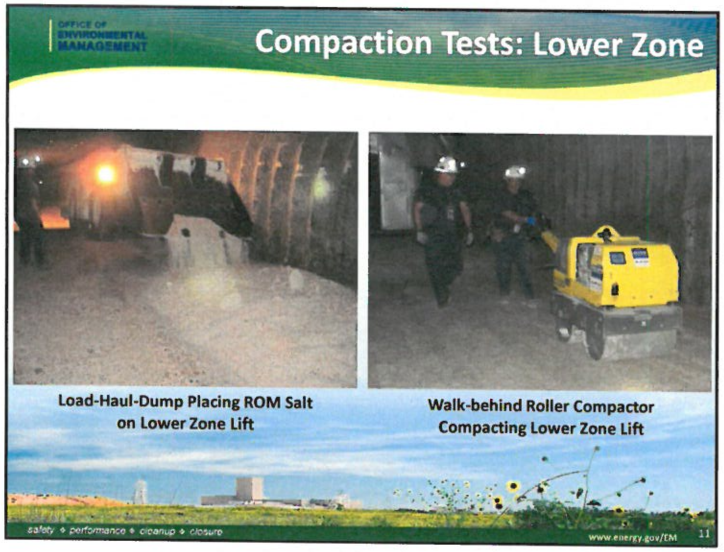
OFFICE OF ENVIRONMENTAL MANAGEMENT
Compaction Tests: Lower Zone
Load-Haul-Dump Placing ROM Salt on Lower Zone Lift
Walk-behind Roller Compactor Compacting Lower Zone Lift
safety ♦ performance ♦ cleanup ♦ closure
www.energy.gov/EM
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OFFICE OF ENVIRONMENTAL MANAGEMENT
Compaction Tests: Upper Zone
Pusher Plate Compacting Upper Zone
safety ♦ performance ♦ cleanup ♦ closure
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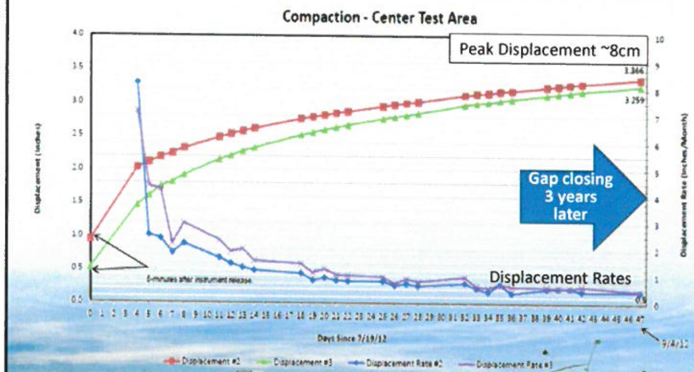
Estimated Settlement Data Based on Observations from Informal Tests



FLAC3D modeling

- Modeling predicts larger air gap forms with lower initial fractional density.
- In-situ testing shows the settling is much smaller than the FLAC3D modeling results (results in table below).
- Adding moisture (1-3%) during compaction did not aid in increasing the initial fractional density (reasons unclear and under investigation).

Top Layer/Bottom Layer	Peak Gap at Mid-Length of Fill (cm)	Peak Gap at End of Fill (cm)	Peak Gap Time (y)	Gap Duration at End of Fill (y)
65%/65%	47	43	2.5	22.8
65%/75%	26	21	2.3	13.7
72%/78%	7.5	3.4	1.4	3.7

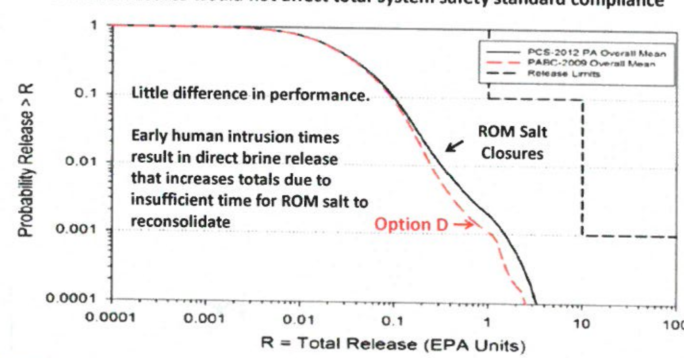
FLAC3D Results

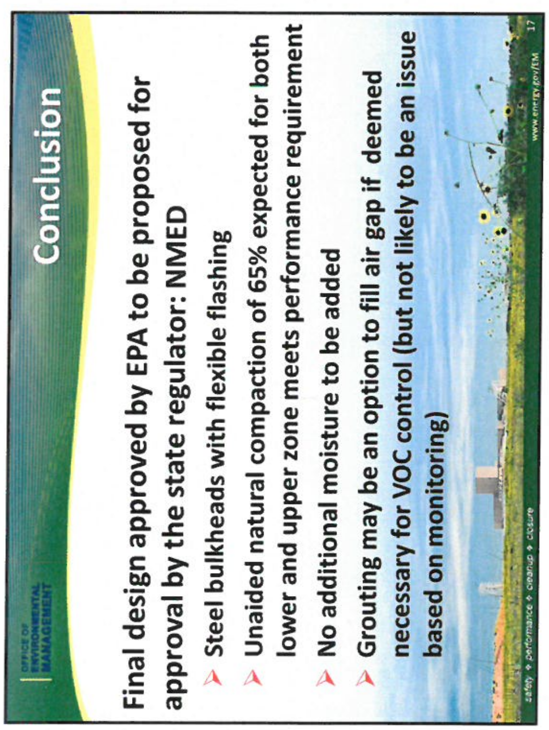
Parameters for Regulatory Analyses

- Numerous technical exchanges with the EPA to discuss concepts and testing results.
- Parameters for performance assessment to show compliance with long-term standards were developed over a period of 1½ years
  - Creep closure of the surrounding rock re-consolidates ROM salt, approaching conditions similar to intact halite
  - Imposed back stress on the surrounding rock will result in eventual healing of the DRZ
    - 0 to 100 years: Emplaced ROM salt undergoes some re-consolidation with no impact on surrounding rock
    - 100 to 200 years: Continued re-consolidation with no impact on surrounding salt rock
    - 200 to 10,000 years: ROMPC is re-consolidated and the surrounding salt rock returns to intact condition

Results: Total Releases

ROM salt closures would not affect total-system safety standard compliance




Conclusion
Final design approved by EPA to be proposed for approval by the state regulator: NMED
Steel bulkheads with flexible flashing
Unaided natural compaction of 65% expected for both lower and upper zone meets performance requirement
No additional moisture to be added
Grouting may be an option to fill air gap if deemed necessary for VOC control (but not likely to be an issue based on monitoring)
safety ❖ performance ❖ cleanup ❖ closure
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Plugging & Sealing project DOPAS

Dr.-Ing. Oliver Czaikowski
GRS, Repository Safety Research Division

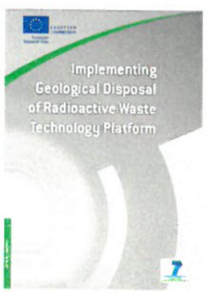
6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Agenda

- DOPAS
- National activities related to DOPAS
- GRS scientific program
- Experimental results

DOPAS partners

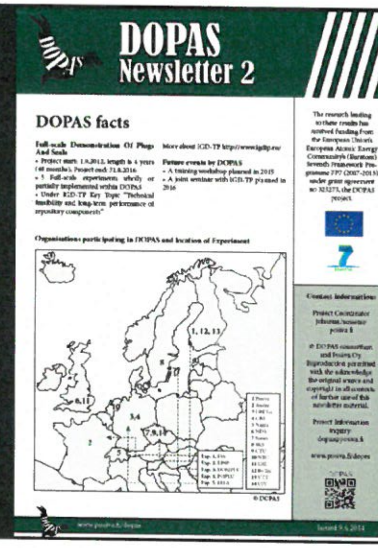
POSIVA, ANDRA, DBE TEC, GRS, Nagra, NDA, Rawra, SKB, CTU, NRG



Key Topics of the Strategic Research Agenda

- ...
- Key Topic 3:
  Technical feasibility and long-term performance of repository components

  Plugging and sealing (Topic 6)
- ...



Exp. 1. FSS
Exp. 2. EPSP
Exp. 3. DOMPLU
Exp. 4. POPLU
Exp. 5. ELSA

1 Posiva
2 Andra
3 DBETec
4 GRS
5 Nagra
6 NDA
7 Surao
8 SKB
9 CTU
10 NRG
11 GSL
12 B+Tec
13 VTT
14 UJV

DOPAS Demonstration Experiments

- **Experiment 1: FSS 1 (Full Scale Sealing)**
  Andra will be responsible for the Full Scale Seal (FSS) project which will be built inside a preexisting drift / tunnel or (more likely) inside a drift model above ground fabricated for the purpose at *URL Bure*.
- **Experiment 2: EPSP (Experimental Pressure and Sealing Plug)**
  CTU together with RAWRA is responsible for the demonstration test performed in *Josef underground facilities*. The Experimental Pressure and Sealing Plug (EPSP) Demonstrator will be constructed and operated in a small niche. In the Czech reference concept, bentonite from Czech deposits and new developed low pH–concretes are foreseen
- **Experiment 3: DOMPLU (full-scale DOMe shaped PLUg)**
  The design of the Swedish full-scale deposition tunnel end plug test was completed during 2011. In 2012 detailed activity plans are being compiled to be able to install the plug in a controlled manner. The SKB full-scale dome shaped plug demonstration (DOMPLU) with sealing parts will take place at *Äspö Hard Rock Laboratory* (Oskarshamn, Sweden)
- **Experiment 4: POPLU (POsiva PLUg)**
  This field work is a full-scale deposition tunnel plug experiment (POPLU) at the *ONKALO* demonstration area including a new and innovative way of excavation the plug location and installing a monitoring system for studying the plug performance in addition to the normal construction work.
- **Experiment 5: ELSA**
  The Federal Ministry of Economics and Energy (BMWi) contracted DBE TEC and GRS to pursue R&D-works for the development of shaft sealing concepts and for the qualification of sealing materials and elements for the safe closure of repositories in geological salt and clay formations containing heat generating high-level radioactive waste (HLW)

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ELSA Project

Phase 1
Boundary conditions and requirements for shaft seals in the host rocks salt and clay in Germany

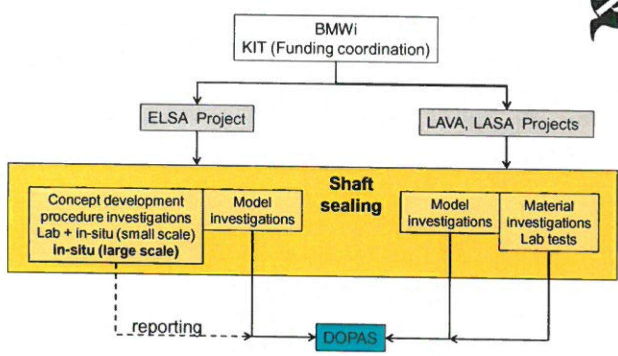
Phase 2
- Development of modular based shaft sealing concepts for salt and clay environment
- Laboratory and in-situ investigations on
  - compaction procedures for crushed salt
  - binary mixtures of prefabricated blocks + fine material
  - injection procedure for EDZ
  - specific bitumen elements
  - uniform bentonite plug saturation
- Process level modelling

Phase 3 (not yet decided)
ELSA-Experiment:
Large scale in-situ demonstration test of individual functional shaft sealing components (sealing and/or supporting modules)

DOPAS Project
(German part)

- Laboratory investigations by GRS (LASA, LAVA, THM-Ton):
  - THM experiments on sealing materials
  - CH experiments on sealing materials
- Process level modelling (DBETEC, GRS)
- Performance Assessment modelling (GRS)

National activities related to DOPAS



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GRS activities related to DOPAS

- **LASA** focusing on *mechanical-hydraulic* properties of candidate seal materials
- **LAVA** focusing on *chemical-hydraulic* properties of candidate seal materials
- **THM-Ton** focusing on the sealing capacity of argillaceous host rocks
- **PASS** focusing on model improvement and integrated long-term performance assessment with associated uncertainty and sensitivity analysis

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Acknowledgement

Federal Ministry for Economic Affairs and Energy

The authors gratefully acknowledge the funding of the European Commission under FP7 framework programme, contract no. FP7-323273 the DOPAS project and the funding received by the Federal Ministry for Economics and Energy (BMWi), represented by the Project Management Agency Karlsruhe (PTKA-WTE), contract no. 02E11122, 02E11132, 02E10377, 02E11142 .

TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
Die Ressourcenuniversität. Seit 1765.

Bundesministerium für Wirtschaft und Energie

PTKA Projektträger Karlsruhe
Karlsruher Institut für Technologie

Microstructure stabilized crushed rock salt backfill material for HAW-repositories in underground saliniferous rock formations

TU Bergakademie Freiberg
Institute of Mining Engineering and Special Civil Engineering

Prof. Dr.-Ing. Helmut Mischo
Dipl.-Ing. Sebastian Becker
Dr.-Ing. Matthias Gruner
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Fuchsmühlenweg 9
09599 Freiberg

Table of contents

1 Introduction

Nuclear Waste Disposal in Underground Geological Formations

Pro:
- Isolation of radionuclides from the biosphere
- Delay of the radionuclide release
- Passive security (Waste disposal over a long time period without any necessary human interactions)
- Prevention of un-/intentionally human access to the waste

Contra:
- High investment of time, research and costs to build a repository
- Human access to the deposit creates anthropogenic path for fluids
- Difficult re-entry to the waste after sealing the repository

1 Introduction

Properties of Saliniferous Rock Formations

Advantages:
- High creep capability
- High heat conductivity
- Low permeability

Disadvantages:
- Solvable with water
- Low sorption of radionuclides

Properties	Rock Salt	Clay	Granite
Heat conductivity	green	red	yellow
Permeability	green	green	yellow
Elasticity	green	yellow	red
Stability of cavities	green	red	yellow
Dissolubility resistance	red	green	green
Sorption ability	red	green	yellow
Solidity	yellow	yellow	green

2 Backfill in HAW-Repositories

Function of Backfill in HAW-Repositories

Purpose of backfilling in HAW-repositories:

- Stabilization of the surrounding rock
- Minimization of rock deformations

➡ Protection of the water-impermeable rock formations

- Decreasing possible paths for fluids

Guarantee of the long-term stability of the repository!

2 Backfill in HAW-Repositories

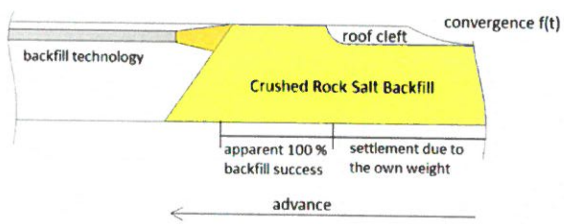
Possible Backfill Materials

Crushed Rock Salt:	Saliniferous composite backfill materials
+ Natural occurring material in a rock salt deposit	+ High backfill success reachable
+ Low acquisition costs	+ No settlements of the backfill
+ Easy manageable material	+ Roof clefts avoidable
	+ Fast support of the surrounding rock
- Late support of the surrounding rock	- High costs of the material
- Settlements of the backfill due to its own weight	- Labor-intensive
- Roof clefts not avoidable	- High amount of solution needed
- 100 % backfill success not possible	

The new backfill material is a combination of the two conventional backfill materials and closes the gap of knowledge.

3 Motivation for the Research Project

Difficulty of Crushed Rock Salt Backfill Material



➡ Clefts and gaps can cause potential path for fluids.

4 Microstructure Stabilized Crushed Rock Salt

Properties of the Microstructure Stabilized Crushed Rock Salt

- Adequate strength to support the surrounding rock
- 100 % refill of openings
- No settlement after putting the backfill into place
- Low permeability (10^{-14} m^2)
- Low content of a binding agent (about 5 mass-% in total)

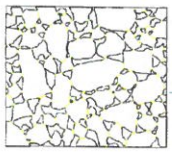
4 Microstructure Stabilized Crushed Rock Salt

Process of the grain structure stabilization of crushed rock salt

Dry Crushed Rock Salt — Binding Agent

Mixture

Phase 1



Formation of new long-term stable minerals

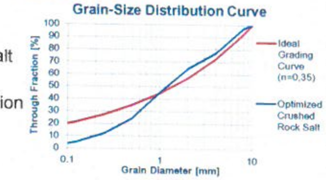
Phase 2

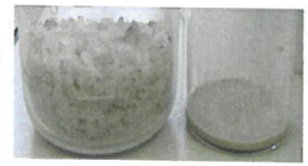
Fixation of the rock salt grains by the long-term stable minerals

4 Microstructure Stabilized Crushed Rock Salt

Components of the New Backfill Material

1. Optimized crushed rock salt
   - taken from a German rock salt mine production
   - optimized grain-size distribution
2. Binding agent
   - calcium sulfate hemihydrate ($CaSO_4 * 0,5\ H_2O$)
   - Potassium sulfate (K_2SO_4)
   - Kieserite, a magnesium sulfate ($MgSO_4 * H_2O$)
   - five molal magnesium chloride solution





4 Microstructure Stabilized Crushed Rock Salt

Process of the grain structure stabilization

- The stabilization of the grain structure is reached by the formation of long-term stable minerals.
- The components of the binding agent form new salt minerals and connect the rock salt grains with each other.
- The stabilization is realized in two steps:

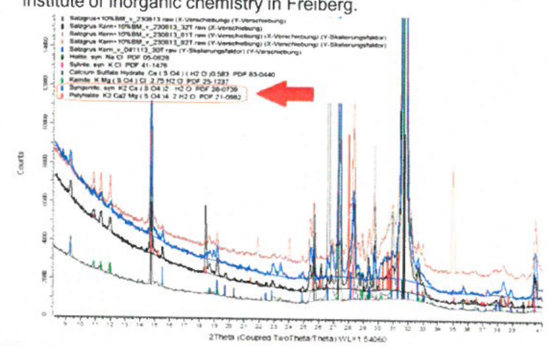
1. Formation of the mineral syngenite
2. Formation of the long-term stable mineral polyhalite

- The stabilization can take up to month but already after a few days the material develops suitable stability and hardness

4 Microstructure Stabilized Crushed Rock Salt

Verification of the grain structure stabilization

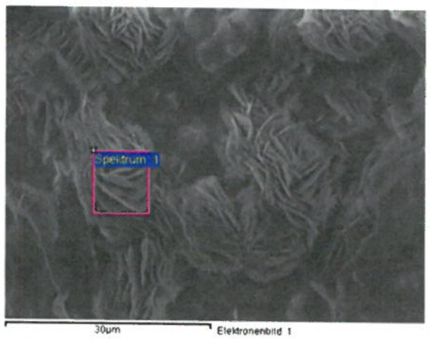
- The formation of long-term stable mineralization was verified by the institute of inorganic chemistry in Freiberg.



4 Microstructure Stabilized Crushed Rock Salt

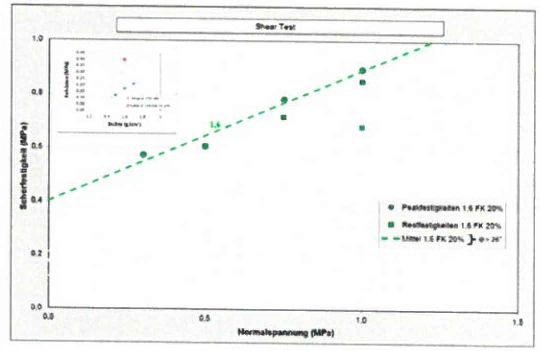
Verification of the grain structure stabilization by polyhalite

Polyhalite verification by EDX analysis.



4 Microstructure Stabilized Crushed Rock Salt

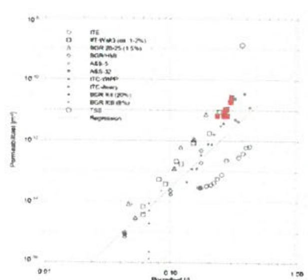
Increased strength by improvement of the cohesiveness



4 Microstructure Stabilized Crushed Rock Salt

Permeability

- Tests have shown that the porosity-permeability behavior of GESAV Material is comparable to common crushed rock salt
- The realizable permeability is mainly influenced by the density of the material after it was put into place



5 Summary

In the research project „Microstructure Stabilized Crushed Rock Salt" a new backfill material for HAW-repositories is developed.

The aim is to develop a backfill material…

- o with a low permeability after the emplacement
- o without any settlements and 100% backfill success
- o with a adequate strength to bear its own weight and support the surrounding rock after the emplacement
- o with a low liquid phase contents (< 5 mass-%)
- o with a formation of long-term stable structure support

Tests have shown that the developed material is able to fulfill the requirements. The results are:

- Low permeability (~ 10^{-12} m²)
- No settlement recognizable
- Increasing shear strength
- Development of long-term stable mineralization
- Low contents of the liquid phase

6 Outlook

Currently the material is still analyzed by different tests. These are:

- Compactation
- Hydraulic stability
- Mineralization change over time

The laboratory phase will end in April of 2016. A second phase is planed to examine the material behavior in-situ. Therefor practical emplacement tests with different technologies are planned to be carried out. The different backfill-bodies will be analyzed.

6 Outlook

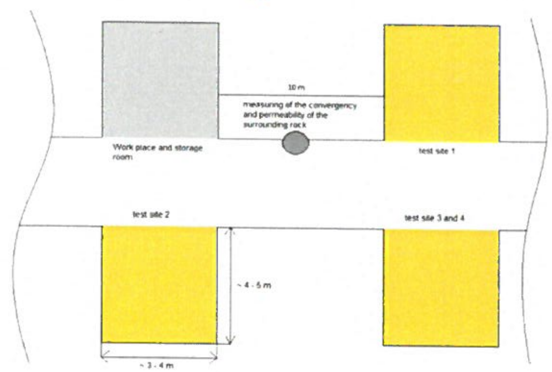
In-situ phase (current planning)

The in-situ phase has the following goals:

- Development of an underground test site at the Sondershausen salt mine
- Examination of the backfill material in-situ in the rock salt mine Sondershausen
- Test of 4 backfill technologies with the new backfill material
- Examination of the backfill material over a time period of 6 month
  - Density
  - Humidity
  - Temperature
  - Mineralization
  - Permeability
- After 6 month the backfill material will be removed and samples are taken for further analysis

6 Outlook

In-situ phase (current planning)



6 Outlook

In-situ phase (current planning)

Quelle: U. Glaubach; ELSA

Acknowledgment

Bundesministerium für Wirtschaft und Energie

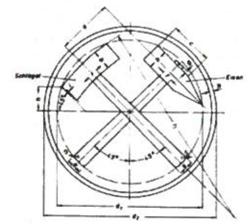
PTKA Projektträger Karlsruhe

The R&D Project, which the presented topic is based on, is funded by the German Federal Ministry for Economic Affairs and Energy under the support code 02E11092.

Our partner:

- Project Management Agency Karlsruhe
- Institute for Inorganic Chemistry of the TU Bergakademie Freiberg
- Institut für Gebirgsmechanik GmbH, Leipzig

Thank you for your attention



Glück Auf!

Sorel building material in salt formations

Daniela Freyer
Institute of Inorganic Chemistry,
TU Bergakademie Freiberg

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sorel Building Material

A new state-of-the-art

from Results of an interdisciplinary research concerning geochemical and geomechanical properties of the magnesia building material

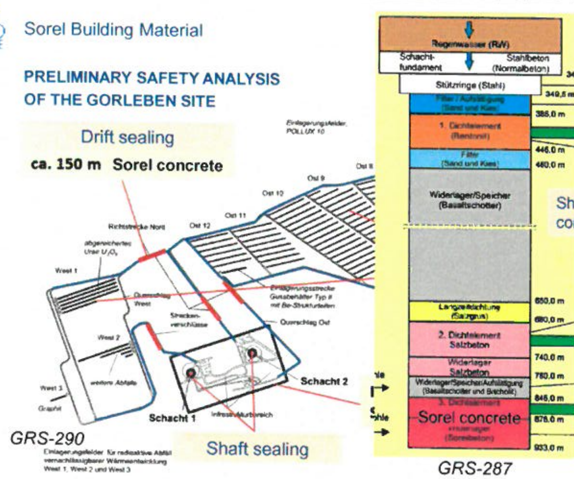
BMWi project (FKZ 02E10880)
"Relationship between geochemical and geomechanical properties of magnesia building material"

In collaboration with
IfAC – Institut für Anorganische Chemie / Institute of Inorganic chemistry
IfBuS – Institut für Bergbau u. Spezialtiefbau / Institute of Mining and Engineering
IfG – Institut für Gebirgsmechanik / Institute of Geomechanics, Leipzig

Sorel Building Material

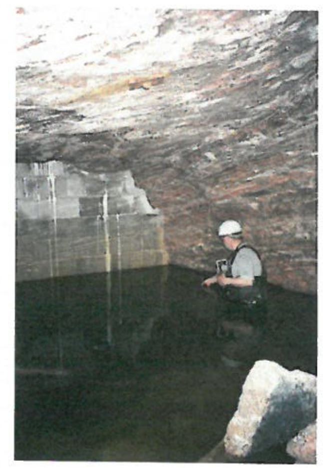
PRELIMINARY SAFETY ANALYSIS OF THE GORLEBEN SITE

Drift sealing
ca. 150 m Sorel concrete



Sorel Building Material

… more than 100 years practical experiences with the material for construction of dam or shaft seals

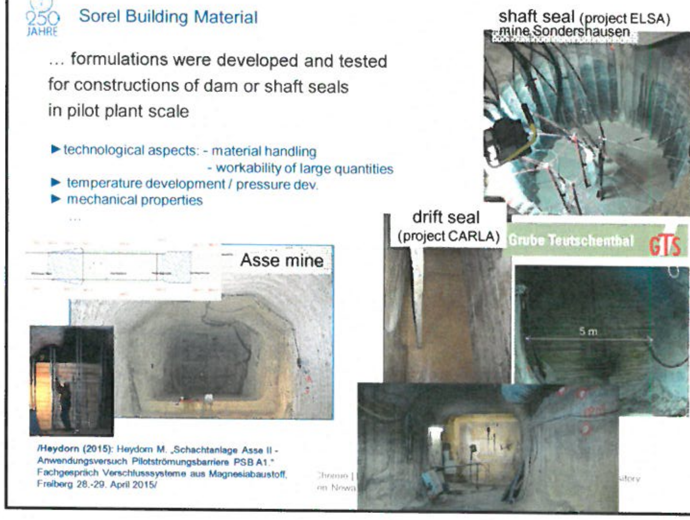


MgO-drift seal,
mine Bischoferode,
Solution acces side

Sorel Building Material

… formulations were developed and tested for constructions of dam or shaft seals in pilot plant scale

- technological aspects: - material handling
  - workability of large quantities
- temperature development / pressure dev.
- mechanical properties
- …



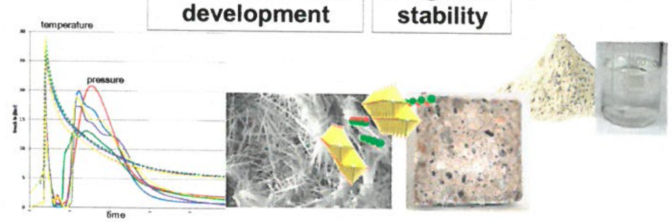
/Heydorn (2015): Heydorn M. „Schachtanlage Asse II - Anwendungsversuch Pilotströmungsbarriere PSB A1." Fachgespräch Verschlusssysteme aus Magnesiabaustoff, Freiberg 28.-29. April 2015/

Sorel Building Material

? ? ? ?

Formulation composition | Temperature development | Binder phase formation

Volume/Pressure development | Long term stability



Sorel Building Material

Complex investigation program

on relationships between

- **Formulation**
- **temperature development** during setting reaction, **binder phase formation** and subsequent **pressure development**
- **geomechanical properties** (strength, compaction and relaxation behavoir)
- behavior in case of solution access (: **long-term stability**)

Sorel Building Material

Long term stability - binder phase formation

? Thermodynamical stable binder phase(s) ?

➡ Knowledge about phase equilibria in the binder phase system !

Determination of solubility equlibria in the System $Mg(OH)_2 - MgCl_2 - H_2O$, 25°C – 120°C

Binder phase compositions:
x $Mg(OH)_2$ · **y** $MgCl_2$ · **z** H_2O
x-y-z: **3-1-8**
5-1-8, …

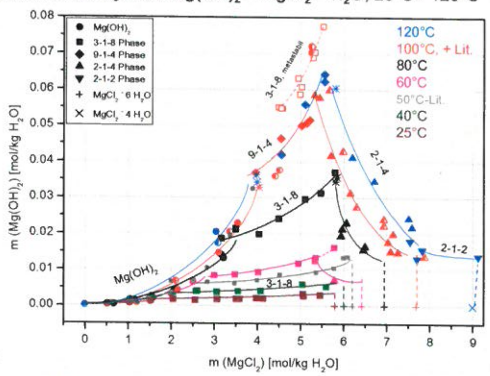
Sorel Building Material

Long term stability - binder phase formation

Solubility equlibria in the **System $Mg(OH)_2 – MgCl_2 – H_2O$**, 25°C - 120°C

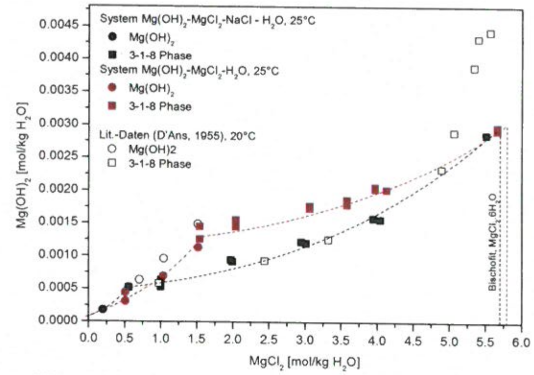
➡ thermodynamically stable up to 80°C: 3-1-8 phase, at higher temperatures: 9-1-4 phase

➡ no existing field for the 5-1-8 phase (metastable)



Sorel Building Material

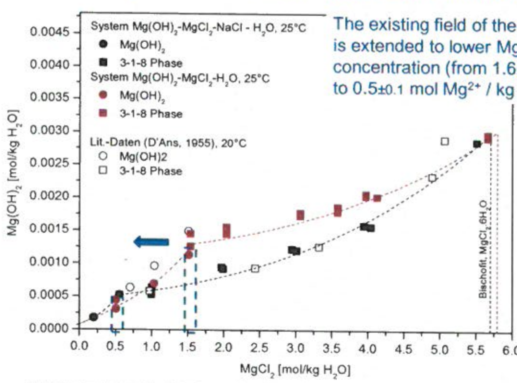
… solubility at NaCl saturation (Rock salt „conditions“)



Sorel Building Material

… solubility at NaCl saturation (Rock salt „conditions“)

The existing field of the 3-1-8 phase is extended to lower $MgCl_2$ solution concentration (from 1.6±0.1 ,NaCl-free) to 0.5±0.1 mol Mg^{2+} / kg H_2O !



Sorel Building Material

Formulation - Binder phase formation

► Long therm stable dam or shaft seal should consits of 3-1-8 phase

► Formulation with MgO : $MgCl_2$: H_2O ratio

$$3\ MgO + MgCl_2 + 11\ H_2O \rightarrow 3\ Mg(OH)_2 \cdot MgCl_2 \cdot 8\ H_2O$$

under considerations of MgO-reactivity and -quality

under the technological aspect of workability:
viscosity and consistency to avoid sedimentation

Rotation viscosimeter

Sorel Building Material

Formulation - binder phase formation

„3-1-8 formulation"

components	amount
MgO	18.7 % (cav* 200-300s) Company Lehmann & Voss, 95% MgO-purity
$MgCl_2$-solution	43.9% 5 mol $MgCl_2$ /kg H_2O
crystaline quartz powder, SiO_2	37.4%
mol ratio $MgO : MgCl_2 : H_2O$	3 : 1 : 11

*cav: citric acid value = reactivity for MgO

Sorel Building Material

Formulation - binder phase formation

„3-1-8 formulation"

C3

components	amount
MgO	18.7 % (cav* 200-300s) Company Lehmann & Voss, 95% MgO-purity
$MgCl_2$-solution	43.9% 5 mol $MgCl_2$ /kg H_2O
crystaline quartz powder, SiO_2	37.4%
mol ratio $MgO : MgCl_2 : H_2O$	3 : 1 : 11

*cav: citric acid value = reactivity for MgO

Sorel Building Material

Formulation - binder phase formation

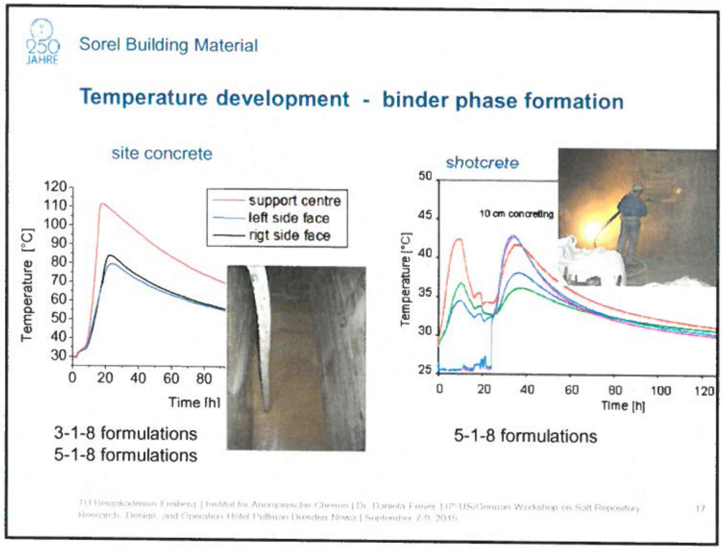
„3-1-8 formulation"

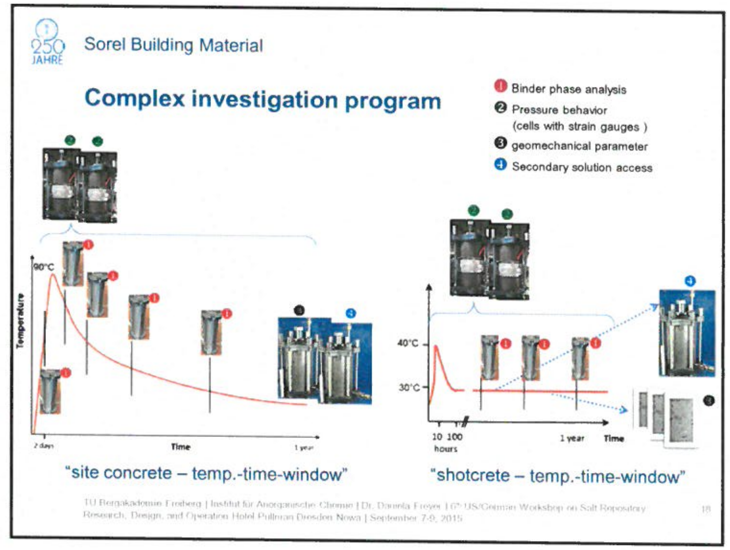
components	C3 amount	C3 concrete
MgO	18.7 % (cav* 200-300s) Company Lehmann & Voss, 95% MgO-purity	6.75%
$MgCl_2$-solution	43.9% 5 mol $MgCl_2$ /kg H_2O	15.82%
crystaline quartz powder, SiO_2	37.4%	77.42% (+ sand/gravel)
mol ratio $MgO : MgCl_2 : H_2O$	3 : 1 : 11	3 : 1 : 11

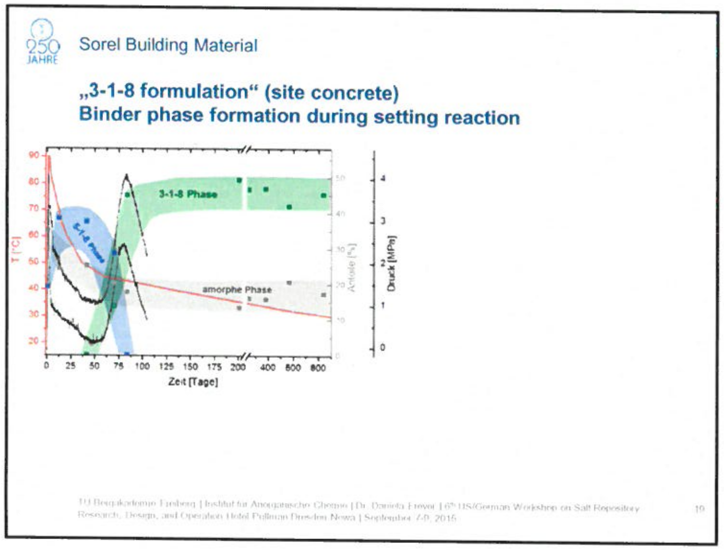
*cav: citric acid value = reactivity for MgO

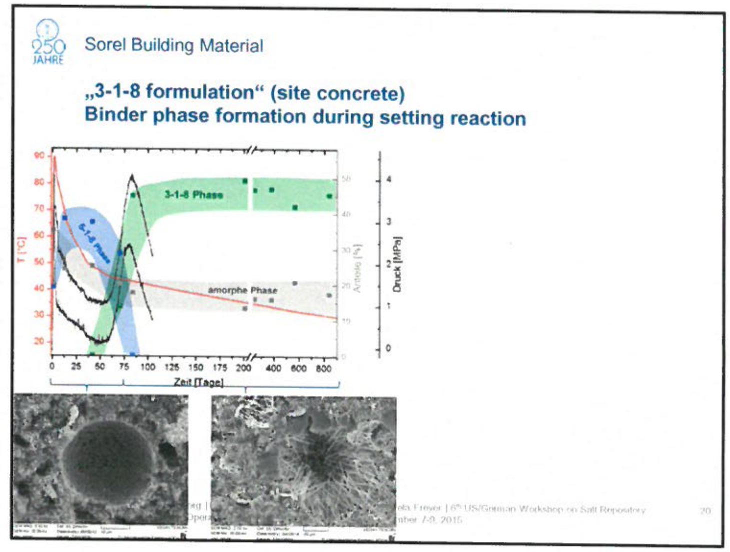
Sorel Building Material - Formulations

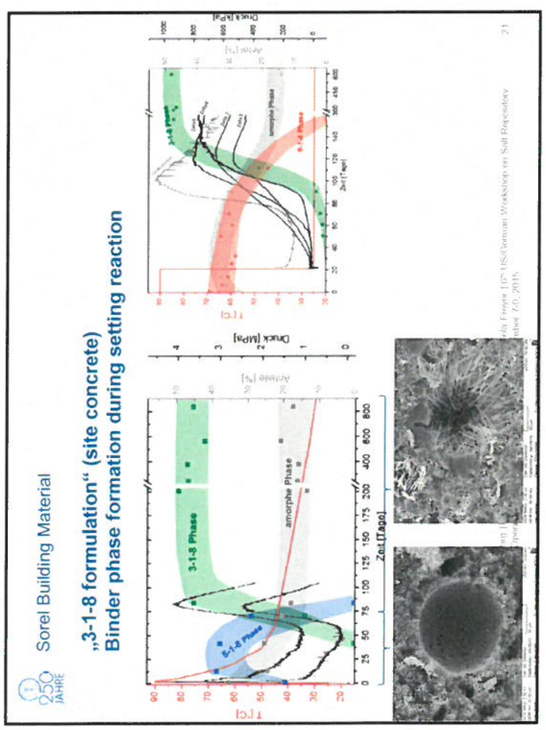
	„3-1-8 formulations"			„5-1-8 formulation"
Formulation components	DBM2	A1	C3 cement	D4
MgO (cav_reactivity[s], pH7)	10.5 % MgO 250±50 s	11.3 % MgO 100-300 s	18.7 % MgO 250±50 s	15.95 % MgO 250±50 s
Mixing solution	20.8 % $MgCl_2$-Lsg. (390-430 g/L, S-30 comp. Deusa)	25.0 % $MgCl_2$-Lsg. (ca. 400 g $MgCl_2$/L, density 1.32 g/cm³)	43.9 % $MgCl_2$-Lsg (5 molal)	15.95 % $MgCl_2$-Lsg. (5 molal)
additives	34.3 % sand 29.5 % anhydrit 4.5 % microsilica (amorphous SiO_2)	63.7 % rock salt	37.4 % quartz powder (SiO_2, crystaline)	68.1% sand/gravel 0-8 mm
Mol ratio $MgO : MgCl_2 : H_2O$	3.5 ... 3.7 : 1 : ~11	3.1 ... 3.3 : 1 : ~ 11	3 ... 3.1 : 1 : 11	6.9 ... 7.3 : 1 : 11
-> binder phases	3-1-8, 5-1-8	3-1-8, 5-1-8	3-1-8	5-1-8, MgO

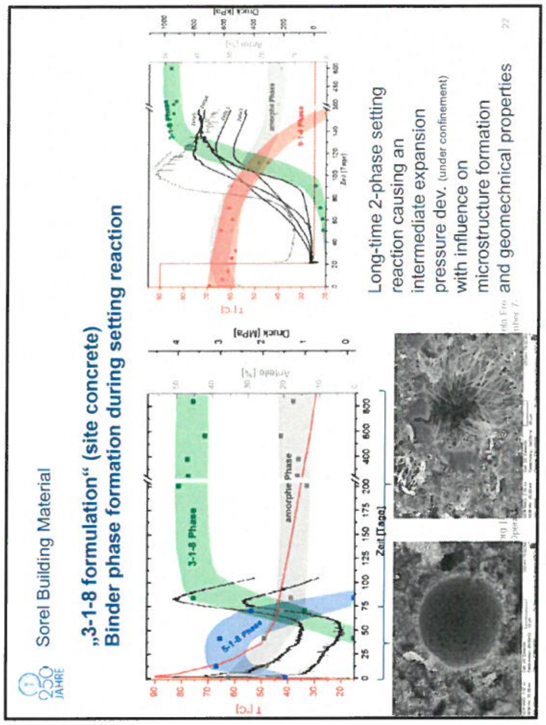

Sorel Building Material
Temperature development - binder phase formation
site concrete
support centre
left side face
rigt side face
Temperature [°C]
Time [h]
3-1-8 formulations
5-1-8 formulations
shotcrete
10 cm concreting
Temperature [°C]
Time [h]
5-1-8 formulations

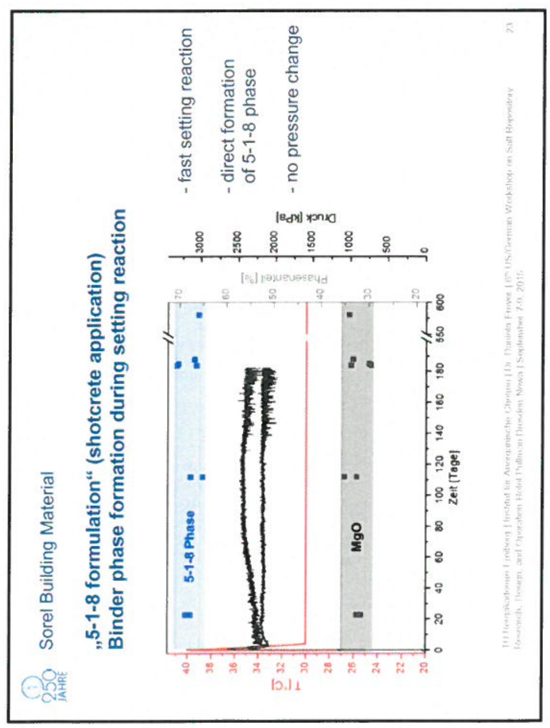

Sorel Building Material
Complex investigation program
1 Binder phase analysis
2 Pressure behavior (cells with strain gauges)
3 geomechanical parameter
4 Secondary solution access
Temperature
Time
"site concrete – temp.-time-window"
"shotcrete – temp.-time-window"

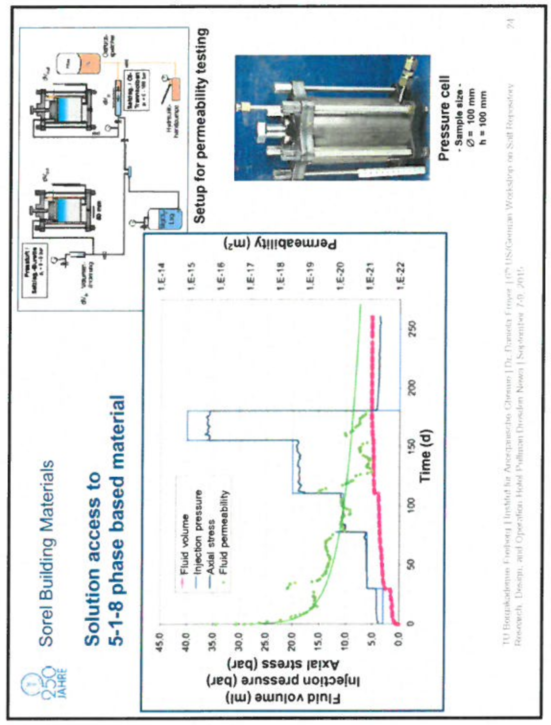

Sorel Building Material
„3-1-8 formulation“ (site concrete)
Binder phase formation during setting reaction
3-1-8 Phase
5-1-8 Phase
amorphe Phase
T [°C]
Druck [MPa]
Zeit [Tage]


Sorel Building Material
„3-1-8 formulation“ (site concrete)
Binder phase formation during setting reaction
3-1-8 Phase
5-1-8 Phase
amorphe Phase
T [°C]
Druck [MPa]
Zeit [Tage]


Sorel Building Material
„3-1-8 formulation" (site concrete)
Binder phase formation during setting reaction
3-1-8 Phase
5-1-8 Phase
amorphe Phase
Zeit [Tage]
T [°C]
Druck [MPa]
21


Sorel Building Material
„3-1-8 formulation" (site concrete)
Binder phase formation during setting reaction
3-1-8 Phase
5-1-8 Phase
amorphe Phase
Zeit [Tage]
T [°C]
Druck [MPa]
Long-time 2-phase setting reaction causing an intermediate expansion pressure dev. (under confinement) with influence on microstructure formation and geomechnical properties
22

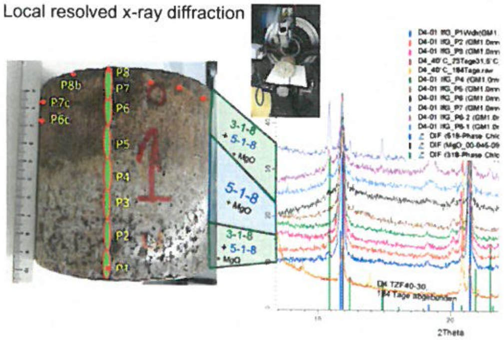

Sorel Building Materials
„5-1-8 formulation" (shotcrete application)
Binder phase formation during setting reaction
5-1-8 Phase
MgO
Zeit [Tage]
T [°C]
Phasenanteil [%]
Druck [kPa]
- fast setting reaction
- direct formation of 5-1-8 phase
- no pressure change
23


Sorel Building Materials
Solution access to 5-1-8 phase based material
Fluid volume
Injection pressure
Axial stress
Fluid permeability
Fluid volume (ml)
Injection pressure (bar)
Axial stress (bar)
Permeability (m²)
Time (d)
Setup for permeability testing
Pressure cell
- Sample size -
Ø = 100 mm
h = 100 mm
24

Sorel Building Material

Solution access to 5-1-8 phase based material

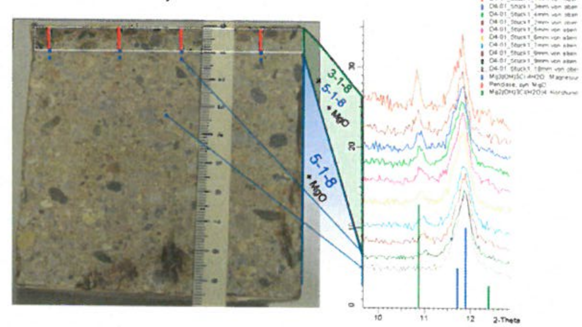
Local resolved x-ray diffraction



Sorel Building Material

Solution access to 5-1-8 phase based material

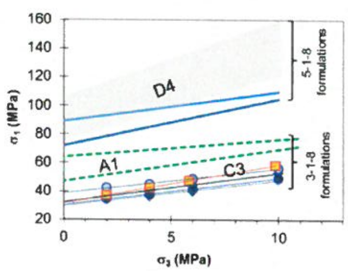
Local resolved x-ray diffraction



Sorel Building Materials

Geomechanical parameter

Strength behavior



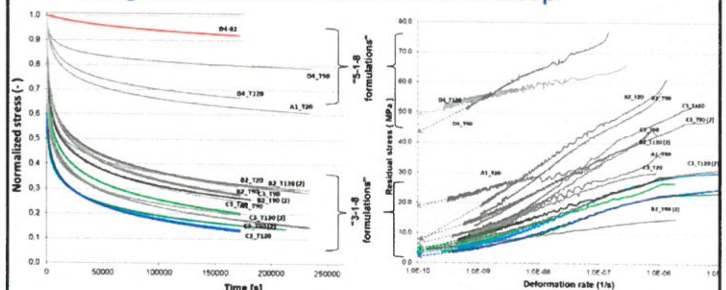
MOHR-COULOMB-diagrams of investigated formulations:

(results of multi-step strength tests)

Axial stress (σ_1) vs. radial stress (σ_3)

Sorel Building Materials

Long term behavior: Relaxation and creep



Relaxation test procedure:

1. Triaxial deformation test up to 80% of the strength
2. At the given stress level, the axial deformation is held constant ⇒ $\dot{\varepsilon}$ ⇒ **Time dependent stress decrease**

Sorel Building Material

Summary (1) – application tool box

Magnesia building material is ...

geomechanical properties

processible — **as site concrete**: as 3-1-8 formulations, as 5-1-8 formulations | **as shotcrete**: as 5-1-8 formulations

with temperature development: **high** | **low**

pressure development (under confinement)
for 3-1-8 formulations:
intermediate expansion pressure
for 5-1-8 formulations: **constant**

5-1-8 formulations:	3-1-8 formulations:
very high strength, low relaxation effects under high loadings	**high, but relatively lower strength, higher compaction behavior, pronounced stress relaxation behavior**
↓ **"stiff" plug/abutment**	↓ **"weak" inclusion**

MgO-concrete types show very low permeability properties (generally lower than 10^{-19} m^2).

Sorel Building Material

Summary (2) – long term stability

Magnesia building material with ...

geochemical properties

3-1-8 binder phase	5-1-8 binder phase
↓ thermodynamically stable phase (up to 80°C)	↓ metastable phase

in presence of salt solution*

long-term safety analysis feasible

based on solubility equilibria	based on hydro-mechanical integrity

* sat. NaCl-solution with at least 0.5 mol Mg^{2+}/kg H_2O

Update on the ABC-Workshop and Pitzer-database

M. Altmaier, *KIT-INE,* **D. Reed** *LANL-CO* **V. Metz,** *KIT-INE,*

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

KIT – University of the State of Baden-Württemberg and National Large-scale Research Center of the Helmholtz Association

(1) Pitzer State-of- Art-Report

OECD Nuclear Energy Agency Thermochem. Database Project

(2) Int'l Workshop on Actinide-Brine-Chemistry, ABC-Salt (IV)

OECD Nuclear Energy Agency Salt Club Activity

Institute for Nuclear Waste Disposal/ KIT

NEA-TDB: Pitzer State-of-Art-Report

Within the scope of **OECD Nuclear Energy Agency (NEA) Thermochemical Database (TDB) Project,**

preparation of **State-of-Art-Report (SOAR)** to assess modeling and experimental approaches used to describe aquatic chemistry and thermodynamics of high ionic-strength solutions - kick-off in April 2015

Assessing modelling & experim. approaches regarding highly saline systems

- Actinides (Am, Cm, Np, Pu, U + Th, Zr …) and inorganic ligands (CO_3^{2-} …)
- actinides (Am, Cm, Np, Pu, U + Th, Zr …) and organic ligands (citrate …)
- heavy metals and iron
- chemistry of spent nuclear fuel reprocessing systems
- oceanic salt system Na-K-Mg-Ca-H-Cl-SO_4-OH-HCO_3-CO_3-CO_2-H_2O

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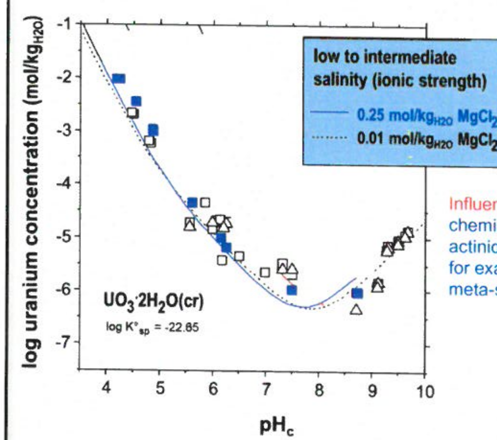
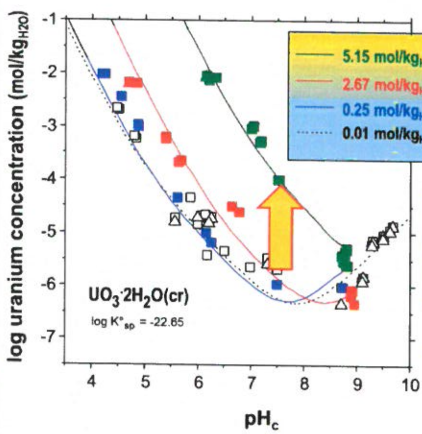
NEA-TDB: Pitzer State-of-Art-Report



Influence of salinity on aquatic chemistry & thermodynamics of actinides →
for example: solubility of meta-schoepite $UO_3{:}2H_2O(cr)$

Institute for Nuclear Waste Disposal/ KIT

NEA-TDB: Pitzer State-of-Art-Report



$UO_3 \cdot 2H_2O(cr)$: Two orders of magnitude higher solubility in saline systems compared to diluted systems

Similar salinity effects for Am(III), Np(V), Pu(III), Tc(IV) …

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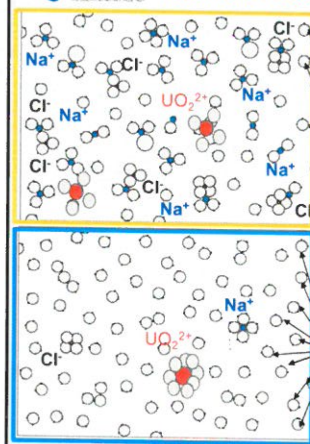
NEA-TDB: Pitzer State-of-Art-Report

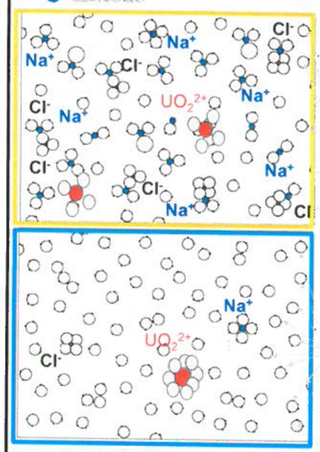


Between saline and diluted systems, differences in solubility of uranium

- are related to differences in chemical water activity a(H_2O),
- and related to binary and ternary interactions amongst dissolved species

Institute for Nuclear Waste Disposal/ KIT

NEA-TDB: Pitzer State-of-Art-Report



Pitzer formalism used for calculating chemical activity of water and chemical activities of dissolved species (e.g. radionuclides)

$$\ln\gamma_M = z_M^2 F + \sum_a m_a (2 \cdot B_{Ma} + zC_{Ma})$$

$$+ \sum_c m_c \left(2 \cdot \Phi_{Mc} + \sum_a m_a \Psi_{Mca}\right)$$

$$+ \sum_{a<}\sum_{a'} m_a m_{a'} \Psi_{Maa'} + |z_M| \sum_c \sum_a m_c m_a C_{ca} + 2\sum_n m_n \lambda_{Mn}$$

binary interactions – Ma, cX: $\beta^{(0)}$, $\beta^{(1)}$, $\beta^{(2)}$, C^{ϕ}
ternary interactions θ_{Mc}, θ_{Xa}, $\Psi_{McaMaa'}$, $\Psi_{cXa/cc'X}$
interactions with neutral species: λ_{Mn}, λ_{nX}
M, c, c': cations; a, a' X: anions; n: neutral species

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NEA-TDB: Pitzer State-of-Art-Report

State-of-the-Art Report (SOAR) on modelling and experimental approaches used to describe high ionic-strength systems

- Review existing data for "oceanic" salt system, metals, organics and key radionuclides (in particular actinides)
- Identify strengths and weaknesses in existing Pitzer data
- Identify data gaps and needs to guide ongoing and future studies

→ *Sections and contributors of SOAR*

→ *Examples: complexes of Th, U, Np, Pu*

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NEA-TDB: Pitzer State-of-Art-Report

Sections and contributors of Pitzer State-of-the-Art Report (SOAR)

- Introduction - SOAR coordinators M. Altmaier (KIT-INE, Germany) and D. Reed (LANL-CO, USA)
- Critical assessment of Pitzer model - A. Felmy (retired, PNNL/WSU, USA)
- Oceanic salt system - W. Voigt (Technical University Freiberg, Germany)
- Heavy metals, Fe - H. Moog (GRS, Germany), L. Brush (retired, SNL, USA)
- Actinides inorganic - M. Altmaier (KIT-INE, Germany), D. Reed (LANL-CO, USA)
- Actinides organic - D. Reed (LANL-CO, USA), M. Altmaier (KIT-INE, Germany)
- Process chemistry (reprocessing context) - W. Runde (LANL, USA)
- Critical summary - All authors will contribute to writing the summary

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Example: Actinide Complexes

Authors: M. Altmaier (KIT-INE, Germany), D. Reed (LANL-CO, USA)

- Salt systems: NaCl, KCl, $MgCl_2$ and $CaCl_2$
- Discussed along actinide oxidation states (III) to (VII), not elements:
  - Th(IV), U(IV,VI), Np(IV,V,VI), Pu(III,IV,V,VI), Am(III,V), Cm(III)
- Chemical analogs included in actinides section
  - Eu(III), Nd(III)
  - Zr(IV)
- Technetium (IV, VII) included in actinides section
- Inorganic ligands:
  - OH^-, Cl^-, F^-, CO_3^{2-}, NO_3^-, SO_4^{2-}, phosphates, silicates, borates
- Organic ligands: EDTA, Citrate, Oxalate, Acetate, ISA, Gluconate …
  - including discussion of Pitzer models for ligands…

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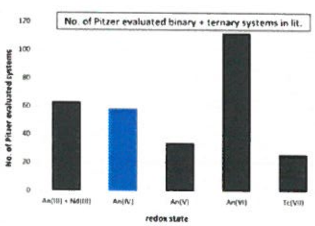
Tetravalent actinides (An)
Th(IV), U(IV), Np(IV), Pu(IV) + Tc(IV)



Pitzer parameters available for:

- Uncomplexed An^{4+}
  Ion interaction parameters for:
  Cl^-, ClO_4^-, NO_3^-, HSO_4^-, SO_4^{2-}
- Binary An-complexes An-X
  with X = OH^-, F^-, CO_3^{2-}, SO_4^{2-}, acetate, lactate
  Ion interaction parameters for:
  Cl^-, ClO_4^-, NO_3^-, HSO_4^- (anions)
  Li^+, Na^+, K^+, H^+, NH_4^+ (cations)
- Ternary An-complexes An-OH-Y
  with Y = ISA, EDTA, $H_3SiO_4^-$, Ca^{2+}
  Ion interaction parameters for Cl^-, ClO_4^-, Na^+

≈ 60 systems in 21 relevant "Pitzer publications"

[1988aKIM/FRE], [1991FEL/RAI], [1992FEL/RAI], [1992ROY/VOG], [1993FEL/RAI], [1997FEL/RAI], [1997RAI/FEL], [1998RAI/FEL], [1999FEL/RAI], [1999RAI/HES], [1999bRAI/HES], [1999MOO/BOR], [2001CHA/MOI], [2003RAI/HES], [2003XIA/FEL], [2004HES/XIA], [2008RAI/FEL], [2008RAI/YIU], [2009ALT/NEC], [2010FEL/NEC]

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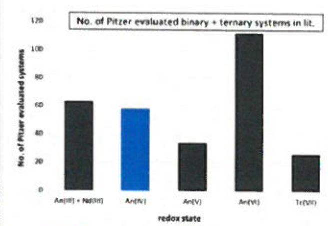
Tetravalent actinides (An)
Th(IV), U(IV), Np(IV), Pu(IV) + Tc(IV)



Relevant for strongly reducing conditions (anoxic corrosion of waste container)

Pitzer parameters available for:

- Uncomplexed An^{4+}
  Ion interaction parameters for:
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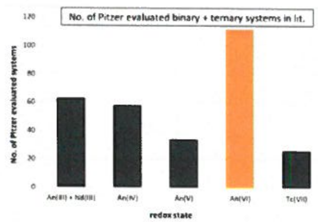
NEA

Hexavalent actinides (An): uranium and plutonium

Los Alamos | KIT

Pitzer parameters available for:

- Uncomplexed AnO_2^{2+}
  Ion interaction parameters for:
  Cl^-, ClO_4^-, NO_3^-, SO_4^{2-}
- Binary An-complexes AnO_2-X
  with X = OH^-, CO_3^{2-}, SO_4^{2-}, organics (acetate, lactate, malonate, succinate, EDTA)
  Ion interaction parameters for:
  Cl^-, ClO_4^-, NO_3^-, SO_4^{2-} (anions)
  Li^+, Na^+, Mg^{2+}, Ca^{2+} (cations)
- Ternary An-complexes AnO_2-OH-Y
  with Y = SO_4^{2-}, organics (acetate, malonate, succinate, …)
  Ion interaction parameters for Cl^-, SO_4^{2-}, Na^+



More than hundred systems in 14 relevant "Pitzer publications"

[1988aKIM/FRE], [1988bKIM/FRE], [1989YAN/PIT], [1991PIT], [1997PAS/CZE], [1998POK/BRO], [1999APE], [1999MOO/BOR], [2001MOY/BAE], [2002RAI/FEL], [2004GIA/MIL], [2005FEL/XIA], [2007CRE/DES], [2008CRE/FOT]

Institute for Nuclear Waste Disposal/ KIT

NEA

Hexavalent actinides (An): uranium and plutonium

Los Alamos | KIT

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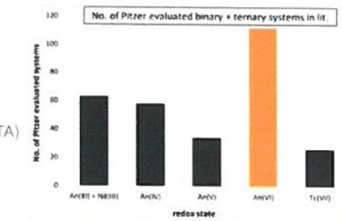
  with Y = SO_4^{2-}, organics (acetate, malonate, succinate, …)
  Ion interaction parameters for Cl^-, SO_4^{2-}, Na^+



Still missing interaction parameters relevant to geochemical milieus of salt based repositories, e.g. AnO_2-OH-Y

More than hundred systems in 14 relevant "Pitzer publications"

[1988aKIM/FRE], [1988bKIM/FRE], [1989YAN/PIT], [1991PIT], [1997PAS/CZE], [1998POK/BRO], [1999APE], [1999MOO/BOR], [2001MOY/BAE], [2002RAI/FEL], [2004GIA/MIL], [2005FEL/XIA], [2007CRE/DES], [2008CRE/FOT]

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NEA

NEA-TDB: Pitzer State-of-Art-Report

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State-of-the-Art Report (SOAR) on modelling and experimental approaches used to describe high ionic-strength systems

- Identify strengths and weaknesses in existing Pitzer data
- Review existing data for "oceanic" salt system, metals, organics and key radionuclides (in particular actinides)
- Identify data gaps and needs to guide ongoing and future studies

Good review team with experts from German and US institutions.

First draft expected by end 2016; publication of Pitzer State-of-Art-Report expected for end 2017

Specific data recommendations will not be made – and - Pitzer State-of-Art-Report will not present a workable database! → NEA Salt Club initiative

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Pitzer Database Activity within NEA Salt Club

Los Alamos | KIT

- Complementary to the SOAR within NEA-TDB, which is focusing on the present(!) state-of-art, a Joint International Pitzer Database Working Group (JIPD-WG) within NEA Salt Club is forming to discuss future steps.
- JIPD-WG focuses exclusively on future joint activities to establish a mutually accepted and highly quality-assured international Pitzer database.
- JIPD-WG has a primary focus on topics related to nuclear waste disposal in deep underground repositories in rock salt.
- NEA Salt Club members have already expressed interest to contribute.
- JIPD-WG invites broad international participation from within and outside the NEA Salt Club.

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Joint Int'l Pitzer Database Working Group

Groups interested to join Joint Int'l Pitzer Database discussions within NEA Salt Club are asked to → contact JIPD-WG (see below), indicating background and interests.

For the institutions having expressed interest in JIPD-WG, points of contact are:

Marcus Altmaier, marcus.altmaier@kit.edu, KIT-INE, Germany
Don Reed, dreed@lanl.gov, LANL, USA
Helge Moog, helge.moog@grs.de, GRS, Germany
Christi Leigh, cdleigh@sandia.gov, SNL, USA

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(1) Pitzer State-of- Art-Report (NEA-TDB)

(2) Int'l Workshop on Actinide-Brine-Chemistry, ABC-Salt (IV)

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ABC-Salt workshop series

ABC-Salt(I) 15-16 Sep. 2010 in Carlsbad, USA, with 40 participants from 4 countries

ABC-Salt(II) 7-8 Nov. 2011 in Karlsruhe, Germany, with 80 participants from 8 countries

ABC-Salt(III) 15-17 April 2013 in Santa Fe, USA, with 60 participants from 8 countries

Institute for Nuclear Waste Disposal (INE)

ABC-Salt workshop series

ABC-Salt(IV)
Int'l workshop on Actinide-Brine-Chemistry was held 14-15 April 2015 in Heidelberg, Germany, with 60 participants from 8 countries

(INE)

ABC-Salt (IV) workshop: organization / topics

Workshop served as a platform for exchange of new scientific results and discuss advanced approaches to establish a better understanding of the aqueous geochemistry and radiochemistry required to describe the long-term safety of a salt-based nuclear waste repository

ABC-SALT (IV) was co-organised by KIT-INE and LANL-CO, sponsored in part by BMWi and DOE, and was integrated in NEA Salt Club activities

ABC-SALT (IV) consisted of invited and contributed talks and a poster session for the presentation of additional topics and focus upon:

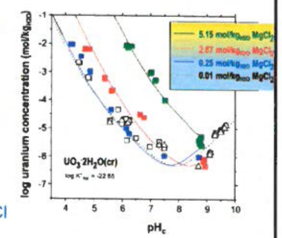
- Overview talks on current repository projects
- Actinide chemistry in brines
- Brine chemistry and brine evolution
- Microbial effects in brines
- Thermodynamic databases and modeling studies

Waste Isolation Pilot Plant
www.wipp.energy.gov

Institute for Nuclear Waste Disposal (INE)

ABC-Salt (IV) workshop: organization / topics

- **Overview talks on current repository projects**
  e.g. WIPP operational and regulatory status, disposal concepts in Germany and Canada
- **Actinide chemistry in brines**
  e.g. actinide speciation and solubility in concentr. solutions, actinide retention by brucite / Sorel
- **Brine chemistry and brine evolution**
  e.g. interactions of metals with brucite / Sorel phases, estimation of Pitzer parameters for Ba/Cl bearing solutions
- **Microbial effects in brines**
  e.g. microbiology research at WIPP, biosorption of uranium
- **Thermodynamic databases and modeling studies**
  e.g. thermodynamic model for WIPP, THEREDA database, NEA-TDB Pitzer State-of-the-Art activities



Institute for Nuclear Waste Disposal (INE)

ABC-Salt - books of abstracts

- Extended abstracts of ABC-Salt workshops are compiled in books of abstracts
- Books of abstracts are available as PDF copies or hard copies for ABC-Salt (I, II, III) from the organizers (dreed@lanl.gov or marcus.altmaier@kit.edu)
- Altmaier, Bube, Kienzler, Metz, Reed (2012) Proc. ABC-Salt(II) is published as KIT Scientific Reports 7625, and available via <http://digbib.ubka.uni-karlsruhe.de/volltexte/1000029520>
- Book of abstracts for ABC-Salt (IV) is currently under preparation at KIT-INE

Proceedings of the International Workshops ABC-Salt (II) and HiTAC 2011

Marcus Altmaier, Christiane Bube, Bernhard Kienzler, Volker Metz, Donald T. Reed (Eds.)

KIT Scientific Publishing

Institute for Nuclear Waste Disposal (INE)

ABC-Salt workshop series

- In view of the very positive feedback received on the ABC-Salt workshop series, the ABC-Salt (V) was announced for spring/summer 2017 in the USA
- A first announcement for ABC-Salt (V) will be distributed in the second half of 2016
- Everyone interested in the topic of Actinide and Brine Chemistry is invited to participate!!

Exceptional service in the national interest — Sandia National Laboratories

BAM-SNL Cooperation on Container Behavior/Influence on Prolonged Storage Periods

BAM — Holger Völzke
Bundesanstalt für Materialforschung und –prüfung
Ken B. Sorenson
Sandia National Laboratories

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories | DBE TEC | PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology | NNSA | U.S. Department of Energy

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Contents

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1. Overview of SNL activities associated with the BAM/SNL collaboration

- Program Objectives
- Storage and Transportation R&D guided by the 2012 Gap Analysis
- High Burnup Spent Fuel Cladding Material Properties
- Analysis
- Normal Conditions of Transport
- Stainless Steel Canister Corrosion

Program Objectives: Storage and Transportation R&D

- Prepare for extended storage and eventual large-scale transport of used nuclear fuel (UNF) and high-level waste
- Develop the technical basis for:
  - Extended storage of used nuclear fuel
  - Fuel retrievability and transportation after extended storage
  - Transportation of high-burnup used nuclear fuel

Storage and Transportation R&D Guided by the 2012 Gap Analysis

Work focused in the red areas.

Source: Gap Analysis to Support Extended Storage of Used Nuclear Fuel, January 2012

System Component	Issue	Importance of R&D
Cladding	Annealing of Radiation Effects	Medium
	Oxidation	Medium
	H_2 effects: Embrittlement	High
	H_2 effects: Delayed Hydride Cracking	High
	Creep	Medium
Assembly Hardware	Stress corrosion cracking	Medium
Neutron Poisons	Thermal aging effects	Medium
	Embrittlement and cracking	Medium
	Creep	Medium
	Corrosion (blistering)	Medium
Canister	Atmospheric corrosion (marine environment)	High
	Aqueous corrosion	High

Storage and Transportation R&D Guided by the 2012 Gap Analysis

Work focused in the red areas.

Source: Gap Analysis to Support Extended Storage of Used Nuclear Fuel, January 2012

System Component	Issue	Importance of R&D
Bolted Direct Load Casks	Thermo-mechanical fatigue of bolts/seals	Medium
	Atmospheric corrosion (marine environment)	High
	Aqueous corrosion	High
Overpack and Pad (Concrete)	Freeze/Thaw	Medium
	Corrosion of steel rebar	Medium

Cross-cutting or General Gaps

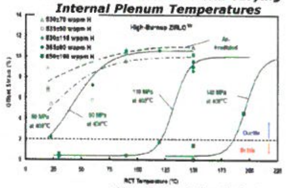
Temperature profiles for fuel	*High*
Drying issues	*High*
Monitoring	*High*
Subcriticality	*High*
Fuel transfer options	*High*
Re-examine INL dry cask storage	*High*

Identification of these data gaps are used to inform new initiatives for FY15

High Burnup Spent Fuel Cladding Material Properties

- Separate effects test to determine effects of hydrides, hydride reorientation, radiation damage, thermal annealing, and clad thinning on materials properties and performance.
- Hydrides and reorientation
  - Ring Compression Tests and determination of Ductile-Brittle Transition Temperature (ANL)
  - Cladding bend test and effects of fuel/clad bonding and pellet/pellet interfaces (ORNL)
- Radiation damage and thermal annealing
  - Irradiate cladding in HFIR reactor at ORNL without all other effects.

DBTT data for Zirlo clad with Varying Internal Plenum Temperatures



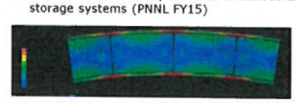
Billone, Argonne National Laboratory, EPRI ESCP Meeting, Dec. 2013

Used fuel rod stiffness experiments (in hot cell and out) and analyses of stress distribution

Jy-An, Wang; Oak Ridge National Laboratory, WM2014 Conference, March 2014

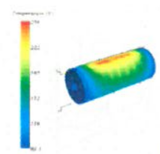
Analysis

- Predictive modeling
  - Thermal Analysis (PNNL) to predict cool down, Ductile-to-Brittle Transition, deliquescence, etc.
    - HBU Demonstration fuel selection and cool down
    - Modern, high heat load, high capacity systems
    - In-service inspections validation data
  - Hybrid hydride reorientation model (SNL)
  - Structural uncertainty analysis at assembly and canister level (PNNL)
  - Finite element analysis validation and application to out-of-cell testing (ORNL)
- Thermal profile analyses
  - Detailed thermal analyses for 2-3 licensed dry storage systems (PNNL FY15)

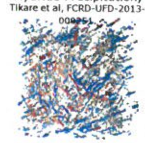


Jy-An, Wang; Oak Ridge National Laboratory, WM2014 Conference, March 2014

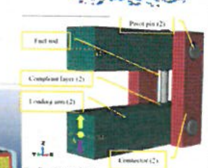
CFD Thermal Analysis of Dry Storage Casks
Suffield, et al, PNNL-21788



Model for Simulation of Hydride Precipitation,
Tikare et al, FCRD-UFD-2013-000251



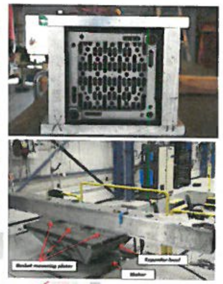
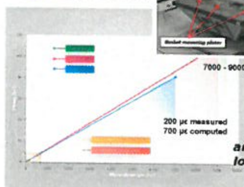
FE Models of Assembly
Klymyshyn, et al,
PNNL, FCRD-UFD-2013-000168



FE Model of Rod Bend Tests
Jy-An Wang et al, ORNL

Normal Conditions of Transport – Loading on Fuel Assemblies

- A surrogate assembly was subjected to a 50-mile over-the-road test on a real truck with representative weight
  - Data results were >10 times below yield strength
  - The strains measured in both were an order of magnitude lower than the elastic Zircaloy rod yield strength and well below the fracture toughness value for brittle behavior
  - Strains were commensurate with strains obtained from the FY13 shaker table test
- If high burnup fuel can maintain its integrity during transport, pressure will be taken off experimental R&D efforts associated with hydride effects on cladding strength and ductility.

Data collection and analysis for NCT loads on a surrogate fuel assembly

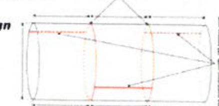
Sorenson, K., Determination of Loadings on Spent Fuel Assemblies During Normal Conditions of Transport, SAND2014-2043P.

Stainless Steel Canister Corrosion

Purpose: Better understand canister degradation, support Aging Management Plans, and license extensions.

- Develop data to understand initiating conditions for corrosion conditions and progression of SCC-induced crack growth
- Obtain site data to assess atmospheric conditions and compare with initiating conditions.
- Procure a full scale (diameter) welded SS canister to investigate residual stresses due to plate rolling and welding.

Enos, et al., Data Report on Corrosion Testing of Stainless Steel SNL Storage Canisters, FCRD-UFD-2013-000324



Conceptual design for full-scale (diameter) SS welded canister

2. Overview of BAM activities associated with the BAM/SNL collaboration

BAM

- Spent Fuel and HLW Storage in Germany
- Extended Dry Interim Storage Issues
- Metal Seal Investigations
- Polymer Degradation Effects
- Elastomer Seal Investigations

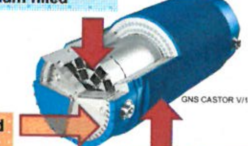
Spent Fuel and HLW Storage in Germany

BAM

- Site specific safety evaluation of casks and specific inventories performed for 40 years
- Accident safe dual purpose casks for storage and transportation
- Valid Type B(U) package design approval required before loading and during storage to guarantee permanent transportability

!


Photos: GNS



Inert cask interior: vacuum dried and helium filled

Permanently monitored bolted double barrier lid system equipped with metal seals

Corrosion protection of outer surfaces

Extended Dry Interim Storage Issues

BAM

Extended Interim Storage beyond 40 years

Ageing effects on DPCs (identification – evaluation)

Consideration of relevant stress factors of specific operation conditions and cask inventories

Examples

Metal Seals:
- Corrosion effects by remaining humidity
- Reduction of seal and bolt pressure force
- Reduction of useable seal resilience
- Resulting leakage rates (temp./time)
- Seal function under accident conditions

Polymer components for neutron shielding:
- Degradation by gamma-irradiation
- Thermal degradation
- Hydrogen release

Elastomer auxiliary seals:
- Degradation by gamma-irradiation
- Thermal degradation
- Loss of elasticity and seal function to provide test spaces for checking metal seal leak-tightness

Outer corrosion protection
- Paints
- Silicone sealings
- Trunnions

Internals:
- Baskets
- Cladding integrity
- Encapsulation of defect fuel assemblies
- Moisture absorbers

Pressure monitoring devices
- Reliability, failure rate

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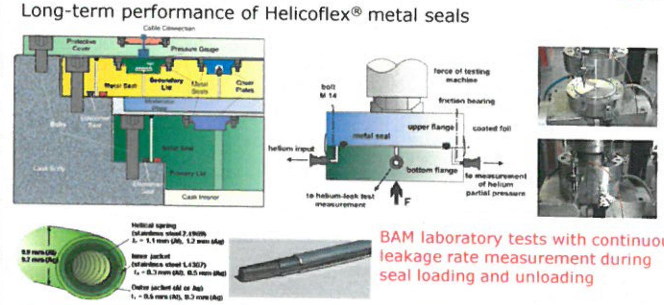
Metal Seal Investigations

BAM

Long-term performance of Helicoflex® metal seals



BAM laboratory tests with continuous leakage rate measurement during seal loading and unloading

Test Parameters

Temperatures:	+20°C	+75°C	+100°C	+125°C	+150°C
Holding times since:	02/2009	01/2014	11/2010	01/2014	02/2009
Seal type	Al + Ag	Al + Ag	Al + Ag	Al + Ag	Al + Ag

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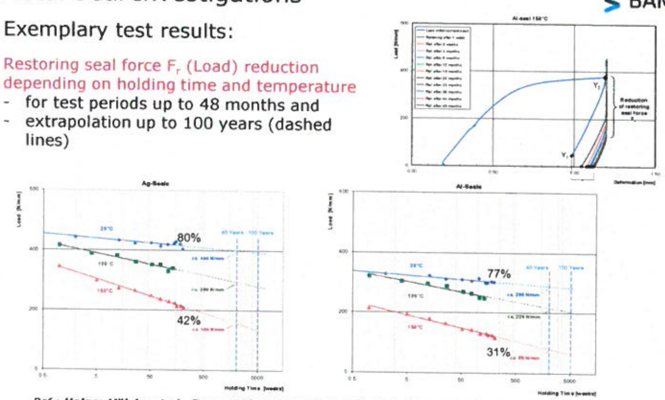
Metal Seal Investigations

BAM

Exemplary test results:

Restoring seal force F_r (Load) reduction depending on holding time and temperature
- for test periods up to 48 months and
- extrapolation up to 100 years (dashed lines)



*Ref.: **Holger Völzke et al., Paper #104**, Proceedings of the 17th International Symposium on the Packaging and Transportation of Radioactive Materials PATRAM 2013, August 18-23, 2013, San Francisco, CA, USA*

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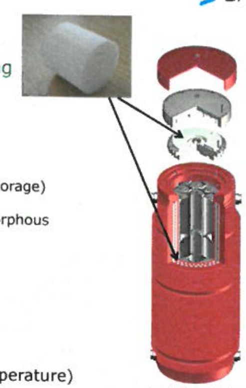
Polymer Degradation Effects

BAM

Ultra-High Molecular Weight Polyethylene **(U)HMW-PE** for neutron radiation shielding



Basic requirement:
Sufficient long-term neutron radiation shielding without safety relevant degradation

Degradation effects:
- **Temperatures** (max. 160°C; decreasing during storage)
  - → Thermal expansion
  - → Structural changes from semi-crystalline to amorphous
- **Gamma radiation** (decreasing during storage)
  - → Structural damages and/or crosslinking
  - → hydrogen separation
- **Mechanical assembling stresses**
  - → Stress relaxation

Gamma irradiation tests by BAM (at room temperature)
- Low dose irradiation (^{60}Co source): 0.5 – 60 kGy
- High dose irradiation (conservative max. storage dose): 600 kGy

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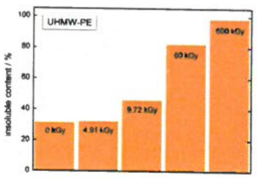
Polymer Degradation Effects

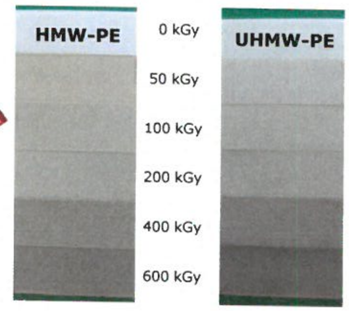
BAM

Outcomes for UHMW-PE from various analyses (exemplary):

→ Increase of insoluble, crosslinked fraction after high dose gamma irradiation



Further gamma irradiation tests with material blocks of 10*10*50 cm³



Future investigations planned:

- Thermal aging of(U)HMW-PE at elevated temperatures
- Combination of radiation and thermal aging
- Development of adequate prognostic methods to allow extrapolation of long-term material performance

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Elastomer Seal Investigations

BAM

Relevance:

- Auxiliary seals in spent fuel and HLW casks
- Primary seals in LLW/ILW casks

Major topics:

1. Low temperature behavior down to -40°C

Recent Publications by Matthias Jaunich, Wolfgang Stark, and Dietmar Wolff:

Low Temperature Properties of Rubber Seals
Kgk-Kautschuk Gummi Kunststoffe, 2011. **64**(3): p. 52-55.

A new method to evaluate the low temperature function of rubber sealing materials
Polymer Testing, 2010. **29**(7): p. 815-823.

Comparison of low temperature properties of different elastomer materials investigated by a new method for compression set measurement.
Polymer Testing, 2012. **31**(8): p. 987-992.

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Elastomer Seal Investigations

BAM

2. Aging under themo-mechanical loads (and by irradiation)

Investigation program with selected rubbers (HNBR, EPDM and FKM) tested as O-rings with an inner diameter of 190 mm and an cross sectional diameter of 10 mm since May 2014.

The O-rings are oven-aged at four different temperatures (75 , 100 , 125 , 150 °C). They are examined after various times (1 d, 3 d, 10 d, 30 d, 100 d, 0.5 a, 1 a, 1.5 a, 2 a, 2.5 a, 3 a, 3.67 a, 4.33 a and 5 a).

In order to be able to compare between compressed and relaxed rubber, the samples are aged in their initial O-ring state (Fig. 1) as well as compressed between plates (Fig. 2) with a deformation of 25 % corresponding to the actual compression during service. Furthermore, we are aging samples in flanges that allow leakage rate measurements (Fig. 3).

Fig. 1 Undeformed O-rings

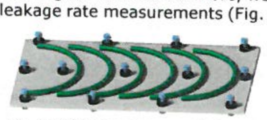

Fig. 2 Half O-rings compressed between plates

Fig. 3 O-ring in flange for leakage measurements

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3. Summary and Outlook

BAM · Sandia National Laboratories

- SNL and BAM collaborate in the areas associated with the backend of the commercial nuclear fuel cycle. Specifically, the focus is on packaging, transportation, and storage of commercial spent nuclear fuel.
- A Memorandum of Understanding (MOU) between SNL and BAM was established by 2012. Bilateral meetings/workshops take place twice a year.
- Extended interim storage of spent fuel and HLW needs to be addressed as a major issue in both countries due to delays disposal siting procedures.
- Various technical issues concerning degradation effects of casks and inventories during extended periods of interim storage have been identified and specific investigations are performed.
- Interim storage, subsequent transportation, and final disposal are closely linked and integrated approaches concerning waste package designs and operations are supposed to be beneficial for efficient long-term spent fuel and HLW waste management strategies
- Both, SNL and BAM perform specific test programs, share and discuss relevant outcomes, and address potential areas of technical and scientific collaboration

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Extended storage approach of COVRA

Erika A.C. Neeft PhD
Central Organization for Radioactive Waste

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories
DBE TEC
PTKA
NNSA
ENERGY

Content

- Why COVRA?
- Why storage ≥ 100 years
- How storage ≥ 100 years
- Active for the future
  - Disposal

2

COVRA NV

Why COVRA?

- From 1967 to 1982 designated end points for
  - Low Level waste ⇒ North East Atlantic; assessment suitability of sites by NEA
  - Spent Research Reactor Fuel ⇒ USA
  - Processed spent Nuclear Power Fuel (vitrified waste) ⇒ geological disposal in rock salt or deep seabed disposal
- Central Organisation for Radioactive waste established in 1982
  - Initiated by the government
  - Centralized collection, processing and storage of waste

3

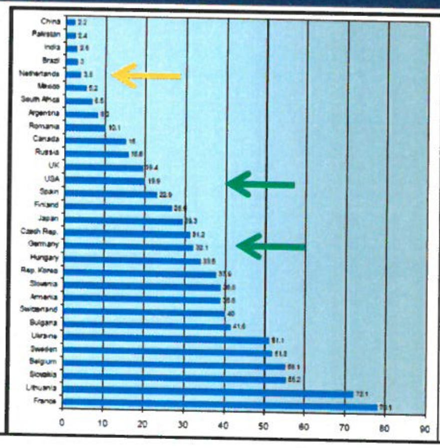
COVRA NV

Why storage: the ‘imaginative’ country

- high ground water table
  - Purple area below sea level
- high population density
  - 17 million people
- high environmental awareness
- advanced spatial planning

4

Why: amount of waste



Nuclear Power Share of Electricity Production (2004)

5

Why: costs geological disposal facility

- estimate NL: € 2.0 billion (2008 cost estimate)
- 500 MWe, 30 years: 1.10^{11} kWh
  >>> 2 eurocent per kWh

  >>> economically not feasible
- capital growth fund is needed:
  Long Term Storage is needed

6 COVRA NV

How: acceptability

Storage is a necessity in any waste management program

Long-term storage must be a **desired** and **planned** step in a waste management program

and not

the result of **failure** of a disposal program

7 COVRA NV

How: ownership and fund

- Investments for fund for GDF controlled by authority (ministry of financial affairs)
- All waste generators pay
  - contribution per m^3
  - HLW : LILW = 2 : 1
- All (nuclear) waste managed and owned by COVRA
- All (nuclear) waste managed at an industrial site
- at least 100 years storage, in buildings
- deep disposal after 100 years
- stable policy since 1984!

8 COVRA NV

How: ownership and fund

Not a "wait and see" option, but practical necessity:

- national geology is suitable
- (modest) research plan for disposal
- transfer of title to COVRA
- capital growth fund within COVRA
- polluter pays now all obligations
- 5 year evaluation of quantities (m^3,€), costs, options

9 COVRA NV

How: waste form

- Only solid waste stored
  - Oxide (glass, depleted uranium)
  - Metal
  - Mortar
- No burnable material (e.g. bitumen)

10 COVRA NV

How: waste form and package

11

How: waste package and facility

Design criteria:

- Keep It Simple S.....
  - concrete building
  - modular design
  - inspection possibilities
  - retrievable
  - packages repairable
  - concrete with properties also suitable for disposal
  - no fixed equipment
  - no forced ventilation
  - mobile system for humidity control

12

Active for the future

- Disposability of the Dutch waste
  - Cooled down for at least 100 years;
  - Is it host rock specific?
- To be prepared for disposal

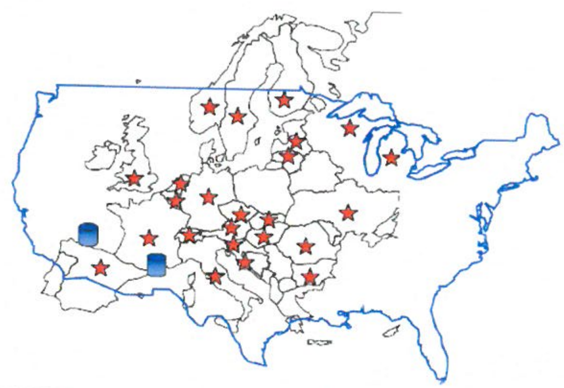
14

Active for the future

- To be prepared for disposal
  - For the next decades
    - Stakeholders
      - Define their role, responsibility ⇒ involvement
      - Arrange access to knowledge (specific for each group of stakeholders)
        - » Show the waste intended to be disposed
    - Maintain knowledge
      - Knowledge = information + experience
        - » Research programme(s) (move at a measured pace, stable and consistent) e.g. do we have the information necessary from the deep underground of the Netherlands?
    - Waste fees update every 5 years
    - Multinational solution e.g. European Repository Development Organisation

15

Should every country have it's own GDF?



Exceptional service in the national interest

Sandia National Laboratories

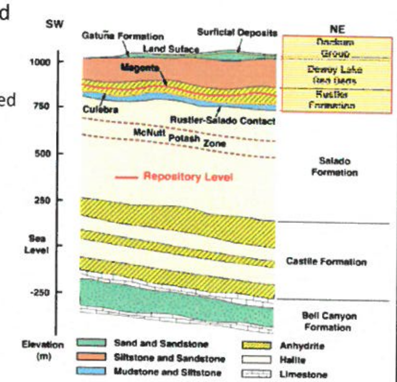
Far-field Hydrogeologic Modeling Around a Salt Repository

Kristopher L. Kuhlman - Sandia National Laboratories
Anke Schneider - Gesellschaft für Anlagen- und Reaktorsicherheit

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
7-9 September 2015

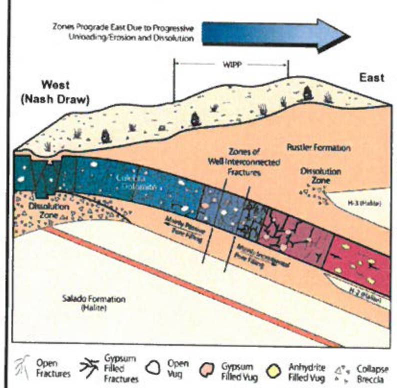
WIPP Hydrogeology

- Repository in Salado bedded salt formation
  - >500-m thick salt unit
  - Immeasurably low undisturbed permeability from surface
- Hydrogeology of overlying formation
  - Rustler Formation
  - Dewey Lake Redbeds
  - Dockum Group



2

Culebra Conceptual Model

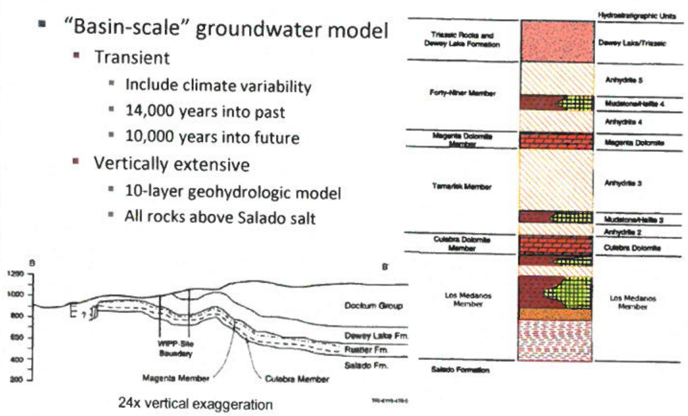


- West of WIPP
  - High permeability
  - Relatively fresh water
- East of WIPP
  - Low permeability
  - Saturated NaCl brine
- WIPP located in middle
  - ~5 miles
- Interest in regional flow above repository
  - Flow included in PA
  - Related to long-term stability of salt

3

Corbet & Knupp WIPP Model

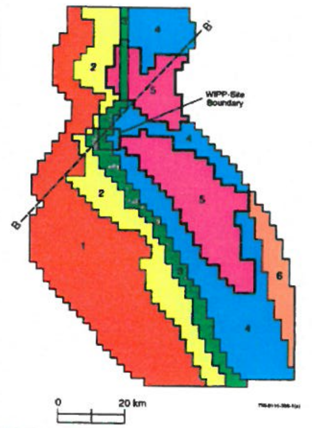
- "Basin-scale" groundwater model
  - Transient
    - Include climate variability
    - 14,000 years into past
    - 10,000 years into future
  - Vertically extensive
    - 10-layer geohydrologic model
    - All rocks above Salado salt



24x vertical exaggeration

4

Corbet & Knupp WIPP Model



- Laterally Extensive
  - ~6000 km² region (39 km × 56 km)
  - Extends south into Texas
- Numerical Model
  - SECOFL3D
  - "water table" moving boundary model
- Solution
  - Coarse mesh (1 km square cells)
  - 12 model layers (10 geo layers)
  - 1,500 cells/layer
  - 18,000 elements total

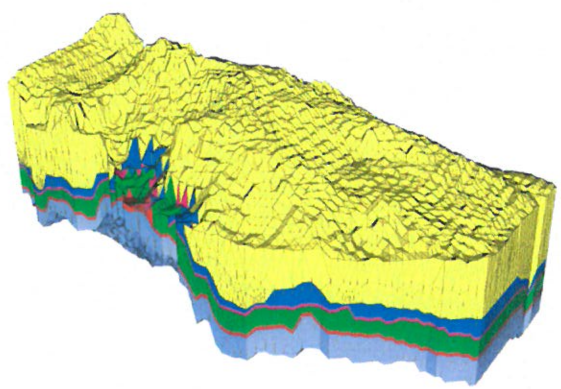
5

Motivation

- Qualification of GRS code d^3f
- Benchmark against SECOFL3D (Corbet & Knupp, 1996)
- Formal uncertainty and sensitivity analysis of *original* model
  - Old mesh, model parameters & boundary conditions
- Include new processes, features & data
  - Density driven flow (Davies, 1989)
  - Change flow boundary conditions (+ include transport BC)
  - Change hydrogeological conceptual model
  - ^{81}Kr GW age data, water level data
- Benchmark
  - PFLOTRAN
  - d^3f
- Formal uncertainty and sensitivity analysis of *modified* model

6

GRS Versions of Basin-Scale Model



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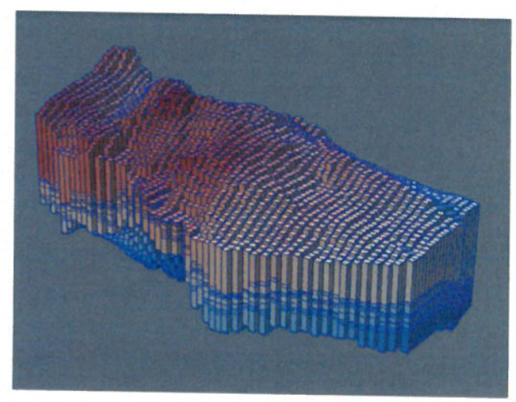
SNL Versions of Basin-Scale Model



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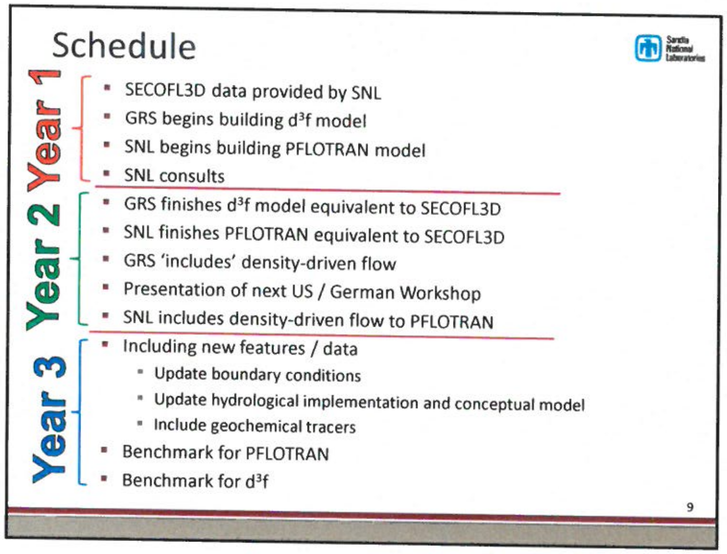
Schedule
Year 1
SECOFL3D data provided by SNL
GRS begins building d³f model
SNL begins building PFLOTRAN model
SNL consults
Year 2
GRS finishes d³f model equivalent to SECOFL3D
SNL finishes PFLOTRAN equivalent to SECOFL3D
GRS 'includes' density-driven flow
Presentation of next US / German Workshop
SNL includes density-driven flow to PFLOTRAN
Year 3
Including new features / data
Update boundary conditions
Update hydrological implementation and conceptual model
Include geochemical tracers
Benchmark for PFLOTRAN
Benchmark for d³f
9

Exceptional service in the national interest — Sandia National Laboratories

Deep Borehole Disposal: Pros and Cons US Experience

Geoff Freeze, Sandia National Laboratories

6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Sandia National Laboratories • DBE TEC • PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology • NNSA • U.S. Department of Energy

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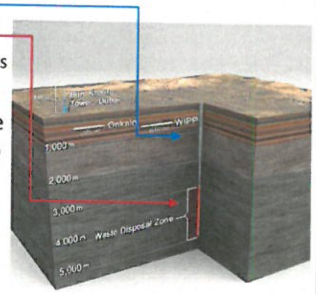
Outline

- Deep Borehole Disposal (DBD) Concept
- Deep Borehole History
- Deep Borehole Field Test (DBFT)
- Summary Pros and Cons

2

Deep Borehole Disposal Concept

- Potential for robust isolation
  - 5,000 m deep borehole in crystalline basement rock
    - Seals in upper 3,000 m
    - Waste canisters in bottom 2,000 m
  - Well below fresh groundwater resources
- Gives DOE the flexibility to consider options for disposal of smaller waste forms in deep boreholes (DOE 2014)
  - Potentially earlier disposal of some wastes than might be possible in a mined repository
  - Reduce costs associated with projected treatments of some wastes



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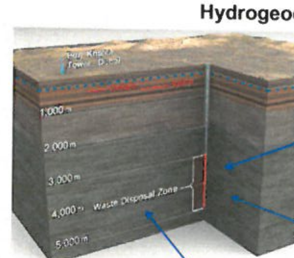
Deep Borehole Disposal Concept – Pros: Long-Term Safety and Feasibility

Hydrogeochemical Factors



Waste emplacement is deep in crystalline basement
- at least 1,000 m of crystalline rock (seal zone) overlying the waste disposal zone
- Crystalline basement within 2,000 m of the surface is common in many stable continental regions

Crystalline basement has very low permeability – limits flow and transport

Deep groundwater in the crystalline basement:
- has very long residence times – isolated from shallow groundwater
- has high salinity and is geochemically reducing – limits the solubility and enhances the sorption of many radionuclides in wastes
- exhibits density stratification (saline groundwater underlying fresh groundwater) – opposes thermally-induced upward groundwater convection

4

Deep Borehole Disposal Concept – Pros: Operational Safety and Feasibility

GRS Sandia National Laboratories

Engineering Factors

Drilling Technology exists to drill and case larger-diameter boreholes to 5,000 m depth in crystalline rock at acceptable cost

Emplacement System Design provides assurance the waste packages can be safely surface-handled and emplaced at depth

Borehole and Casing Design maintains borehole integrity and minimizes probability of waste packages becoming stuck during emplacement

Waste Package Design maintains structural integrity and prevents leakage of radioactive materials during operations

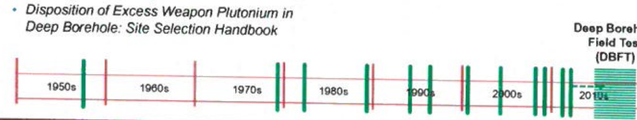
Borehole Seals maintain a low-permeability barrier, at least over the time scale of thermally-induced upward flow

5

Deep Borehole Disposal History

GRS Sandia National Laboratories

- **Hess et al. (1957) NAS Publication 519**
  - *The Disposal of Radioactive Waste on Land. Appendix C: Committee on Deep Disposal*
- **Obrien et al. (1979) LBL-7089**
  - *The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste disposal*
- **Woodward-Clyde (1983) ONWI-226**
  - *Very Deep Hole Systems Engineering Studies*
- **Juhlin and Sandstedt (1989) SKB 89-39**
  - *Storage of Nuclear Waste in Very Deep Boreholes*
- **Ferguson (1994) SRNL WSRC-TR-94-0266**
  - *Excess Plutonium Disposition: The Deep Borehole Option*
- **Heiken et al. (1996) LANL LA-13168-MS**
  - *Disposition of Excess Weapon Plutonium in Deep Borehole: Site Selection Handbook*
- **Harrison (2000) SKB-R-00-35**
  - *Very Deep Borehole – Deutag's Opinion on Boring, Canister Emplacement and Retrievability*
- **Nirex (2004) N/108**
  - *A Review of the Deep Borehole Disposal Concept*
- **Beswick (2008)**
  - *Status of Technology for Deep Borehole Disposal*
- **Brady et al. (2009) SNL SAND2009-4401**
  - *Deep Borehole Disposal of High-Level Radioactive Waste*
- **Arnold et al. (2011) SNL SAND2011-6749**
  - *Reference Design and Operations*
- **DOE UFD R&D Reports (2012 - Present)**



6

Deep Borehole Drilling History

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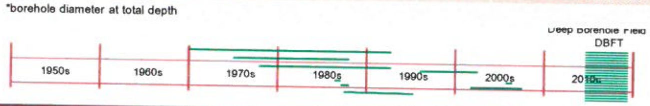
Site	Bores	Location	Years	Depth [km]	Diam* [in]	Purpose
Kola SG-3	1	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Technology Development
Fenton Hill	3	New Mexico	1975-1987	3, 4.2, 4.6	8¾, 9⅞	Enhanced Geothermal
Urach-3	1	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	1	Central Sweden	1986-1987	6.6	6½	Gas Wildcat in Siljan Impact Structure
Cajon Pass	1	California	1987-1988	3.5	6¼	San Andreas Fault Exploration
KTB	2	SE Germany	1987-1994	4, 9.1	6, 6½	Geologic Exploration + Technology Development
Soultz-sous-Forêts GPK	3	NE France	1995-2003	5.1, 5.1, 5.3	9⅝	Enhanced Geothermal
SAFOD	2	Central California	2002-2007	2.2, 4	8½, 8¾	San Andreas Fault Exploration
Basel-1	1	Switzerland	2006	5	8½	Enhanced Geothermal

*borehole diameter at total depth



7

Deep Borehole Field Test (DBFT) – Overview

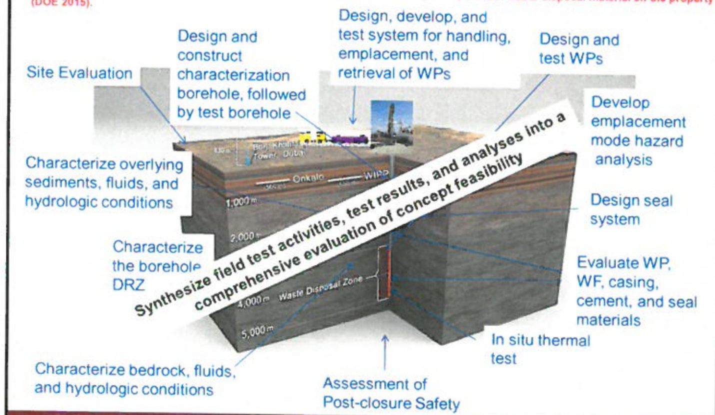
GRS Sandia National Laboratories

- Characterization Borehole (CB) - smaller-diameter (8.5 in.) to 5,000 m
  - Drilling and completing
  - Downhole characterization testing
- Field Test Borehole (FTB) - larger-diameter (17 in.) to 5,000 m
  - Drilling and completing
  - Emplacement testing
- Package Handling and Emplacement Testing
  - Package design and fabrication
    - Surrogate canisters without radioactive waste
  - Surface handling demonstration
  - Downhole emplacement and retrieval demonstration
- Seals Research
- Assessment and Analysis
  - System Modeling

8

DBFT Objectives

In no case will the US Government place or otherwise have nuclear material, waste, or other waste disposal material on the property (DOE 2015).



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DBFT Timeline and Budget

- Schedule
  - 09/30/14 – Final Project Plan Rev. 0 Submitted (SNL 2014a)
  - 07/09/15 – Issued RFP for Site Management and Drilling CB
  - 09/23/15 – RFP Responses Due
  - 01/29/16 – Award Contract for Site Management and Drilling CB
  - 09/01/16 – Start Drilling CB
  - 09/07/17 – Start Drilling FTB
  - 03/06/18 – Start Emplacement Demonstration
- Budget
  - ~$80M over 5-year duration (FY15-FY19)
    - Significant drilling and engineering costs

10

Deep Borehole Disposal Summary

- Pros
  - Potential for robust isolation of waste
  - Flexibility for disposal of smaller waste forms
  - Deep Borehole Field Test to provide insights into operational and hydrogeochemical factors contributing to concept feasibility
- Cons to be addressed
  - Applicability of existing regulations
  - Operational concerns
    - Deep drilling
    - Package handling and emplacement
  - Seals and disturbed rock zone (DRZ) evolution

Deep Borehole Field Test (DBFT)

11

References

- DOE (U.S. Department of Energy) 2014. Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel, October 2014.
- DOE (U.S. Department of Energy) 2015. RFP Deep Borehole Field Test: Site and Characterization Borehole Investigations. Solicitation Number: DE-SOL-0008071. US Department of Energy Idaho Operations Office, Idaho Falls, ID.
- SNL (Sandia National Laboratories) 2014a. Project Plan: Deep Borehole Field Test. SAND2014-18559R; FCRD-UFD-2014-000592, Rev. 0. U.S. Department of Energy, Washington, DC.
- SNL (Sandia National Laboratories) 2014b. Evaluation of Options for Permanent Geologic Disposal of Used Nuclear Fuel and High-Level Radioactive Waste Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy. FCRD-UFD-2013-000371. SAND2014-0187P; SAND2014-0189P. Revision 1. Albuquerque, New Mexico: Sandia National Laboratories

12

References – DBD History

- Hess, H. H., J. N. Adkins, W. B. Heroy, W. E. Benson, M .K. Hubbert, J. C. Frye, R. J. Russell, and C. V. Theis 1957. The Disposal of Radioactive Waste on Land. Appendix C: Committee on Deep Disposal. NAS Publication 519. National Academy of Science – National Research Council, Washington, DC. http://www.nap.edu/openbook.php?record_id=10294&page=82
- Obrien, M. T., L. H. Cohen, T. N. Narasimhan, T. L. Siskin, and H. A. Wollenberg (Lawrence Berkeley Laboratory) and W. F. Brace, S. Green, and H. P. Pratt (Terra Tek) 1979. The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste disposal. LBL-7089. Revised contribution to Draft Environmental Impact Statement: Management of Commercially Generated Radioactive Waste (DOE/EIS-0046-D) August 1978.
- Woodward-Clyde Consultants 1983. Very Deep Hole Systems Engineering Studies. ONWI-226. San Francisco, CA. https://inis.iaea.org/search/search.aspx?orig_q=RN:15053861
- Juhlin, C., and H. Sandstedt 1989. Storage of Nuclear Waste in Very Deep Boreholes: Feasibility study and assessment of economic potential. SKB 89-39. Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.
- Ferguson, K. L. 1994. Excess Plutonium Disposition: The Deep Borehole Option. SRNL WSRC-TR-94-0266. Westinghouse Savannah River Company, Savannah River Site, Aiken, SC. http://www.osti.gov/scitech/servlets/purl/10187048
- Heiken, G., G. Woldegabriel, R. Morley, H. Plannerer, and J. Rowley 1996. Disposition of Excess Weapon Plutonium in Deep Borehole: Site Selection Handbook. LA-13168-MS. Los Alamos National Laboratory, Los Alamos, NM. http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-13168-MS
- Harrison, T. 2000. Very Deep Borehole – Deutag's Opinion on Boring, Canister Emplacement and Retrievability. SKB-R-00-35. Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden. http://www.mkg.se/uploads/DB/SKB_R-00-35_Very_deep_borehole_Deutags_opinion.pdf
- Nirex Report 2004. A Review of the Deep Borehole Disposal Concept. N/108. United Kingdom Nirex Limited. http://www.mkg.se/uploads/Nirex_Report_N_108_-_A_Review_of_the_Deep_Borehole_Disposal_Concept_for_Radioactive_Waste_June_2004.pdf
- Beswick, J. 2008. Status of Technology for Deep Borehole Disposal. EPS International. http://www.mkg.se/uploads/DB/NDA_Status_of_Technology_for_Deep_Borehole_Disposal_April_2008.pdf
- Sapiie, B. and M. J. Driscoll 2009. A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes. MIT-NFC-TR-109. MIT Center for Advanced Nuclear Energy Systems (CANES).
- Brady, P. V., B. W. Arnold, G. A. Freeze, P. N. Swift, S. J. Bauer, J. L. Kanney, R. P. Rechard, and J. S. Stein 2009. Deep Borehole Disposal of High-Level Radioactive Waste. SAND2009-4401. Sandia National Laboratories, Albuquerque, NM. http://prod.sandia.gov/techlib/access-control.cgi/2009/094401.pdf
- Arnold, B.W., P.V. Brady, S.J. Bauer, C. Herrick, S. Pye, and J. Finger. 2011. Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste. SAND2011-6749. Albuquerque, NM: Sandia National Laboratories.

BACKUP SLIDE - Wastes Being Considered for Deep Borehole Disposal

- DOE-Managed small waste forms are candidates for deep borehole disposal (SNL 2014b)
  - Cesium and strontium capsules stored at the Hanford Site
  - Untreated calcine HLW currently stored at INL in sets of stainless steel bins within concrete vaults
  - Salt wastes from electrometallurgical treatment of sodium-bonded fuels could be packaged in small canisters as they are produced
  - Some DOE-managed SNF currently stored in pools at INL and SRS
  - Vitrified HLW that has not yet been made could be redesigned and packaged for deep borehole disposal

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Deep borehole disposal: "pros" and "cons"

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6th US/German Workshop on Salt Repository Research, Design, and Operation
Hotel Pullman Dresden Newa
September 7-9, 2015

Outline

- The Idea/ Technical Approach
- State of the Art
- Situation in Germany
  - Endlagerkommission
  - Workshop in Berlin, summer 2015
- "Cons" from a Safety Perspective
- Summary and Conclusions

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The Idea

- improvement of long-term safety „the deeper the better"
  - enlargement of distance between emplacement horizon and biosphere may improve isolation-potential
  - low vertical radionuclide transport in particular because of high density of saline groundwater and possible low permeability of host rock formation in 3000 to 5000m depth
  - minimization of radionuclide mobilisation due to reducing conditions
- simplification of siting process
  - assumption that host rock is almost everywere availble in the country
  - minimization of waste package shipments
- saving money
  - few boreholes vs mined repository

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Technical Approach

- drilling of deep vertical lined boreholes up to 5000m depth into crystalline basic host rock
- dimensioning of the minimum liner diameter according to the outer diameter of the waste package
- disposal of waste packages from surface
- sealing of borehole by means of different columns of adequate sealing materials (cement, bentonite, asphalt, etc.) in parallel to the dismantling of the liner
- retrievability is not planned so far

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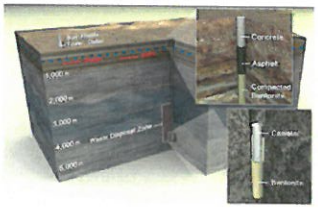
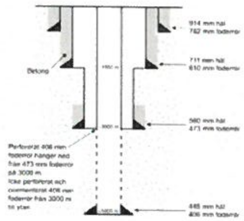
Technical Approach

- Examples:

- USA:
  basic concept for deep borehole disposal of HLW and spent fuel [Sandia 2012]
- Sweden:
  Concept of a drilled and lined borehole (perforated liner in emplacement level at about 3000 to 5000 m) [SKB 2014]

State of the Art

- drilling of deep boreholes:
  - ✓ > 10,000m depth
  - ✓ > 30cm in diameter up to 3000m depth
  - ✓ > 100cm in diameter up to some hundreds of meters depth (200 times the diameter)
  - ✓ liners: different materials available; designed for oil/gas production
  - ✓ hook load > several 100 tons
  - ✓ retrieving materials out of boreholes: fishing tools

Situation in Germany

- Endlagerkommission:
  - task: is the idea of deep borehole disposal a realistic option?
  - hearing in summer 2015
    - ➢ conclusion: continue to observe international developments
- Workshop in Berlin , summer 2015
  - presentations on the state of the art
    - ➢ conclusions:
    - ✓ borehole drilling with diameters of some 30 to 40 cm up to a depth of 5000m is state of the art,
    - ✓ disposal of waste packages in deep boreholes under radiation protection conditions unknown
    - ✓ retrieval of waste packages out of deep boreholes neither considered nor planned

„Cons“ from a safety perspective

- quality assured characterization of the disposal horizon between 3000 and 5000m is not state of the art; thus development of an adequate geological model is problematic
- safety concept showing a containment providing rock zone not available today
- drilling boreholes with several meters in diameter as suggested by the Endlagerkommission” is not state of the art for depths between 3000 and 5000m
- safe operation of hoisting of nuclear materials into 5000m deep boreholes never designed nor demonstrated
- handling of operational disturbances during disposal or retrieval process of waste packages unknown

„Cons" from a safety perspective

- ❑ monitoring in depths of 3000 to 5000m is complex/or impossible in particular with regard to wireless data transfer and energy supply
- ❑ retrievabiliy is not included in international available technical approaches or concepts for deep borehole disposal
- ❑ a removal of waste packages until 500 years after repository closure is not included in any concepts and deemed to be nearly impossible
- ❑ safeguards concepts do not exist, to maintain non criticality might be more difficult in Germany because of 10% MOX fuel elements
- ❑ qualified sealing of the filled borehole under radiation protection conditions in a "invisible" area is a real challenge

Summary and Conclusions

- ❑ drilling of deep boreholes is state of the art
- ❑ a series of nearly irresolvable technical challenges still remain:
  - demonstration of rock characteristics and containment providing rock zone
  - error correction and safe retrieval of waste packages
  - demonstration of qualified construction of borehole seals / seal elements
  - demonstration of seal tightness
- ❑ desk study at least necessary to investigate if DBD is a realistic disposal option

Note: „keep waste package handling generally simple and waste packages accessible as long as they are transported"

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Thank you
for your attention.