Proceedings of 3rd US/German Workshop on Salt Repository Research, Design and Operation

Fuel Cycle Research & Development

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☒ Technical Review	☐ Peer Review
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ABSTRACT

The 3rd US/German Workshop on Salt Repository Research, Design and Operation was held in Albuquerque and Carlsbad, New Mexico on October 8-11, 2012. Thirty salt research scientists from Germany and an approximately equal number from the United States (US) met to discuss repository science state of the art. The main workshop topics were 1. Readiness for the safety case for high-level waste (HLW) disposal in salt, 2. Joint Project on the Comparison of Constitutive Models for Rock Salt, which involves benchmark modeling of thermomechanical field-scale tests, and 3. Reconsolidation of granular salt. Effort was focused on building new collaborations and researcher-to-researcher relationships.

The Joint Project meeting occurred the day before the 3rd US/German Workshop on Salt Repository Research, Design and Operation (day one of the agenda). A summary of the Joint Project in the context of benchmark modeling within the 3rd Workshop is contained here, but abstracts or presentations from the Joint Project are not included because it is being conducted under a Memorandum of Understanding agreement and has its own schedules and deliverables. The coincidence of the Joint Project meeting and the 3rd US/German Workshop on Salt Repository Research, Design and Operation allowed a larger number of salt scientists to attend and participate.

This document follows the workshop in chronological order. Both the agenda and these Proceedings are organized topically as follows:

1. Safety case for heat-generating waste disposal in salt. The international salt research community has a solid foundation for a safety case and the associated performance assessment. Workshop material covered Germany's preliminary safety analysis for the Gorleben site (Vorläufige Sicherheitsanalyse Gorleben or VSG). Consistent with German progress, the US has the technical basis and ability to make a safety case for salt disposal of high level waste in the immediate future—if the nation adopts this strategy (Section I).
2. Benchmark modeling. The Joint Project has been extremely timely and helpful in assessing the salt science community's ability to model salt coupled thermal and mechanical behavior using appropriate, yet different, constitutive models. Progress made to date guides formulation of a strategy for generic modeling of thermomechanical field-scale tests (Section II).
3. Reconsolidation of granular salt. Salt repository scientists benefit from significant existing information on granular salt consolidation. It is essential to understand granular salt reconsolidation under a wide range of conditions to establish certain performance bases for heat-generating waste salt repositories (borehole and drift emplacement concepts). Mechanical and hydrological crushed salt properties depend strongly on porosity, which decreases as the surrounding salt creeps inward and compresses granular salt within the rooms, drifts, or shafts (Section III).

Significant effort was focused on laying the groundwork for future collaborations and building relationships among the many newer and younger members of the salt research community to facilitate knowledge transfer and succession planning. Exchanges were renewed regarding exploiting our respective underground resources through new field-scale collaborative projects. A dialogue of this progress is included in the Section IV of these Proceedings. As with previous US/German salt repository workshops, these Proceedings are posted on our Salt Repository Website (http://www.sandia.gov/SALT/SALT_Home.html). The 4th US/German salt repository workshop is planned for Berlin Germany in September 2013. The main topics will include repository research on granular salt reconsolidation, the safety case for salt disposal of heat-generating waste, confidence and data supporting plugging/sealing/barriers, and an introduction of hydrology collaborations.

The US/German workshop series concerned with salt repository research, design and operation is a significant part of US/German salt repository collaboration. Contemporary developments in both

countries have given rise to renewed interest and collaborations in salt repository investigations and related studies. A Waste Management 2013 paper authored by the US and German collaboration leadership (Steininger et al., 2013) summarizes the various ways in which salt repository research is unfolding. This Waste Management paper's development directly reflects achievement of collaboration goals as laid out in our prospectus for our US/German Workshops on Salt Repository Research, Design and Operation.

Both the German rock salt repository program and the US waste management program grapple with challenges in terms of maintaining and honing their respective current state-of-the-art core capabilities in rock salt repository science and technology. The following sections describe several venues of constructive international collaborations being pursued by US and German salt repository researchers.

CONTENTS

ACRONYMS

ALOHA	Investigation of the Excavation Disturbed Zone / Germany
BAMBUS	Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt / Germany
DOE	Department of Energy
EM	Office of Environmental Management
EPA	Environmental Protection Agency
FEP	Features, Events, and Processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HLW	High-Level Waste
IGD-TP	Implementing Geological Disposal of Radioactive Waste – Technology Platform
NE	Office of Nuclear Energy
NEA	Nuclear Energy Agency
PTKA	Project Management Agency Karlsruhe
RD&D	Research Development and Demonstrations
SDDI	Salt Defense Disposal Investigations
SDI	Salt Disposal Investigations
SNF	Spent Nuclear Fuel
TDSE	Thermal Simulation of Drift Emplacement
TSI	Thermal/Structural Interactions
UFD	Used Fuel Disposition
URL	Underground Research Laboratory
US	United States
VSG	Vorläufige Sicherheitsanalyse Gorleben (preliminary safety case)
WIPP	Waste Isolation Pilot Plant
WTE	Water Technology and Waste Management

Proceedings of 3rd US/German Workshop on Salt Repository Research, Design and Operation

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1. SAFETY CASE FOR HEAT-GENERATING WASTE DISPOSAL IN SALT

A safety case is the formal compilation of evidence, analyses, and arguments that quantify and substantiate the repository safety. Building a safety case to provide the entire scientific-technical basis is one of the most important issues in any nuclear waste repository program. As noted by the Nuclear Energy Agency (NEA, 2004): “An initial safety case can be established early in the course of a repository project. The safety case becomes, however, more comprehensive and rigorous as a result of work carried out, experience gained and information obtained throughout the project.”

The German Ministry of the Environment is funding a multi-organizational project to make a preliminary safety analysis for a possible High-Level Waste/Spent Nuclear Fuel (HLW/SNF) repository in domal salt (GRS, 2012). Heat generation is the important differentiating characteristic of this nuclear waste. A comprehensive approach has been developed to address all necessary issues (e.g., a Features, Events, and Processes (FEP) catalogue, safety concept, repository concepts, inventory, geology, and retrievability).

The information needed to develop a bedded salt safety case for United States (US) Department of Energy (DOE) waste is already available due to the enormous amount of work done in salt waste disposal, both domestically and internationally. Many of the major elements of a safety case could be addressed with existing technical bases and experience from prior salt repository work. Use of existing information will reduce or minimize research development and demonstrations (RD&D) efforts identified while creating a salt safety case. Future repository development costs should be reduced and schedules shortened by leveraging the US repository experience on the Waste Isolation Pilot Plant (WIPP) and the Yucca Mountain Project, various historical investigations at other potential salt repository sites in the US (such as Lyons, Kansas and Deaf Smith County, Texas), and collaborations with the German salt repository program. Key experiences include siting, repository development, emplacement technologies, operations, safety assessment, licensing, repository and seal system design, pre-closure safety analysis, and application of performance assessment methodology.

The safety case will provide the necessary structure for organizing and synthesizing existing salt repository science and identifying issues and uncertainties pertaining to safe disposal of heat-generating nuclear waste in salt. It is also very important as a management tool for RD&D planning, performance and quality measures. A safety case synthesis would help DOE plan its future RD&D activities for improving the defensibility of the safety case through a risk-informed approach, based in part on performance assessment modeling. If deemed necessary, a limited set of additional laboratory, field, and site investigations may be undertaken to reduce uncertainties associated with the evolution of heat-generating waste emplacement in salt. The German safety case is made for a domal salt structure. Most of the repository relevant salt studies in the US involved bedded salt. Taken together, these foundations of salt repository science contribute significantly to an associated safety case.

Much of this material presented at the 3rd US/German Workshop could help accelerate development of a defensible safety case for a repository of DOE heat-generating nuclear waste in bedded salt. A safety case will not only provide decision makers and stakeholders with a concise summary of existing technical information mapped to the elements of the safety case, but also the basis for beginning the process of licensing and conducting public and regulator interactions. It will also provide a basis for identifying and prioritizing those activities necessary to finalize a safety case for a license application (Sevougian et al., 2013). A US heat-generating waste salt safety case could be developed using the extensive existing technical basis for radioactive waste disposal from Germany with experience and technical basis from the WIPP certification and operation (Sevougian et al., 2013). Due to the topic's scientific relevance, agreement was reached to increase dialogue and information exchange between US and German scientists on safety case development for salt HLW disposal. This increase is important for both the US and German disposal programs.

2. BENCHMARK MODELING

The Joint Project is a very important collaboration addressing the benchmarking of rock salt constitutive models. The project began on a national (Germany only) basis. The project focuses on modeling thermal effects on salt deformation and modeling sealing and healing of damaged rock salt (BMBF, 2010). Sandia National Laboratories recently joined the project as the seventh partner by signing a Memorandum of Understanding. Sandia is a welcome addition to the Joint Project because of their recognized expertise and modeling tools in salt repository thermomechanical analysis. The Joint Project provides a basis for objective comparison of the partners' advanced geomechanical constitutive models, procedures for determination of location-specific parameters, and implementation and performance of numerical simulations. The benchmark study allows partners to evaluate the models' ability to correctly predict relevant deformation phenomena in rock salt under various influences, increasing confidence in the results of numerical simulations.

The current project phase entails simulation of laboratory and in situ tests, including a heated borehole experiment performed in the former Asse mine. Accurate simulation of in situ test results is fundamentally important to qualify the models. Each partner's modeling results are compared to each other and to in situ borehole closure measurements. The next modeling benchmark exercise includes healing of a drift excavated in the Asse II salt mine in 1911. A 25-m long section of the drift was lined after 3 years with a cast-steel tube and concrete. The simulation results will be compared to each other and to in situ permeability measurements recently made through the liner as part of the ALOHA II (Investigation of the Excavation Disturbed Zone / Germany) project (Bechthold et al. 2004).

The Joint Project partners intend to perform future benchmark simulations of two full-scale WIPP experiments. The modeling will be accompanied by extensive laboratory testing of WIPP salt cores to parameterize the constitutive models for Permian bedded salt. This international collaboration is very important to generic salt repository science. German salt constitutive models were developed for domal salt, while US repository studies have mostly been in bedded salt. The proposed laboratory and modeling benchmark studies reverse these trends. Laboratory tests will provide new data for the US bedded salt and allow evaluation of salt constitutive models from a generic standpoint. WIPP Room D and Room B experiments were respectively isothermal and heated experiments in the Thermal/Structural Interactions (TSI) testing program. These particular experiments have been chosen for benchmarking because TSI tests were unequalled for meticulous quality control and quality assurance and were located in the same general stratigraphic horizon. Differential closure and temperature were monitored in Room B, which was subjected to a total power of nearly 60 kW between approximately 30 heaters installed in boreholes in the floor (representative of Defense High Level Waste). Room D was an unheated version of Room B, with similar differential closure measurements.

The ability to model salt behavior has been examined extensively in earlier salt programs (Project Salt Vault, Avery Island, WIPP, Deaf Smith County, and Asse). Since the significant benchmarking efforts of the 1980s, there have been approximately 30 years of software and hardware advances. Sandia is developing a next-generation coupled massively-parallel multi-physics computational framework called SIERRA Mechanics. Sandia is developing this capability to support the Engineering Science mission and is leveraging the capability to build the next generation coupled geomechanics simulator, appropriate for a waste repository setting. Simulations of Room B and D closure have been recently recomputed (Rath and Arguello, 2012) using the SIERRA Mechanics fully-coupled mechanics calculations. SIERRA Mechanics predictions are comparable to historic numerical calculations and experimental data. The Room B/D dataset from WIPP is ideal for benchmark exercises.

German researchers propose to collect additional specific laboratory tests results for WIPP bedded salt to support generic benchmarking calculations. Düsterloh of the Technical University Clausthal provided an overview of the proposed testing philosophy and specific testing matrix. (See presentation in these Proceedings.) Short-term tests will determine bedded salt failure strength, while certain creep tests are needed to determine constitutive model creep parameters. Creep tests will be conducted both below and above damage stress levels. Salt healing tests will be a component of the test matrix. Laboratory tests will be designed to quantify damage-free creep, damage-induced creep, and healing creep over a range of equivalent stress levels and temperatures.

3. GRANULAR SALT RECONSOLIDATION

Crushed or run-of-mine salt makes an excellent backfill material for salt repositories for several reasons. Due to salt’s healing properties, the crushed salt will ultimately regain the host rock’s favorable impermeability to brine flow and radionuclide transport. Crushed salt is available and easy to emplace in drifts, unlike engineered concrete or other man-made seal material. A large number of laboratory and in situ tests have already been conducted to determine the properties of crushed salt under a wide variety of conditions. Additional testing may be required to fully understand some of the details of reconsolidating salt in low-permeability regions.

During the workshop, a questionnaire was distributed regarding the role of crushed salt in repository science to all workshop attendees. The results of the survey indicated a general consensus among attendees related to the nature and importance of crushed salt reconsolidation in repository performance. Results indicate all processes were considered relatively important, with hydrology of crushed salt ranked most important, followed by crushed salt thermal characteristics, and mechanical behavior. The survey also inquired about our general understanding of thermal processes related to salt reconsolidation in a repository setting. Consensus indicates a moderate understanding, with room for improvement. Another question asked whether all the relevant processes in crushed salt reconsolidation have been considered. Responses were generally positive, but not convincingly high. The last required question asked about the apparent degree of confidence in current model calibrations related to crushed salt reconsolidation. The answer to this question was average, with “experts” responding with higher confidence than “non-experts.”

Of the 16 replies, six had formal text comments. Several other people informally gave additional statements when they submitted their questionnaire.

- Test scale was a common theme in the comments. Testing time and space scales need to be reconciled with the desired predictions. Tests are typically core-scale, high-strain, high-temperature, and are on the scale of hours to days, while repository processes related to closure and healing of crushed salt in backfill are drift-scale, lower-strain, often lower-temperature, and are on the order of months to hundreds of years. The German drift-scale Thermal Simulation of Drift Emplacement (TSDE) test, and the BAMBUS II (Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt / Germany) analysis which followed, addressed some of these concerns of scale. It was generally agreed during the discussion that these types of tests are very expensive and difficult to conduct.
- Most backfill research and design now uses run-of-mine crushed salt without additives or amendments like bentonite or vermiculite. Previous backfill research during the 1970s and 1980s investigated many potential mixtures and combinations of backfill. Repository science would be well served to answer the question: "Why are additives not being used in repository backfill design?"
- Low-porosity (≤ 5% porosity) crushed salt consolidation, permeability, and thermal tests need to be performed to systematically quantify the effects of water content on reconsolidation. Many tests have been conducted to characterize behavior at higher porosities. Low-porosity tests are more difficult, but are related to the regime where crushed salt changes from a “high” permeability porous medium to the “low” permeability more representative of intact salt. This transition to healed salt is assumed to happen eventually, being one of the main benefits for salt repositories. Regarding moisture, existing understanding is limited to the benefits of a “small” amount of water on consolidation, or consolidation issues associated with a “large” amount of water. It is important to understanding the timing and dependence on stress, temperature, and moisture for this crucial transition from low to high permeability.
- There is a need to perform laboratory tests to understand how different physical creep mechanisms fit into and explain salt reconsolidation. Some creep mechanisms are responsible for healing, which produces intact salt from crushed backfill.

The results of this survey were illuminating. Whereas some technical experts believe the phenomena associated with crushed salt reconsolidation are well understood, it is clear this view is not held by all experts and informed lay personnel. The perception that salt reconsolidation processes and associated phenomena are imperfectly known is vital to license application. A regulatory authority will ultimately weigh the objective evidence and decide the merit of performance arguments (see for example the timely contribution of Tom Klein in these Proceedings). Some aspects of the transition from loose, permeable crushed salt to impermeable nearly intact salt have not been adequately parameterized. Comprehensive matrices of tests under low porosity and variable water content would increase our understanding and modeling predictive ability to repository time and length scales. In consideration of our own high expectations for scientific rigor, continued research on reconsolidation of granular salt remains a focus of US/German collaborations.

4. COLLABORATIONS

Collaboration between individual researchers is fundamentally important to advancement of international repository viability, although not a specific item on the agenda. Significant collaboration has already occurred and continues on key topics of safety case, model benchmarking, and granular salt reconsolidation. As pointed out earlier, derivative areas for collaboration emerge as Principal Investigators come together in workshops, such as these. In several instances, the US/German Workshops are accomplishing goals set by the NEA Salt Club (www.oecd-nea.org/rwm/saltclub/). Specifically, these include development of a rock salt FEPs catalogue regardless of location and formation (domal or bedded), development of salt knowledge archive, and a natural analogue workshop. In addition, other discussions addressed use of space at WIPP for an underground research laboratory (URL) (what testing and demonstrations might be of international interest) and treatment of uncertainties in long-term safety of final repositories. This progress is summarized in this section.

4.1 FEPs Catalogue for Generic Heat-Generating Waste Salt Repository

The DOE Used Fuel Disposition (UFD) Campaign recently developed a preliminary list of FEPs potentially relevant to the long-term disposal of SNF and HLW. The UFD FEPs were applicable to generic (i.e., not site- or design-specific) repository concepts for mined geological disposal of SNF and HLW in salt, clay, and granite formations, and deep borehole disposal in crystalline rock. The UFD FEP list (Freeze et al. 2010; Freeze et al. 2011) was developed from prior FEP identification performed as part of the NEA International FEP Database (NEA, 1999; NEA, 2006) and in support of the Yucca Mountain Project (BSC 2005; SNL 2008).

Hansen and Leigh (2011, Appendix A) developed a list of FEPs for disposal of SNF and HLW in a generic bedded salt formation. The FEP list was constructed from the UFD generic FEP list with consideration of WIPP program FEPs. Sevougian et al. (2012, Appendix A) documented the resulting list of 208 US generic salt repository FEPs. The generic US salt FEPs follow the NEA hierarchical numbering scheme, include some salt-repository-specific processes, and have been cross-checked against the WIPP FEPs.

Planned collaborative activities include producing a single consolidated salt repository FEP list by cross-checking the US salt FEP list against the German FEP catalogue for the Gorleben salt dome (Wolf et al., 2012). A draft of the consolidated salt FEP list is expected in the spring of 2013.

4.2 Salt Knowledge Archive

In recent years noteworthy progress was made in the US and Germany on safety assessment exercises, geomechanical benchmark modeling, and technological developments, including waste emplacement techniques. Comprehensive knowledge and sound expertise have been acquired across salt repository science and engineering over the years. Therefore, German and US financial and intellectual investments in salt repositories are unique and represent state-of-the-art global assets. As noted by Steininger, et al. (2013) perhaps the most imperative outcome of the re-strengthened cooperation is long-term knowledge preservation. The solution to this problem includes both preservation of knowledge and training young scientists and engineers. Attracting qualified staff and transmitting the accumulated know-how to the next generation is therefore a major challenge.

Sandia has developed a database of salt-related research, reports, and publications called SITED (Kuhlman et al., 2012). The database has a publicly-viewable web interface, allowing researchers from various institutions and locations to read, update, and add records (https://sited.sandia.gov/sited). The database has over 10,000 entries, initially populated through queries of public DOE-sponsored databases (i.e., DOE Office of Science Information Bridge and Energy Citations database), national laboratory technical libraries (e.g., Sandia, Oak Ridge, and Los Alamos National Laboratories), the European Union "Bookshop," and scholarly journals and conference proceedings. Most database entries have an electronic pdf document attached, which can be downloaded from the SITED webpage directly. This tool and associated database are hopefully useful to both our US and German colleagues.

4.3 Natural Analogue Workshop

On 4-6 September 2012, the Project Management Agency Karlsruhe – Water Technology and Waste Management (PTKA-WTE) and the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH hosted the joint NEA Salt Club Workshop "Natural Analogues for Safety Cases of Repositories in Rock Salt" in Braunschweig, Germany. The workshop was attended by 37 participants from research institutes, universities, regulators, federal institutes, engineering companies, and related salt industries (i.e., mining and hydrocarbon storage).

The workshop aimed to compile studies about global natural and anthropogenic analogues for potential used in safety cases for salt-based radioactive waste repositories. More specifically, the following topics were discussed:

- long-term rock salt formations integrity
- technical barrier integrity
- microbial, chemical, and transport processes

These topics were presented in several talks during the first part of the workshop. Further discussion of these topics identified key unresolved issues. The discussion culminated in recommendations for future salt natural analogue studies. Active discussion topics included compaction of crushed salt, microbial activity, anhydrite deformation and fluid inclusion movement. In 2013, the outcomes of this workshop will be published in a NEA report.

4.4 Use of a Salt Underground Research Laboratory

The salt repository community has benefitted from recent international salt repository workshops specifically geared to research, design, and operations. Building on these timely workshops and interactions, new uses for underground space have been identified through an objective-driven agenda. This agenda was put forward for independent and transparent evaluation (Hansen, 2013; also see presentation in these Proceedings). Several field-scale activities have been described for the purpose of beginning a dialogue regarding choices and priorities for use of this valuable space. These activities could help bolster the "sound-science" prerequisite for public and political acceptance in the US as well as foster international collaboration and advance goals of the NEA Salt Club.

These activities include field demonstrations involving modest heat loads of interest to the DOE Office of Environmental Management (DOE-EM), phenomenological testing at elevated thermal loading that may be of interest to the DOE-Office of Nuclear Energy (DOE-NE), and several additional investigations that promise to fortify the basis for salt disposal and future repository design strategies:

- Salt Defense Disposal Investigations (SDDI)
- Salt Disposal Investigations (SDI)
- Large-Scale Seal Demonstration
- Mining Research
- Wedge Pillar Test
- Mine-By Disturbed Rock Zone Measurement
- Standardized Borehole Heater Test

For the most part these testing and demonstration activities are large in scale, with commensurate commitments of time and resources. Opening of new underground space connected to the excellent infrastructure at WIPP provides a research development and demonstration facility of enormous potential value to the US and international salt repository programs.

None of the field tests or demonstrations constitutes a roadblock to the development of a safety case for heat-generating waste disposal in salt. The process of developing a safety case may illuminate uncertainties to be mitigated or minimized through appropriate testing. Ongoing testing and monitoring is a common requirement in geologic repository licensing. The WIPP compliance certification requires monitoring ten parameters as a condition of the Environmental Protection Agency (EPA) certification and permit and, likewise, the license application for Yucca Mountain included an extensive commitment of ongoing science under the performance confirmation program. Therefore, use of the new underground space at WIPP allows for continued advancement of the technical basis for disposal of heat-generating nuclear waste in salt, to further demonstrate repository performance to stakeholder and regulators, to demonstrate disposal concepts, and to refine mining and design considerations.

4.5 Quantifying Uncertainty

Sandia was invited to participate in a future European collaboration network addressing the issue of uncertainties in long-term safety case of final repositories. The basis is called a joint activity, which is addressed in the Deployment Plan of the IGD-TP (Implementing Geological Disposal of Radioactive Waste – Technology Platform) (http://igdtp.eu/index.php/key-documents).

As these collaborations take form, possible research subjects of the project could include

- quantifying and categorizing uncertainties
- handling aleatoric/epistemic uncertainties
- refining methods for uncertainty/sensitivity analysis
- benchmarking of modeling tools

This type of collaboration is further evidence of benefits derived from the US/German Workshops on Salt Repository Research, Design and Operation. The European Commission encourages additional areas of collaboration between potential partners (e.g. http://www.eurunion.org/FP7-USGuide-12-09.pdf). Contributions from US participants would be *quid pro quo*, as only technical information would be exchanged.

The preceding synopsis provides participants and sponsors a sense of progress attained in these collaborations (see also Steininger, et al., 2013). As collaborations continue, the salt repository science community should strive to a point where a substantial report is compiled, perhaps in 2014. This landmark report would summarize the state-of-art and serve as an instrument for knowledge transfer. Such a document would provide the foundation for succession planning.

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APPENDIX A: AGENDA

Final Agenda October 4 2012

US-German Meetings

7th Project meeting of the Joint Project "Comparison of current constitutive models and simulation procedures on the basis of model calculations of the thermo-mechanical behavior and healing of rock salt"

and

3rd US/German Workshop on Salt Repository Research, Design and Operation

Albuquerque and Carlsbad, New Mexico, USA
October 8 -10, 2012
Hosted by Sandia National Laboratories

Venue
Sandia National Laboratories
Rooms 1154/1155 at International Programs Building 10600 Research Rd SE

DAY 1—October 8—Monday 09:00-17:00

08:00 – Badging for Foreign Nationals will be held in the IPOC Building

0:800 – Badging for US Citizens will be held in the IPOC Building

08:00 – Doors Open – Coffee and Light Breakfast

Project meeting of the Joint Project "Comparison of current constitutive models and simulation procedure on the basis of model calculations of the thermo-mechanical behavior and healing of rock salt"

12:30 – Lunch, catered at facility

Dinner on your own.

<u>Project partners and participants of the project meeting:</u>

- Dr. Andreas Hampel, Scientific Consultant, Mainz, Germany,
- Institut für Gebirgsmechanik GmbH (IfG), Leipzig, Germany,
- Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany,
- Leibniz Universität Hannover, Institut für Unterirdisches Bauen, Hannover, Germany,
- Technische Universität Clausthal, Lehrstuhl für Deponietechnik und Geomechanik, Clausthal-Zellerfeld, Germany,
- Technische Universität Braunschweig, Institut für Grundbau und Bodenmechanik, Braunschweig, Germany,
- Sandia National Laboratories, Albuquerque, USA.

Cont. 3rd US/German Workshop on Salt Repository Research, Design and Operation

The workshop / project meeting on Monday will be conducted as an "internal" Joint Project status meeting. The presentations and discussions will be specialized and detailed. A summary of the benchmark collaborations will be presented within the 3rd US/German Workshop (on Wednesday October 10) and included in the workshop proceedings. The Joint Project is expected to be extended with special emphasis on benchmarking WIPP experiments in Rooms B&D, which is of extreme importance to generic US salt repository investigations. Sponsors of this collaboration such as Sandia and DOE and other particularly motivated collaborators are welcome.

DAY 2—October 9— Tuesday

07:30 – Doors Open – Coffee and Light Breakfast

07:30 -- Badging for Foreign Nationals will be held in the IPOC Building

08:15: Introductory comments: Steininger, Biurrun, Hansen

Topic: *Selected aspects of the Safety Case for salt disposal of HLW/SNF*

08:30 USDOE Perspectives (Gunter-NE, Buschman-EM)
09:00 Salt Repository Prospects in Germany (Biurrun, DBE Tec, Steininger, PTKA)
09:30 Preliminary Safety Assessment for a Repository at the Gorleben Site (Bollingerfehr, DBE Tec)
10:00 FEP Catalogue and Scenario Development for a Repository in Salt (Wolf, GRS)
10:30 FEP Catalogue for HLW/SNF Disposal in Salt (Leigh, Sandia)

Break 11:00 – 11:15

11:15 Safety Case for Salt Disposal of High-Level Waste and Spent Nuclear Fuel (Freeze, Sandia)
11:45 Performance Assessment for HLW/SNF Disposal in Salt (Sevougian, Sandia)
12:15 Uncertainty Treatment in Performance Assessment (Sallaberry, Sandia)
12:45 Investigations on Sensitivity Analysis of Complex Final Repository Models (Becker, GRS)
13:15 Workshop Photo on the patio—then lunch

Lunch 13:15, catered at facility

Topic: *Plugging and Sealing*

14:00 First Results from the Project: Numerical Efficiency Optimization of Sensitivity Analysis Methods with regard to Analysis Models of Long-Term Safety for Nuclear Waste Disposal Sites (Kuhlman, TUC)
14:30 Methods for assessing the long-term performance of geotechnical seals in a repository in rock salt (Plischke, TUC)
15:00 Full Scale Demonstration of Plugs and Seals (Jobmann, DBE Tec)

Cont. 3rd US/German Workshop on Salt Repository Research, Design and Operation

15:30 In Situ Verification of a Drift Seal System in Rock Salt--Operating Experience and Preliminary Results (Mauke, BfS)
16:00 FCT UFD Crushed Salt Mechanical Testing Results to Date (Broome, Sandia)

Break 16:30-16:45

Topic: Focus on Granular Salt Consolidation

Format: International salt repository researchers, designers and operators are interested in assessing the state of the science regarding granular salt reconsolidation. This session will focus on salt reconsolidation. We will include short technical presentations to help establish current understanding and participants will be encouraged to answer a survey/questionnaire with a list of questions probing the importance of salt consolidation. Ultimately, we hope to use the information from this focus session to provide an outline for a position paper on the topic, ongoing research and open questions. Technical presentations will be followed by open forum on the survey.

16:45 Microstructural Deformation Processes in Granular Salt during Mechanical Compaction (Till Popp, IfG)
17:00 Recent Experimental and Modeling Results on Crushed Salt Consolidation (Klaus Wieczorek, GRS)
17:15 Crushed Salt Model Regions of Influence (Gary Callahan, RESPEC)
17:30 Perspectives on Granular Salt Reconsolidation (Frank Hansen, Sandia)

17:45 Discussion of the survey results (Moderator Kris Kuhlman, Sandia).

Adjourn 18:30

Bus will pick up everyone at Meeting Facility (IPB) drive over to Sandiago's at the Tram. At the end of the evening, the bus will return first to the Meeting Facility (IPB) and then to the Hyatt Hotel.

DAY 3— October 10—Wednesday

07:30 Doors Open – Coffee and Light Breakfast

Topic *Rock/Salt mechanics*

08:00 Salt Compaction Use for Panel Closures (Kline, WTS)
08:30 Mechanical-Hydraulic Conditions for an Integrity Loss of Salinar Barriers (Popp, IfG)
09:00 Thermomechanical-Hydrology Modeling for HLW Disposal (Bean, Sandia)
09:30 Microstructure Simulation Based on Discrete Element Models (Müller, DBE Tec)
10:00 Benchmark Modeling Status Report of the Current Joint Project III (Hampel)
10:30 Comparison of Constitutive Models (Günther, IfG)

Cont. 3rd US/German Workshop on Salt Repository Research, Design and Operation

Break 11:00-11:15

11:15 Approved Methods for Determination of Salt Specific Parameters and Laboratory Test Program Matrix for WIPP Salt (Düsterloh, TUC)
11:45 High Temperature Uniaxial Stress Tests on WIPP Salt (Mellegard, RESPEC)

Repository, Design and Operation, and Miscellaneous

12:15 Outlook on the Benchmark Proposal for WIPP Rooms B & D (Argüello)
12:45 Results of the Salt Club Workshop: Natural Analogues for Safety Cases of Repositories in Rock Salt (J. Wolf)
13:15 Conceptual Aspects of HLW/SNF Repositories (Bollingerfehr, DBE Tec)
13:45 Repository Engineering

- Disposal Concepts for Large Spent Fuel Waste Packages in Salt (Hardin, Sandia)
- Hoisting and Disposal of Dual-Purpose Storage Containers (Biurrun, DBE Tec)

14:15 Wrap Up—Brief Summary

Adjourn 14:30

Bus will pick up Participants at Meeting Facility (IPB) and Transport everyone to Carlsbad
Box lunch will be provided upon boarding bus

DAY 4-- October 11—Thursday—

Tour WIPP and return to Albuquerque

8:00 Bus pick up at Stevens Inn and transport to Sandia Carlsbad Office
8:30 Sandia Carlsbad Overview (Shoemaker, Sandia)
9:15 Safety Briefing
9:45 Underground Salt Research Laboratory at the Waste Isolation Pilot Plant (Hansen, Sandia)
10:15 Summary Comments and Future Planning (All)
10:45 Depart for the WIPP Site. ***A separate WIPP Tour agenda will be provided.***

APPENDIX B: DAY TWO: ABSTRACTS

Preliminary Safety Assessment for a Repository at the Gorleben Site

Wilhelm Bollingerfehr
DBE TECHNOLOGY GmbH, Eschenstraße 55, 31224 Peine, Germany

Abstract

In the summer of 2011, the Federal Government of Germany decided to phase out of nuclear energy production until 2022. One year earlier the preliminary safety assessment of the Gorleben salt dome was launched. The objective of this preliminary safety assessment is a traceably documented prognosis on the suitability of the site as a HLW repository. This requires in a first step the development of an adjusted repository design. In addition to the reduced amount of radioactive waste and spent fuel, the new "Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" of September 30, 2010, had to be taken into account. In this context one main challenge was to show that repository design could be developed that meets the new retrievability requirements. For this purpose, basic repository concepts were designed first which will be optimized in subsequent design steps and will provide the basis for long-term safety models and analyses.

Compared to the German reference repository concept which considers emplacing spent fuel elements in self-shielding POLLUX casks in horizontal drifts and unshielded vitrified waste canisters in deep vertical boreholes, different emplacement strategies were investigated. The following two main variants were considered. One Variant consists of the Emplacement of all heat-generating radioactive waste (spent fuel and vitrified waste) in self-shielding waste containers (POLLUX cask) in horizontal drifts. Within the other variant the Emplacement of all heat-generating radioactive waste in multi-purpose cylindrical containers in deep vertical boreholes has been considered. As an option, the emplacement of a certain amount of non-heat-generating radioactive waste was taken into account (in horizontal emplacement chambers).

As the repository safety concept considers the safe enclosure of the waste containers by the host rock (rock salt) itself the most important factors defining the repository concept are the geologic conditions at the site on the one hand and the type and the amounts of waste to be disposed of on the other hand. Both factors were elaborated in detail. It could be shown that both strategies lead to reliable repository concepts. Technical approaches how to retrieve emplaced waste containers were developed as well. The results of the repository design including the backfill and sealing measures will be displayed as well as the process how to analyze the safety of the entire system.

Uncertainty Treatment in Performance Assessment for a Salt Repository – the Sandia Approach

SAND 2012-8040A

Cédric J. Sallaberry
Sandia National Laboratories, Albuquerque New Mexico USA

Abstract

Treatment of Uncertainty is nowadays one of the major components of any complex system analysis. Sandia has advertised and incorporated probabilistic approaches since the 70ies and used it notably for the 1996 certification of Waste Isolation Power Plant (WIPP). In the top down concept used by Sandia, the three Kaplan-Garrick Risk questions are considered (What can happen ? How likely it is to happen? What are the consequences if this happens?) and complemented by a fourth one with respect to lack of knowledge uncertainty (How confident I am in the answers of the previous three questions?) to develop a mathematical framework fit to the model in consideration. Such characterization allows to successfully separate randomness (aka aleatory uncertainty) from lack of knowledge (aka epistemic uncertainty) and give more insights, via uncertainty and sensitivity analysis for the decision maker. Since WIPP certification, Sandia worked in maintaining its expertise and knowledge with respect to uncertainty treatment as well as extend it by new concepts and methods to real life problems.

Investigations on Sensitivity Analysis of Complex Final Repository Models (Part I)

D.-A. Becker
Gesellschaft fuer Anlagen- und Reaktorsicherheit, Braunschweig, Germany

Abstract

Numerical models for calculating the potential impact of a repository to the biosphere have to take account of various coupled effects and often show a non-linear, non-monotonic, or even non-continuous behavior. This is detrimental for the performance and robustness of known methods of sensitivity analysis. This applies specifically to repository systems in rock salt, which, due to the creeping ability of salt, can develop very differently if some input parameters are only slightly varied. Numerical experiments showed that in specific cases even several ten thousand model runs are not enough to reach numerical convergence of the results.

Current investigations at GRS and TU Clausthal aim at identifying the typical problems arising with sensitivity analysis of complex final repository models and proposing solutions.

In the first part of the presentation the general approach to sensitivity analysis is explained and the identified problems are illustrated using two example systems. One is based on an existing LLW/ILW repository in Germany, the other is a generic concept for a future HLW repository.

First Results from the Project: Numerical Efficiency Optimization of Sensitivity Analysis Methods with Regard to Analysis Models of Long Term Safety for Nuclear Disposal Sites

Sebastian Kuhlmann, Klaus-Jürgen Röhlig, Elmar Plischke
Institute for Disposal Research, Clausthal University of Technology, Germany

Abstract

The project's overall goal is a guide trough Sensitivity Analysis (SA) in long-term disposal of nuclear waste. This should be achieved by evaluation of SA-Methods and assessment with regard to requirements and particularities in long-term disposal. Further aspects are methods development considering the identified requirements and the study of time dependency, transformation's effects and usage of metamodels.

The first simulation model is a simple disposal site in salt for low and intermediate level waste. Site volume and waste inventory is based on an existing disposal site to approach realistic behavior. The site consists of two disposal chambers, one shaft, intermixture chamber and oddment chamber. The disposed waste is composed by 43 radionuclides with a total activity of 3.23·1014Bq.

The near field model uses 21 probabilistic input parameters. The nuclide specific near field output in a timescale from 105 to 108 years is subject of actual studies. Cormenzana's Mean Ranks Plots are based on Cobweb Plots which are used in different fields of SA. Instead of plotting ranks of all realizations only mean ranks of subsamples are used. This allows to show much information or to compare different cases in one figure. Statistically not significant range of values can be identified with knowledge of mean ranks with no effect.

Project's next step is to extend the model with far field and biosphere followed by using graphical methods on total output. Further steps are consideration of numerical methods, treatment of correlations and preparation of a model for high level waste and spent nuclear fuel.

First project's conclusion is to start by visualizing data in order to get familiar with the dataset and the system behavior. Therefore many graphical methods can be uses, i.e. Histograms, Scatterplots, superimposed evolutions in time, Cobweb Plots, Mean Ranks Plots. Color coding may help to interpret the plots but interpretation should always be done carefully because the human brain tends to construct structures from randomness, a fact well known from optical illusions. Time dependency is another aspect which should be kept in mind while interpreting.

Methods for Assessing the Long-term Performance of Geotechnical Seals in a Repository in Rock Salt

J. Orzechowski, E. Plischke, K.-J. Röhlig, X. Li (TUC)
J. Krone, N. Müller-Hoeppe (DBE TEC)

Abstract

Engineered seals (e.g. dams to be constructed in drifts) play a central role in the safety concept for a HLW/SNF repository in rock salt: Their primary safety function is to prevent liquid (brine) inflow in "early" timeframes during which the crushed salt backfill will still undergo compaction and therefore will not be completely able to prevent inflow and the resulting contaminant migration.

The construction and reliability demonstration for seals can be based upon existing engineering experiences, standards and practices as codified e.g. in the so-called "Eurocodes." Reliability issues are mostly being addressed by means of semi-probabilistic methods. However, such methods are usually only being applied for comparably short design lifetimes (up to 100 years).

The presentation reports about a project aiming at an approach which combines these practices with the requirements for long-term safety assessment and at the adaption of engineering standards in order to support the post-closure safety case.

The project addressed two issues:

1. Derivation of probability distributions based on existing data and derivation of reliability statements using probabilistic methods
2. Considering FEP of long-term relevance in terms of engineering approaches (actions and resistances) using methods stemming from classical engineering as well as from long-term safety assessment (based on FEPs and scenarios)

It was concluded that Monte Carlo simulations enhance confidence in the cautious estimates calculation. The application of a probabilistic / geostatistical approach for effective conductivity sampling and the derivation of reliability statements is, in principle, possible. The question remains, however, whether it will be affordable and achievable to acquire a sufficient amount of date satisfying the rather demanding needs of reliable variography and geostatistics.

With respect to FEP of long-term relevance and their interactions the heat production of the radioactive waste was identified as the most important FEP as it significantly influences geomechanics und geochemistry. An iterative methodology was proposed accounting for both engineering and safety assessment requirements. It seems to be possible that one can map safety function indicators to indicators/criteria describing the resistance of a structure, thus combining engineering and assessment aspects. Here further investigations are needed.

Full Scale Demonstration of Plugs and Seals DOPAS / ELSA

Michael Jobmann
DBE TECHNOLOGY GmbH, Eschenstraße 55, 31224 Peine, Germany

Abstract

DOPAS aims to improve the adequacy and consistency regarding industrial feasibility of plugs and seals, the measurement of their characteristics, the control of their behavior over time in repository conditions and also their hydraulic performance acceptable with respect to the safety objectives.

This DOPAS project addresses the design basis, reference designs and strategies to demonstrate the compliance of the reference designs to the design basis, for plugs and seals in geological disposal facilities. The project focuses on shaft seals for salt rock (German repository concept), tunnel plugs for clay rock (French and Swiss repository concepts), and tunnel plugs for crystalline rock (Czech, Finnish and Swedish repository concepts). Five different demonstration experiments are part of the project and will take place in Sweden, France, Finland, Czech Republic and Germany. They are in different state-of-development. The Swedish demonstrator will be constructed prior to start of the DOPAS project and will basically provide experience on demonstration of compliance of reference design to the design basis. The German demonstrator (ELSA) will be installed after the DOPAS project and will focus on demonstration of suitability by performance assessment. The French-Swiss, Finnish-Swedish and the Czech experiments will address developments in all phases of design basis, reference designs and strategies to demonstrate compliance of reference designs to design basis. The studied concepts will be developed in the DOPAS's five thematic scientific/technological work packages, which each integrate the results of the individual experiments.

The project is carried out in a consortium of 12 organisations representing waste management organisations, research organisations, academia and consulting.

The DOPAS project is derived from the IGD-TP's Strategic Research Agenda that points out the topic of “plug and seals” as a first priority issue for joint European RTD projects.

In situ-Verification of a Drift Seal System in Rock Salt - Operating Experience and Preliminary Results

R. Mauke, Bundesamt für Strahlenschutz (BfS) [Federal Office for Radiation Protection], Salzgitter

Abstract

Seals are to be erected in the repository for radioactive waste Morsleben (ERAM). These will form a partition between the repository areas in which the radioactive waste is emplaced and the remaining mine workings into which a solution inflow cannot be ruled out. The seals should prevent the penetration of solution into the waste emplacement areas and the emission of radionuclides out of these areas. Special requirements are therefore placed on these constructions. Adherence to these requirements will be investigated and tested on a real scale test construction.

The drift seals located in rock salt are made up of one or more segments of salt concrete in lengths between 25 and 30 m. A succession of several segments will be separated from each other by plastic joints to prevent the occurrence of restraint stresses. Injection of the contact joint between the sealing body and the surrounding rock salt will be carried out on at least one segment. In this respect the trial construction consists of three system components, namely the sealing body made of salt concrete, the contact zone between the seal body and the surrounding rock salt and the rock salt excavation damaged zone (EDZ). All these components will be observed during the in situ investigation.

A test drift and an accompanying parallel drift have been newly excavated for the experiment. Boreholes for the measurement cables have been drilled from the gently rising parallel drift. Also emanating from the parallel drift hydraulic pressurisation tests could be performed by using the pressure chamber adjoining the seal construction. The cross-section of the newly excavated drift was gently rounded and the roof ridges have been chamfered with a 3 gon inclination approx. 6 months after its excavation minimising the EDZ. Concreting of the construction with salt concrete took place “wet on wet” in December 2010 within approx. 20 hours. Injection of the contact zone between the seal body and the surrounding rock salt was carried out in February 2011.

Starting from the excavation, the prominent construction phases and significant preliminary measurement results were presented at the 2nd US/German Workshop in Peine in November 2011.

This article continue the reporting of the operational experiences and described more preliminary results including the continuation of the geotechnical stress measurements, the over-drilling and sealing of the cladding tube, core scanning and micro-sectioning investigations to visualise the grouted contact zone, mechanical investigations on core sample of the contact zone as well as some information about the numerical calculations to evaluate the overall functional tests and measurements. Finally actual results and the progress of work of the hydraulic testing (pre-test and first period of the main test) of the in situ drift seal construction were presented.

All presently available results indicate that the in situ test was successful.

Microstructural Deformation Processes in Granular Salt during Mechanical Compaction

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Abstract

Disposal of nuclear waste in salt is an established technology, as evidenced by the successful operations of the Waste Isolation Pilot Plant (WIPP) since 1999. As backfill material in the underground openings crushed salt is emplaced around the waste. The crushed salt is expected to be compacted with time by the convergence process of the rock mass, and to finally reach a similar mechanical stability and hydraulic resistance like the surrounding rock salt. With respect to the safety concept, where the compacted salt serves as an efficient long-term seal it has to demonstrated, that the backfill of crushed salt is really compacted to a porosity of nearly zero, like that of undisturbed rock salt.

The creep behaviour of dense rock salt and of crushed rock salt with porosities above 10-15% has been thoroughly studied, and it is well-established that the principal deformation mechanisms in these materials are dislocation glide/creep and solution-precipitation creep or “pressure solution”. However, limited knowledge exists regarding the processes that convert permeable salt backfill materials (porosity <10%) into an impermeable backfill with properties similar to those of natural salt rock. This contribution summarises work done in the last 10 years, e.g. under NF-PRO and BAMBUS.

Results obtained to date by various groups involved in research of granular salt (e.g. from University Utrecht, BGR and IfG) have demonstrated that moisture strongly enhances compaction of granular salt aggregates at low porosities (< 10%), and that compaction is a strongly time/rate dependent process. Compaction of dry samples at fixed stress is slow and dominated by a dislocation glide/creep mechanism. Compaction of water-bearing samples (lab-dry or with added brine), at comparable conditions, is always faster and becomes grain size sensitive as water-assisted processes such as pressure solution and plasticity-coupled solution transfer become active.

Referring to the seal efficiency, laboratory tests with brine as test fluid show that the permeability of highly compacted samples is low and, in addition, capillary threshold effects will prevent fluid mobility.

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 resulting in tightness against gases and fluids which is the prerequisite to act as a long-term seal. However, some principal challenges are remaining in relation to the salt backfill materials. First and foremost, it is important that the mechanistic understanding and empirical data gained to date lead to a consensus on constitutive models for compaction that can be reliably extrapolated to in-situ conditions. These models should be appropriately generalised to a full 3-D description and must be verified against long term tests in the lab and field scale to ensure that reaching of in-situ conditions closely to natural salt is possible.

Recent Experimental and Modeling Results on Crushed Salt Consolidation

Klaus Wieczorek, Oliver Czaikowski, Chun-Liang Zhang, GRS, Germany
Dieter Stührenberg, BGR, Germany

Abstract

Crushed salt backfill is expected to take an important barrier function in a salt repository in the long term. The crushed salt will be compacted by convergence of the rock. It is expected that the porosity and permeability of the backfill will eventually be low enough to take the barrier function. A sound understanding of the processes relevant for backfill compaction, constitutive models that enable us to simulate these processes, a good database to calibrate the models and also to show that they are robust enough for reliable predictions are needed for the prediction of backfill behavior. Important factors that influence the compaction behavior are - besides the mechanical boundary conditions - temperature, grain size distribution, and solution content.

BGR has performed numerous compaction rate controlled oedometer experiments in order to determine the backfill resistance to compaction (or stress build-up in the backfill) as a function of compaction rate, including tests at different temperatures and solution contents (salt brine). The tests were performed at different compaction rates between $6.6 \cdot 10^{-7}$ s^{-1} and $6.6 \cdot 10^{-10}$ s^{-1}. The similarity between the curves for different compaction rates in the backfill resistance / void ratio diagram can be exploited to extrapolate to lower compaction rates which cannot be realized in laboratory but will be relevant in situ. The results show that

- For dry crushed salt, backfill resistance exceeds 20 MPa with a compaction rate of 10^{-10} s^{-1} already at void ratios around 0.1 (T = 50 °C). Compaction rates in situ may become so small that sufficient compaction may not be reached within a reasonable time scale with dry crushed salt at ambient temperature.
- Elevated temperature reduces backfill resistance, which will result in increasing compaction rates.
- A small solution content in the range of 1 wt.% is even more effective. In a recent test a void ratio below 0.02 was reached. The backfill resistance / void ratio curve at 10^{-10} s^{-1} blends in well with earlier tests at 0.6 and 1.2 wt.% of solution.

Load controlled tests appear more suitable for model calibration, because they allow the distinction between time-independent and viscous behavior, especially for multistep loading. Tests performed at GRS have been used for calibration of Zhang's model for crushed salt compaction and are currently used for calibration of the model implemented in the simulation tool CODE_BRIGHT used by GRS. A problem of these tests is the time needed to achieve low porosity at relevant stress states.

Zhang's model is an empirical model for isostatic time-dependent compaction which has the form of a creep law. Parameters were determined for different salt types in oedometer and triaxial tests, and good approximations of experimental behavior were reached. The minimum porosity in the test was, however, always above 10 %.

The CODE_BRIGHT model involves a superposition of different deformation mechanisms: Elasticity, dislocation creep, viscoplasticity simulating grain reorganisation and crushing, and fluid assisted diffusional transfer (pressure solution). The model is currently calibrated on three load controlled oedometer tests: one using dried crushed salt, the second on crushed salt with natural moisture content (below 0.02 wt.%), and the third on artificially wetted crushed salt (1.0 wt.% of solution). Results look

promising, but after 500 days of testing, the porosity of the non-wetted samples has reached only 17 %, while the wetted sample is at 9 % porosity. Effects of temperature or variations in grain size distribution still have to be investigated in the future.

Besides the experimental time, an important issue in both the compaction rate controlled and the load controlled tests is the uncertainty in porosity determination deriving from the uncertainty in salt density. The porosity uncertainty is estimated to amount to about 1 % and is therefore in the range of the supposed porosity itself at the end of compaction.

For the assessment of the barrier function of the backfill towards the end of the compaction phase it is important to deduce a reliable porosity / permeability function. It is believed that a relevant compaction history of samples used for permeability measurements is necessary to give meaningful results.

Crushed Salt Model Regions of Influence

Gary D. Callahan
RESPEC, Rapid City, South Dakota USA

Abstract

Crushed (disaggregated) salt will most likely be used for repository room backfill and as a component in the repository shaft seal system. In these situations (with sufficient stress, temperature, and time), the crushed salt will evolve from a loose, highly porous material to a dense, low porosity material or essentially intact salt. To model the mechanical behavior of crushed salt in a repository setting, a constitutive model was developed to capture the major deformation components of the crushed salt. The constitutive model comprises nonlinear elastic and creep consolidation components. The creep consolidation portion of the model used to describe the time-dependent, creep consolidation salt includes two mechanisms—dislocation creep and grain boundary diffusional pressure solution. The constitutive model is generalized to represent three-dimensional states of stress. Upon complete consolidation, the crushed-salt model reproduces the multimechanism deformation (M-D) model typically used for the Waste Isolation Pilot Plant (WIPP) host geological formation salt.

Parameter values for the model are based on laboratory tests including 40 hydrostatic consolidation tests and 18 shear consolidation tests. Parameter values for the model were determined through nonlinear least-squares model fitting to the experimental database. Using the fitted parameter values, the constitutive model was validated against constant strain-rate tests, which is a load path outside of the laboratory experimental database. The initial database encompasses predominately room temperature tests; however, eight short duration isostatic tests were conducted up to temperatures of 100°C. Additional isostatic and shear consolidation tests are being conducted by Sandia National Laboratories at temperatures up to 250°C. Following completion of this testing program, the ability of the crushed-salt model to capture the deformation processes at higher temperatures will be examined.

In this presentation, the crushed-salt model is examined through a variety of simulations of a shaft with emplaced crushed salt. This simple, axially symmetric representation is a good demonstration problem for examining the impact and influence of the components included in the crushed-salt constitutive model. Three different depths are assumed: 430 m, 515 m, and 600 m. Emplacement of the crushed salt (fractional density = 0.75) is assumed to occur at time zero. Comparative analyses include representation of the crushed salt with the full crushed salt constitutive model and the nonlinear elastic component only, which are compared against an empty shaft. Results for the problems are obtained through 1,000 years. The results indicate that the granular salt reconsolidation model does not have to be very robust from a mechanical standpoint in the high porosity region of deformation as long as the representation is not overly stiff. However, this conclusion probably does not hold true for fluid flow and thermal analyses.

Perspectives on Granular Salt Reconsolidation

SAND 2012-8039A
Frank Hansen
Sandia National Laboratories, Albuquerque New Mexico USA

Abstract

Design, analysis and performance assessment of potential salt repositories for heat-generating nuclear waste require knowledge of thermal, mechanical, and fluid transport properties of reconsolidating granular salt. Ambient reconsolidation of granular salt with a small amount of moisture is well understood mechanistically as underpinned by large-scale tests, laboratory consolidation measurements, and microscopic documentation of deformational processes. Permeability/density functions developed from the shaft seal experience provide a starting point for drift sealing design, analysis or experimentation. However, large-scale reconsolidation under hot or potentially dry conditions has been less well described. Perspectives on these elements of salt reconsolidation are provided in this presentation.

The salt repository community benefits from large amounts of pertinent information on granular salt consolidation ranging over a length scale from angstroms to hundreds of meters. Understanding granular salt reconsolidation under a wide range of conditions is essential to establish certain performance bases for salt repositories for heat-generating nuclear waste. Historical information and experience are provided to set the stage for current research efforts.

Mechanical properties are functions of porosity which decreases as the surrounding salt creeps inward and compresses granular salt within the rooms, drifts or shafts. We have undertaken an experimental program to determine properties of reconsolidated granular salt as a function of porosity and temperature and to establish the deformational processes by which the salt reconsolidates. Extensive deformation is exhibited in the final state; widespread crystal plasticity is manifested in elongate and sinuous grain fabric. Etching techniques highlight heavily deformed grains that exhibit climb recovery processes with an associated minute subgrain size. Free dislocation density is sparse in the highly deformed grains. Despite massive tangles of substructure and hence potentially high internal strain energy, only minor dynamic recrystallization is observed. Despite drying the granular salt to attain an acceptable moisture free condition, apparently sufficient brine remains within the crystal lattice as fluid inclusions to facilitate fluid assisted diffusional transfer.

APPENDIX C: DAY THREE: ABSTRACTS

Department of Energy Waste Isolation Pilot Plant

Thomas Klein
URS-RES

Abstract

There are two primary regulatory requirements for Panel Closures at the Waste Isolation Pilot Plant (WIPP), the nation's only deep geologic repository for defense related Transuranic (TRU) and Mixed TRU waste. The Federal requirement is through 40 CFR 191 and 194, promulgated by the US Environmental Protection Agency (EPA). The state requirement is regulated through the authority of the Secretary of the New Mexico Environment Department (NMED) under the New Mexico Hazardous Waste Act (HWA), NMSA 1978, §§ 74-4-1 through 74-4-14, in accordance with the New Mexico Hazardous Waste Management Regulations (HWMR), 20.4.1 NMAC. The state regulations are implemented for the operational period of waste emplacement plus 30 years whereas the federal requirements are implemented from post closure through 10,000 years. The 10,000 year federal requirement is related to the adequate representation of the panel closures in determining long-term performance of the repository. In Condition 1 of the Final Certification Rulemaking for 40 CFR Part 194, the EPA required a specific design for the panel closure system. The US Department of Energy (DOE) Carlsbad Field Office (CBFO) has requested, through the Planned Change Request (PCR) process, that the EPA modify Condition 1 via its rulemaking process. The DOE has also requested, through the Permit Modification Request (PMR) process, that the NMED modify the approved panel closure system specified in Permit Attachment G1.

The WIPP facility is carved out of a bedded salt formation 2,150 feet below the surface of southeast New Mexico. Condition 1 of the Final Certification Rulemaking specifies that the waste panels be closed using Option D which is a combination of a Salado mass concrete (SMC) monolith and an isolation/explosion block wall. The Option D design was also accepted as the panel closure of choice by the NMED. After twelve years of waste handling operations and a greater understanding of the waste and the behavior of the underground salt formation, the DOE has established a revised panel closure design. This revised design meets both the short-term NMED Permit requirements for the operational period, and also the Federal requirements for long-term repository performance. This new design is simpler, easier to construct and has less of an adverse impact on waste disposal operations than the originally approved Option D design.

The Panel Closure Redesign is based on: (1) the results of in-situ constructability testing performed to determine run-of-mine salt reconsolidation parameters and how the characteristics of the bedded salt formation affect these parameters and, (2) the results of air flow analysis of the new design to determine that the limit for the migration of Volatile Organic Compounds (VOCs) will be met at the compliance point.

Analysis of the new design demonstrates that there is: (1) no impact of changing from Option D to the new design on the long-term performance of the repository, since the reconsolidation of the run-of- mine salt will meet the same low permeability as seen with intact salt and Option D, and (2) there is no impact on the short-term effectiveness of the panel closure to limit the concentration of VOCs at the WIPP site boundary to a fraction of the health-based exposure limits during the operational period.

Mechanical-Hydraulic Conditions for an Integrity Loss of Salinar Barriers

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Abstract

Long-term storage of high-level radioactive waste in deep geologic formations is worldwide the only accepted solution for entire inclusion. The main objective is to keep the waste materials freely of aftercare and permanently away from the biosphere, a security claim which can reliably guaranteed only by a geologic system. The geologic barriers are the main feature of the safety concept. The geomechanics has to prove that the mechanical and hydraulic integrity of the geologic barriers are preserved under all given geogen and anthropogen conditions in the long term scale permanently.

With respect to a newly driven underground repository in a salt formation with steep inclined or flat bedding the dimensioning of sufficient salt barriers is the main task for warranty of dry inclusion of the waste. As important for a potential loss of salt barrier integrity three main processes exist:

- mechanical damage due to transgression of the dilatancy boundary. This process acts mainly in the EDZ and its extension is limited (dm up to several metres)
- convergence and thermo-mechanical induced stress re-distribution. Depending on the size of the underground excavations and due to the temperature accelerated creep this process reaches to considerable extend (decametre up to several hundred meters)
- fluid pressure driven creation of hydraulical pathways along discontinuities in the micro- and macro-scale in the rock salt (grain boundaries, bedding planes) at fluid pressures > minimum stress, i.e. σ_{min}.

The analysis of integrity for a radioactive waste repository is based on the comprehension of geomechanical processes - gained during the recent decades from lab and field investigations and supplemented by numerical modelling studies. However, despite all advantages the employability of the salt concept for storage of radioactive waste in Germany suffers from the fact that in the past the way of the proof of a lasting inclusion was not pursued in the salt strictly enough and, instead of that, due to the recent choice of little suitable old salt mines for research and final disposal site purposes special emphasis was placed in consideration of worst case scenarios.

To illustrate how the analysis can be performed the example Gorleben is presented. Actually, in the framework of the preliminary safety analysis (Vorläufige Sicherheitsanalyse Gorleben, VSG) a comprehensive assessment is being performed (until end of 2012) with focus on long-term safety. Following the German safety requirements, released in 2010 by the Federal Ministry of the Environment (BMU), the long-term integrity of the geological barrier salt is crucial for protection from damage caused by ionising radiation during the post-operational phase. The purpose of thermo-mechanical analysis is to demonstrate that the mechanical integrity of the salt barrier is preserved permanently under all given geogen and anthropogen conditions in the long term scale.

Thermomechanical/Hydrology Modeling for HLW Disposal

SAND 2012-8038A

James Bean, Sandia Staffing Alliance
Mario Martinez and Teklu Hadgu, Sandia National Laboratories

Abstract

The impact of different physical processes (e.g., Thermal (T), Hydrologic (H), Mechanical (M), Chemical (C) and the coupled interactions between them must be evaluated to assess the performance of a nuclear waste storage facility situated in geologic media. A thorough examination of repository performance, typically in a performance assessment evaluation, requires the use of process models that accurately capture key phenomena relevant to a nuclear waste repository design concept. Different repository settings (e.g. host rock media) will experience a combination of these processes in a unique fashion. For example, the Waste Isolation Pilot Plant facility in southeastern New Mexico is used to store transuranic waste that does not produce significant heat; therefore, the influence of transient thermal effects has been considered less important than other processes. The thermal environment resulting from the storage of high level nuclear waste (HLW) is important because it can significantly impact the rate at which the host rock creeps inward. Repository design concepts that are currently under investigation consider nuclear waste packages with high heat loads; therefore, it is important to accurately describe thermally-driven processes making THM coupled phenomena a research priority in current and future model representations.

Three-dimensional analyses were performed using the SIERRA family of finite element codes developed at Sandia National Laboratories. SIERRA/Arpeggio, an interface controller, effectively couples the code SIERRA/Aria (used for thermal (T), single or multiphase porous flow hydraulic (H) or coupled TH modeling) and the quasi-static mechanics (M) code SIERRA/Adagio by controlling the transfer of data between the codes and the solution time stepping in the TM simulations. The TH simulations are performed using SIERRA/Aria exclusively. The SIERRA codes can be used on single processor workstations or massively parallel computer systems.

The modeling described in this presentation examines coupled TM processes and separate treatment of TH processes. It includes the influence of heat generated by a single waste package and the transfer of heat to the crushed salt backfilling within the excavated region and the host salt. The TM simulations examine the influence of moisture in the crushed salt backfill on the closure rate of mined regions. The TH model examines moisture transport due to heat from the waste package. The numerical models used in these simulations could be easily modified to study waste forms with different heat characteristics as well as additional numbers of waste containers making this approach amenable to the study of generic nuclear waste repository design concepts in salt. Other geologic features such as clay seams and anhydrite layers could also be included in future analyses.

In closing we will discuss additional work needed to complete the coupling of thermal-hydraulic and mechanical process modeling for the study of HLW disposal.

Microstructure Simulation Based on Discrete Element Models

Christian Müller
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Abstract

The objective of the investigation is the development of a numerical model at grain-scale that can be utilized to study both the damage behaviour and the percolative behaviour of the hydraulic conductivity of the EDZ in rock salt. In order to simulate the shape and arrangement of crystal grains in rock salt the distinct element code 3DEC is applied consisting of polyhedral-shaped elements. Considering that inter-crystalline pathways are predominant for the hydraulic behaviour of rock salt, the fracture distribution may be a direct function of grain or rather polyeder size. Inter-crystalline flow calculations are based on the cubic law, using the fracture hydraulic aperture as the relevant hydraulic parameter. The mechanical behaviour of rock salt is generally controlled by both inter- and intra-crystalline deformation. Inter-crystalline mechanical calculations are based on a Mohr Coulomb elasto-plastic criterion (shear yield function) including a tension cut-off condition (tension yield function). In order to simulate intra-crystalline processes with an associated mechanism of hardening, a continuum-based Mohr Coulomb criterion with an additional strain-hardening approach is applied. Since there is no implementation of a viscous model to simulate creep so far, only fracture processes during the short-time compression can be simulated.

The model was calibrated and validated using the results of available laboratory test observations. Splitting tensile tests reveal that the crack-damage corresponds well with laboratory observations, showing a splitting of the cylindrical sample due to the generation of tensile cracks. Uniaxial compression simulations also show a failure mode mainly through tensile cracks, which can be substituted by the low tensile strength of rock salt. At the beginning of loading, tensile cracks are uniformly distributed, but forming a continuous network during the end of the loading. There is no evidence of conjugate shear band development which is in agreement with published test results in literature. To estimate the hydraulic properties of the observed fracture network, hydraulic simulations were performed. Hydraulic results exhibit a permeability increase above a certain fracture density, verifying the percolation concept which is commonly proposed to explain the hydraulic behaviour of the EDZ.

The conducted simulations show that the discrete element code 3DEC in combination with polyhedral-shaped elements provides a computational basis to enhance the understanding of fracture processes occurring in the EDZ. The objective of further research should focus on the implementation of a viscous model, to study the long-term visco-elasto-plastic behaviour of rock salt at grain-scale.

Benchmark Modeling Status Report of the Current Joint Project III

Andreas Hampel, Scientific Consultant, Mainz, Germany

Abstract

Since 2004, three Joint Projects on the Comparison of Constitutive Models for the Thermo-Mechanical Behavior of Rock Salt have been funded by two German Federal Ministries: the Ministry of Education and Research (BMBF) and the Ministry of Economics and Technology (BMWI). The general objectives have been to document, check, and compare with benchmark calculations current constitutive models and modeling procedures, to validate their suitability and reliability, to increase confidence in the results of numerical simulations performed with the models, and to enhance the acceptance of the results and conclusions. The projects have also been indicating possibilities for the further development and improvement of the models.

The first project phase (2004-2006) aimed at the demonstration, check and comparison of the capabilities of the considered models to describe reliably the basic relevant deformation phenomena in rock salt: transient and steady-state creep, evolution of damage and dilatancy, failure, post-failure behavior and residual strength. In the second phase (2007-2010), the suitability of the models to perform 3-D simulations, predictions of the future behavior, and calculations of the permeability in damaged salt was investigated.

The third project phase started in October 2010. Here, the focus is on the modeling of the temperature influence on deformation and the modeling of sealing and healing of damaged rock salt. This third study is carried out by the following project partners:

- Dr. Andreas Hampel, Scientific Consultant, Mainz, Germany
- Institut für Gebirgsmechanik GmbH (IfG), Leipzig, Germany
- Technische Universität Clausthal (TUC), Clausthal-Zellerfeld, Germany
- Karlsruhe Institute of Technology (KIT), Germany
- Leibniz Universität Hannover (LUB-IUB), Germany
- Technische Universität Braunschweig (TUBS), Germany
- Sandia National Laboratories (SNL), Albuquerque, New Mexico, USA.

This project phase comprises the performance and back-calculations of specific laboratory tests as well as simulations of the following in-situ structures: The modeling of temperature influence is investigated by means of benchmark calculations of a heated borehole in the Asse II salt mine in Germany; the results are being compared with each other and with in-situ measurements of the Netherlands Energy Research Foundation ECN. The modeling of healing of pre-damaged rock salt is studied with simulations of a drift in the Asse II salt mine that was excavated in 1911, and of which a 25 m long section was lined after 3 years with a cast-steel tube and concrete. The simulation results will be compared with each other and with data from in-situ permeability measurements of the GRS within the ALOHA2 project, that were performed 85 years after the installation of the liner in the rock salt behind the bulkhead.

The partners intend to extent the project by 2 ½ more years (until 2016) in order to perform benchmark simulations with the considered models of a heated drift at the Waste Isolation Pilot Plant (WIPP) in New Mexico. The study is planned to be accompanied by an extensive laboratory test program with WIPP salt to generate data for the parameter determination for this salt type. The extension will provide a great opportunity to intensify and deepen the collaboration of the German project partners with Sandia National Laboratories.

Comparison of Constitutive Models

by Ralf-Michael Günther, Institut für Gebirgsmechanik Leipzig GmbH

Abstract

Rock salt formations are most suitable as possible host rock for a safe long term deposit of nuclear waste, because of their unique rock mechanical and hydraulically properties.

The preservation of the natural tightness of the geologic barriers is an important feature of the safety concept. The geomechanics has to prove the preservation of the mechanical and hydraulical integrity of the geologic barriers and the reestablishment of the tightness in the area of geotechnical sealing systems in the frame of the long term safety case.

For this purpose, numerical long term calculations are necessary which are based on a high comprehension of the geomechanical processes, which have been gained in lab and field investigations in the last recent decades.

However the reliability of the numerical calculation results highly depends on the quality of the used material model. Due to further developed laboratory test methods and improved in situ measurements the knowledge in the field of salt-mechanics has significant increased in recent years.

This better understanding has led to the fact, that today the formulation of constitutive models is much more sophisticated and more complex than earlier.

Several model developer have found partially very different ways to modeling creep, damage, dilatancy, peak and residual strength. The following presentation gives an overview about the similarities and differences of the latest advanced constitutive models, which participate in the current joint project phase III.

Participants of the joint project III are

Dr. Andres Hampel	CDM-Model
IUB Hannover	Lubby-MDCF Model
Institut für Gebirgsmechanik Leipzig	Visco-Elasto-Plastic Model (Minkley)
Institut für Gebirgsmechanik Leipzig	Advanced Strain Hardening Model (Günther/ Salzer)
Karlsruhe Institute of Technology	KIT-Model
Sandia National Laboratories	MD Model
TU Braunschweig	Modified Döring Model
TU Clausthal	Lux/ Wolters Model

Approved Methods for Determination of Salt Specific Parameters and Laboratory Test Program Matrix for WIPP Salt

Uwe Düsterloh

Abstract

The task of lab testing is given by the demand to guarantee in each case the ability to determine the specific model parameters. Therefore the aim of the presentation is characterized by the appointment of similarities between different constitutive models.

By using a phenomenological consideration it could be asserted that albeit the differences between the constitutive models in each case damage strength is used to decide weather damage free, damage induced or healing respectively damage recovery deformation processes will occur. Additionally it is obvious, that regarding to the intensity of exceeding or undercutting damage strength the damage respectively healing rate is determined. Therefore additionally to the damage strength the failure strength is needed in each case to quantify respectively to normalize the degree of exceeding or undercutting the damage strength. As a consequence a first main task of the lab program is given by triaxial short term tests to determine failure strength and damage strength. The lab procedure and methods demanded to determine failure strength and damage strength depending on minimum principal stress, temperature, stress respectively deformation rate and stress geometry will be characterized and commented considering the proposed test program.

Albeit the various formulations of creep behaviour by different constitutive models used within the joint project the creep rate of rock salt in general is characterized by superposition of an elastic deformation rate, a damage free transient and stationary deformation rate, a damage induced deformation rate and a healing deformation rate in each case ($\rightarrow \dot{\varepsilon}_v = \dot{\varepsilon}_e + \dot{\varepsilon}_{tr} + \dot{\varepsilon}_s + \dot{\varepsilon}_d + \dot{\varepsilon}_h$). That is to say, beside the short term tests to determine the failure strength and damage strength creep tests are needed in each case to determine the creep parameters used in the different constitutive models to quantify the creep behaviour. As a consequence a second main task of the lab program is given by triaxial long term tests to determine various parts of the total creep rate.

From a phenomenological point of view the damage free transient and stationary creep behavior of rock salt can be taken from classical creep tests if the stress level is below damage stress. A stress level above damage strength in general leads to an increasing creep rate and depending on the intensity of exceeding the damage strength on the one hand and the duration of exceeding the damage strength on the other hand at least to a creep rupture. Finally a healing creep rate could be observed, if a previous damaged sample will be loaded by a stress level below damage strength. To consider the effects of equivalent stress level, temperature and time to the creep behaviour of WIPP salt a lab program was evaluated and proposed. The lab procedure and methods demanded to determine damage free creep behaviour, damage induced creep behaviour and healing creep behaviour depending on equivalent stress level, temperature, damage strength and damage will be characterized and commented considering the proposed test program.

Conceptual Aspects of HLW/SNF-Repositories

Wilhelm Bollingerfehr
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Abstract

All countries in the world operating nuclear power stations for energy production did develop repository concepts for Spent Nuclear Fuel and/or High Level Waste from the very beginning. All these concepts were designed with the common objective to permanent isolate the SNF/HLW from human beings and the biosphere. Thus, the disposal in deep geological formations is considered as a suitable approach for repository development. According to the geological situation available in the specific country different host rocks were and still will be investigated on its suitability to host the SNF/HLW.

As the approaches how to achieve the permanent isolating of the waste are different the main parameters determining the design of a repository are more or less of the same origin:

- The type and amount of SNF/HLW (waste packages)
- The type of host rock
- The selected safety concept
- National laws/regulations/set of requirements

The type and amount of SNF and HLW is directly dependent on the national energy policy (portion of nuclear in energy production, reprocessing or direct disposal of SNF); whereas the selection of the host rock mainly is defined by the geologic situation on the national territory. The selection of an adequate safety concept is strongly related to the selected host rock; either the safety will be provided mainly by technical barriers (e.g. waste package) and/or geotechnical barriers or the safety mainly relies on the host rock features (geological barrier) itself.

Other aspects with strong impact on the repository design are requirements according to national or international laws and regulations. This might include requirements towards reversibility/retrievability or to construct a common repository for HLW and LILW. The process from concept development to Implementation includes the following design steps: conceptual design, technical design, as-built design, demonstration of constructability and reliability and eventually the construction. As repositories are unique installations the demonstration phase is of uppermost importance and has to be planned and performed in due time with adequate measures; preferably with 1:1 industrial demonstrators.

According to the EU-Directive (2011) member states in the European Union have to provide to the EC a national program and implementation plan for repositories. Long-term-storage and PuT are not accepted as long-term solution

Hoisting and Disposal of Dual-Purpose Storage Containers

Enrique Biurrun

Abstract

In Germany, a large number of dual-purpose CASTOR casks are used as standard cask for transportation and interim storage of vitrified HLW and spent nuclear fuel. Currently there are two centralized interim storage facilities (at Gorleben and Ahaus) and 12 further on site storage facilities in operation. As at the end of nuclear power use in the country no further use for such casks is anticipated, a study of the feasibility of disposing of the HLW and spent nuclear fuel in the CASTOR casks without transfer into a special-purpose disposal cask or container was carried out. The work included the development of adequate repository layouts for disposal in underground galleries excavated in a salt dome at a depth of about 860m below surface. Furthermore, the waste aging time needed to deal with the significant decay heat load of the waste without infringement of the temperature design limit of 200 °C was determined. Since disposal of such casks appeared feasible without inducing either undue temperatures or excessive stresses in the salt host formation, further studies focused on the technological aspects.

A crucial issue is the transport of the heavy waste packages from the surface to the disposal level underground. Based on handling safety and long-term safety considerations the use of an access ramp is deemed in principle inadequate in Germany. On the other hand, shaft hoisting of such heavy payloads is quite a technological challenge and worldwide not state-of-the-art. Therefore, a shaft hoist design was elaborated as a further development of the existing German design for 85 tons payload, for which the feasibility and safety has been demonstrated in a 1:1 scale dedicated test facility. The combined results of the thermo-mechanical repository design work and the hoist and handling equipment design show the feasibility of disposal of CASTOR casks in a repository built in a Northern-German salt formation.

Disposal Concepts for Large Spent Fuel Waste Packages in Salt

Ernest Hardin and Dan Clayton
Sandia National Laboratories

Abstract

Large waste packages for spent nuclear fuel (SNF) can be emplaced in salt, from thermal considerations, including the dual-purpose canisters (DPCs) that currently store approximately 35% of SNF in the US. The current inventory of SNF considering all sources has relatively low average burnup and is decades old. Finite element calculations using temperature-dependent thermal conductivity show that the existing SNF inventory could be disposed starting immediately, in waste packages containing at least 21 PWR elements (or BWR equivalent). The generic salt repository concept allows economical disposal compared to several other reference concepts evaluated. For DPCs containing 32 or more PWR assemblies, aging of at least 50 yr would be needed before emplacement, or slightly longer for current fuel discharges with higher burnup. The effect on predicted peak salt temperatures, from coupled thermal conductivity increase associated with thermally activated creep-consolidation of crushed salt backfill, was evaluated using the Sierra simulation tools and found to be secondary to the effect of temperature if the initial backfill porosity is limited. These results offer a technical solution to thermal management for SNF disposal without long-term underground ventilation, while using large packages and thereby limiting re-packaging.

APPENDIX D: DAY FOUR: ABSTRACTS

Underground Salt Research Laboratory at WIPP

SAND 2012-8028A
Frank Hansen
Sandia National Laboratories, Albuquerque New Mexico USA

Abstract

Creation of new underground space at the Waste Isolation Pilot Plant (WIPP) provides a unique opportunity to advance the bases for heat-generating, high-level waste (HLW) disposal in salt. With this opportunity comes a significant obligation to use this space as intelligently and cost-effectively as possible. Use of the underground will be highly visible, with a responsibility to serve the needs of various clients. A technical Sandia report is being drafted on this topic and the current US/German Workshop provides an opportunity to review potential testing prospects and objectives for the purpose of creating recommendations for utilization of the new underground research lab (URL) at WIPP.

State-of-the-art laboratory thermomechanical testing and computational joint projects are forming a firm technical basis to support potential activities in the URL. Laboratory results and benchmark simulations will help assess credibility of proposed testing or demonstration efforts. International research programs are using currently available information to establish a safety case for salt disposal of HLW. The Germans recently issued their preliminary safety analysis for Gorleben (Vorläufige Sicherheitsanalyse Gorleben or VSG). Therefore, enduring science and engineering demonstrations in salt should be balanced against the recognition that a strong scientific basis for a salt repository safety case already exists. Performance confirmation demonstrations and salt research activities in a new URL could further bolster the safety case as well as further advance the knowledge base for repository design and analyses. In performing activities described here, salt repository scientists could demonstrate good faith and due diligence in advancing future salt repository designs and disposal options.

Potential activities immediately address findings of the Blue Ribbon Commission to undertake prompt efforts to develop one or more geologic disposal facilities. In addition, these efforts include possible field demonstrations of interest to the Department of Energy Office of Environmental Management (DOE-EM), longer-term considerations at higher thermal loading that may be of interest to DOE-Nuclear Energy and several investigations that demonstrate capabilities lending themselves to future repository design strategies. The 3rd US/German Workshop provides a unique gathering of salt repository scientists to discuss the merits of possible uses of the URL. These discussions will serve to strengthen the basis for possible investigations undertaken in a salt URL.

APPENDIX E: LIST OF PARTICIPANTS AND OBSERVERS

7th Project meeting of the Joint Project "Comparison of current constitutive models and simulation procedures on the basis of model calculations of the thermo-mechanical behavior and healing of rock salt"

and

3rd US/German Workshop on Salt Repository Research, Design and Operation
October 8 -10, 2012

Current List of Participants

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APPENDIX F: BIOS

J. Guadalupe Argüello

Dr. Argüello is a Principal Member of the Technical Staff at Sandia National Laboratories. He holds a Bachelor of Science, a Master of Engineering, and a PhD from Texas A&M University. Lupe has over 27 years of experience in performing numerical modeling of rock and salt mechanics-related problems. He has supported various civilian, as well as defense-related, underground-design efforts and provided technical expertise to the underground mining and storage industries. His rock mechanics experience includes interpretation of laboratory and in situ testing, constitutive model development and implementation, and numerical modeling of the underground. He also has broad expertise in coupled Geomechanical/porous-flow/thermal processes and in numerical modeling of reservoir and basin-scale problems using large-scale massively-parallel, three-dimensional, large-deformation finite element codes. Lupe has been a member of the American Ceramic Society, the Society of Petroleum Engineers, and the American Rock Mechanics Association.

Dirk-Alexander Becker

Mr. Becker is a physicist with 19 years of experience in long-term safety assessment for radwaste repositories. He has been working with GRS since 1995 and has been involved in various national and international projects. He has specific experience in contaminant transport modeling, assessment of model output, and probabilistic uncertainty and sensitivity analysis. Since 2004 he has been in charge of the numerical performance assessments for the German LLW/ILW repository Morsleben. Currently, he is managing a project on sensitivity analysis methods for repository models.

Enrique Biurrun

I was born and grew up in the vast plains of western Argentina. There, I used to look every day through the cleanest air I ever saw to the 120 km distant Nevado, a 4000m high volcano, to guess how weather would develop. In this impressing landscape I could well have become a volcanologist, but Nevado is silent for now, and I am not patient enough to wait. Obtaining a MS in Mechanical Engineering in 1975, with the Jesuits at Catholic University of Córdoba was hard, but an excellent training for a second MS degree I got in Nuclear Engineering at RWTH Aachen University in Germany in 1980. And once there I stayed to get a PhD in Radioactive Waste Disposal. After 8 years working on final repositories R&D I joined DBE in 1988 and was involved first in R&D and later on repository design projects for foreign customers. In 2002 followed an appointment as Head of the International Cooperation Department in DBE TECHNOLOGY GmbH, DBE’s engineering subsidiary. Currently I represent both companies in international forums and events and participate and lead engineering repository related work, at present for customers in Ukraine Bulgaria, Belgium and Japan.

Wilhelm Bollingerfehr

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

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 head of the Research and Development 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. His recent work is focussing on the development of a repository design and closure measures for a HLW repository in salt formations in the context of a preliminary safety case.

Scott Broome

Mr. Broome received his MS in Mechanical Engineering in 2007 from Northern Arizona University. He has over 14 years of experience in various Geomechanics laboratories. He has been at Sandia National Laboratories for 5 years in the Geomechanics laboratory performing unique and complicated pressure sensitive experiments. Many of these experiments have been on salt, both intact and crushed for a wide array of industry (energy storage) and government applications (waste repository). He is currently a senior member of the technical staff.

Michael Bühler

Mr. Bühler is a civil engineer (geotechnical engineering) and worked at the Karlsruhe University on projects in the fields of rock and salt mechanics, numerical modeling with finite elements, mining and radioactive waste disposal for more than fifteen years. Between 2001 and 2005 he was member of a project group on the official approval of plans for the closing of the LLW and ILW repository Morsleben (ERAM) at the state agency for geology and mining in Saxony-Anhalt. Since 2005 he is Program Manager in the Project Management Agency Karlsruhe, Water Technology and Waste Management (PTKA-WTE) in the Karlsruhe Institute of Technology. PTKA is an organization unit acting on behalf of Federal Ministries (Ministry of Economics and Technology, Ministry of Education and Research) and is managing R&D programs and funding projects. He supervises R&D projects on HLW disposal (plugging and sealing, modeling, benchmarks). He is also member of the task force AGO on the evaluation of options for the closing of the Asse Mine, a LLW and ILW repository in Lower Saxony.

Nancy Buschman

Nancy Buschman began her career in chemical manufacturing, where she gained hands-on experience in operations, process design and facility construction and developed a passion for managing projects. Since joining the Department of Energy in 1991, she has overseen programs within the NNSA, Office of Nuclear Energy, and Office of Environmental Management (EM). At EM, her program management responsibilities include technology development and spent nuclear fuel management. Nancy is a registered professional engineer, certified project management professional and federal project director.

Gary Callahan

Gary Callahan has been with RE/SPEC Inc. for over 40 years and has held a variety of positions during his employment. He is currently a Vice President and Principal Consultant. His first work efforts were associated with Project Salt Vault in Lyon’s, Kansas, and he has worked on many national and international repository programs since that time. His research interests have been in areas associated with material properties testing and numerical analyses. He has worked on many enjoyable projects investigating rock properties including transport properties (heat and fluid), strength and deformational behavior, and evaluation of constitutive relationships for multiaxial salt creep, salt dilation, granular salt consolidation, and jointed rock behavior.

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

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, thermomechanical numerical analysis of underground structures, radioactive waste disposal, field measurements.

Geoff Freeze

Geoff Freeze is a Principal Member of the Technical Staff at Sandia National Laboratories in Albuquerque, New Mexico. Mr. Freeze has over 25 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 for the national governments of the US (Yucca Mountain Project (YMP) and WIPP), Japan, Germany, and Switzerland, including 4 years as the YMP Lead for Features, Events, and Processes (FEPs).

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.

Andreas Gährken

Andreas Gährken has been working as scientific staff at the Institute for Soil Mechanics and Foundation Engineering at the Technische Universität Braunschweig since September 2011. He studied civil engineering and has worked on salt mechanics and the development of a constitutive model for rock salt.

Timothy Gunter

Tim Gunter is a nuclear engineer (B.NE 1979, Georgia Institute of Technology) with over 30 years of professional experience in nuclear related fields. He is currently a Federal Program Manager for Used Nuclear Fuel Disposition Research and Development in the DOE Office of Nuclear Energy. His previous experience includes naval nuclear reactor plant systems testing and nuclear performance assessment at Charleston Naval Shipyard; startup and facility engineering for the DOE Savannah River Site Defense Waste Processing Facility, the first high-level waste vitrification facility in the US; and the DOE lead for the pre-closure safety assessment and also interim project manager for license application completion for the High-Level Waste Repository at Yucca Mountain, Nevada. Member of the American Nuclear Society.

Ralf-Michael Günther

Dr. Günther is an engineer for geotechnics. Since 1995 he is project engineer at the IfG Institute for Rock Mechanics GmbH in Leipzig. The focus of his work is on numerical calculations and on the geomechanical assessment of different mining problems. He developed also a constitutive model for rock salt. For this work he got a Doctor of Engineering from the Technical University of Freiberg in 2009.

Andreas Hampel

Dr. Andreas Hampel is a physicist who earned his PhD with a thesis on the investigation and modeling of deformation processes in metals and alloys. In 1993, he started at the BGR Hannover with laboratory and in-situ investigations and constitutive modeling of the thermo-mechanical behavior of rock salt. On this basis, he has developed the Composite Dilatancy Model (CDM). Since 1998, he is working as an independent scientific consultant. Since 2004, he has been taking part and coordinating three Joint Projects on the Comparison of Constitutive Models for the Thermo-mechanical Behavior of Rock Salt. In the third project phase he is also coordinating the collaboration of the German project partners with Sandia National Laboratories.

Frank Hansen

Almost all of Frank Hansen‘s entire career has been dedicated to repository science and engineering, especially salt RD&D. Frank has enjoyed rare opportunities, nationally and internationally, which include research in rock mechanics, seal systems, materials, design, and analysis. He has had the good fortune to work alongside and publish frequently with gifted scientists and engineers. Frank has been a registered professional engineer since 1978, elected ASCE Fellow in 2006, and promoted to Senior Scientist at Sandia National Laboratories in 2012.

Ernest L. Hardin

Since 2006, Ernest Hardin has been a technical lead for repository and nuclear fuel-cycle system studies at Sandia National Laboratories in Albuquerque, New Mexico, USA. Before that he served as a managing scientist for Bechtel-SAIC on the Yucca Mountain Project in Las Vegas, Nevada, starting in 2001. Previous to that he was an environmental scientist for Lawrence Livermore National Laboratory, starting in 1997. He has more than 25 years experience as a geoscientist and engineer for several private companies and two US national labs. This includes contributions to engineering of oil-and-gas, hydropower, mining, environmental remediation, and nuclear waste projects in Europe and the US. His interests include system analysis, coupled-process testing and modeling, groundwater chemistry and contaminant transport, and geophysical methods. He has two degrees in geophysics, and a PhD in Hydrology from the University of Arizona in Tucson.

Sebastian Kuhlman

Mr. Kuhlmann is a Ph.D.-Student at Clausthal University of Technology. He is a graduate engineer (Dipl.-Ing. (FH)) for environmental engineering / environmental measurement engineering and holds a M.Sc. in Radioactive and Hazardous Waste Management.

Ralf Mauke

- Born in Meißen, Germany at 3 March 1969
- 1986 – 1988 diploma from German secondary school qualifying for university admission and professional training (toolmaker)
- 1990 – 1995 civil engineering studies at faculty of Geosciences, Geotechnique and Mining at Technical University "Bergakademie Freiberg" and degree as geotechnical engineer
- 1995 – 1999 technical employee at WBI GmbH in Aachen, Germany (Prof. W. Wittke) – rock mechanic related repository and tunnelling projects: Schacht Konrad, Stuttgart 21, Morsleben: i. g. Permeability measurements together with SANDIA Lab
- 1999 – today scientific employee at Federal Office for Radiation Protection (BfS) in Salzgitter, Germany - Department "Safety of Nuclear Waste Management" - over 10 years: Section "Post-Closure Safety" (now: after reorganisation: Section "Morsleben Subject-Specific Questions")

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 (like "Konrad" and "Stuttgart 21").

For the BfS he led the design and analysis work for the Morsleben drift seal systems over 10 years, oversee backfilling measures, and is responsible for different research items related to the closure concept of the Morsleben repository including the ongoing large scale testings of the sealing measures.

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.

Christian Müller

After finishing his studies at the University (of Goettingen) in Germany in geosciences in 2004, he started to work on his PhD geology. The work was sponsored by a Scholarship Programme of the German Federal Environmental Foundation (DBU). His PhD research dealt with the hydromechanical characterisation of rocks with regard to the utilisation of geothermal energy. This included field studies, geomechanical measurements, and numerical modelling. At DBE TECHNOLOGY GmbH, he currently works on the development of a modelling strategy that can be applied to describe the hydromechanical processes inside the excavation damaged zone of rock salt at grain scale.

Prasad K. Nair

Dr. Nair has a strong technical background in engineering and natural material performance as applied to engineered systems and nuclear high level waste disposal programs. With over 25 years of experience in the nuclear high-level waste (HLW) management program in the US, Dr. Nair has lead the engineered barrier system program at the Center for Nuclear Waste Regulatory Analyses (CNWRA) and provided technical licensing support for the Department of Energy (DOE) license application for a deep mined nuclear HLW repository development. Currently, he is DOE's technical lead for the Natural System Evaluation and Salt R&D work activities under the DOE Office of Nuclear Energy's Used Fuel Disposition Campaign.

Andrew Orrell

Mr. Andrew Orrell is the Director of Nuclear Energy & Fuel Cycle Programs for Sandia National Laboratories, responsible for research and development initiatives involving all facets of the nuclear fuel cycle. His professional experience spans technical and managerial efforts at the Waste Isolation Pilot Plant and the Yucca Mountain Programs in the US, as well as technical support for several international programs involving geologic repository development. Mr. Orrell is versed in the complex issues regarding the transportation, storage and disposal of radioactive waste and the interdependencies between the technical, program and policy elements of nuclear waste management and nuclear energy.

Elmar Plischke

Mr. Plischke is a mathematician who received his Ph.D. from the Institute for Dynamical Systems, University of Bremen. Since 2008, he is working at the Institute of Disposal Research in Clausthal specialising in safety assessment and sensitivity analysis methods.

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 Institute for Geomechanics GmbH, Leipzig as project manager, mostly responsible for research projects aiming on disposal of radioactive and toxic waste in salt and argillaceous clay formations.

Alexandra Pudewills

Alexandra Pudewills is a research scientist at the Institute of Nuclear Waste Disposal in Karlsruhe. She is responsible for the geomechanics research programs related to performance assessments for geological radioactive waste repositories. The work involves the development and application of numerical models to describe the long-term behaviour of rocks with main focus on the rock salt and backfill. She participated in several European projects on numerical simulation of large-scale in situ experiments regarding the heat generating waste disposal. Her present research activities include the numerical analysis of the THM processes in salt and clay formations.

Cédric J Sallaberry

Dr. Sallaberry has been working in the field of uncertainty characterization, as well as uncertainty and sensitivity analysis for +10 years. He has been working on that field for the Yucca Mountain Project up to 2009 and has been since involved in the same area for various projects in collaboration with US-NRC.

Dr. S. David Sevougian

Dr. S. David Sevougian is a principal member of the technical staff at Sandia National Laboratories with over 30 years of experience in earth sciences, including repository sciences, hydrogeology, geophysics, and petroleum engineering. He received PhD and MS degrees in petroleum engineering from the University of Texas at Austin and an AB degree in physics from Cornell University. Dr. Sevougian was the lead author of Section 2.4, "Demonstration of Compliance with the Postclosure Public Health and Environmental Standards," of the Safety Analysis Report for the proposed Yucca Mountain geologic repository. Prior to that, he managed the technical development and design of the total system performance assessment (TSPA) models for the Yucca Mountain Final Environmental Impact Assessment, Site Recommendation, and Viability Assessment. Recently he has been leading an effort to develop requirements and architecture for a TSPA model for a generic bedded salt repository for HLW and SNF, and has been working on a safety case for such a repository. Previous work has included systems engineering and decision analysis models for optimizing the nuclear fuel cycle, modeling of aquifer remediation following in-situ uranium leaching, modeling of acid stimulation of oil and gas wells, and borehole geophysical logging.

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.

Leo Van Sambeek

While working at RESPEC, Dr. Leo L. Van Sambeek has made 40-years' continuous technical contributions in nuclear-waste disposal in salt, use of salt generally as a storage medium, salt mining, and high-level salt-mechanics research. He has personally been involved in developing RESPEC's innovative laboratory testing of salt and design and fielding of in situ tests at Avery Island, WIPP, and commercial salt facilities. His work in nuclear waste began in 1972 doing testing and modelling of the Project Salt Vault (Kansas) experiments. This was followed by the Avery Island (Louisiana) heater tests and its companion laboratory testing, which resulted in perhaps the greatest number of tests on one salt in the world. Since the early 1980s, he has been a rock mechanics and mining engineering consultant for the WIPP (New Mexico). He is widely recognized in the salt-cavern storage and salt- and potash-mining industry, including serving a term as President of the Solution Mining Research Institute (SMRI).

Klaus Wieczorek

Klaus Wieczorek is a geophycist and has been working in the field of repository safety research for 27 years, first at the GSF Institut für Tieflagerung and since 1995 with GRS. He has been project manager of various R&D projects. His main expertise is in field testing in underground laboratories in different types of rock, especially salt and argillaceous formations.

Jens Wolf

Mr. Wolf is a Scientist at Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH. He holds a Diploma in Geology/Hydrogeology and a Ph.D. in Civil Engineering (Hydraulic and Environmental Systems). For six years he has been engaged in the department of long-term safety analyses for repository systems. Since 2010 the point of main effort has been the preliminary safety analysis for the salt dome Gorleben.

APPENDIX G: PRESENTATIONS

U.S. DEPARTMENT OF ENERGY

Office of Environmental Management (EM) Perspectives

Nancy Buschman

3rd U.S./German Workshop on Salt Repository Research, Design and Operations
Albuquerque, New Mexico
October 9, 2012

EM Environmental Management
safety ❖ performance ❖ cleanup ❖ closure
www.em.doe.gov 1

Presentation Outline

- Environmental Management (EM) Overview:
  Mission, Budget, Priorities
- Recommendations from the Blue Ribbon Commission on America's Nuclear Future (BRC) Report
- DOE's Response to BRC
- Implications and Possible Next Steps

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EM Mission

"Complete the safe cleanup of the environmental legacy brought about from five decades of nuclear weapons development, production, and Government-sponsored nuclear energy research"

- …From a legacy of weapons production to the world's largest environmental cleanup program
- …Operating in the world's most complex regulatory environment
- EM cleanup enables DOE to maintain ongoing operations and other critical missions while achieving compliance with governing environmental laws.

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The Inherently High-Risk Work of Nuclear Cleanup

Workers using glovebox to handle plutonium

Stabilizing spent (used) nuclear fuel

Performing first-of-a-kind tasks in highly hazardous work environments

High level waste canisters

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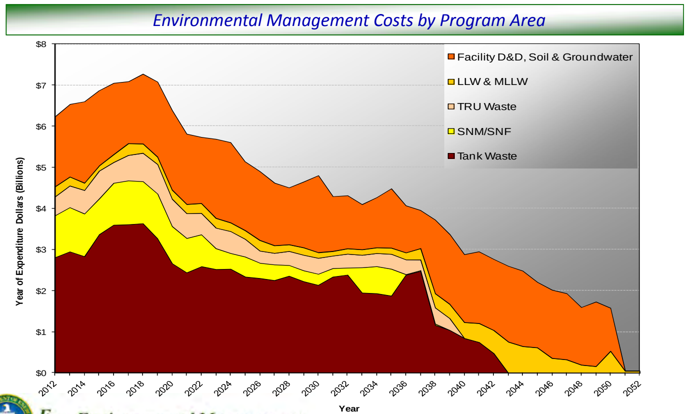
Life-Cycle Cost Profile Over Time



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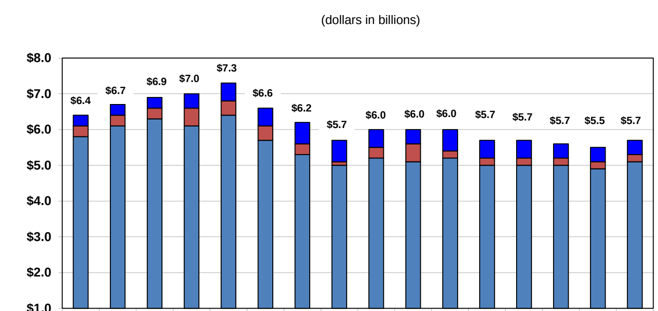
EM Funding History



	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY09 ARRA	FY10 Approp	FY 2011 Oper Plan	FY 12 Approp	FY 2013 Req.	FY 2013 HEWD	FY 2013 SEWD
UE D&D	0.3	0.3	0.3	0.4	0.5	0.5	0.6	0.6	0.5	0.4	0.6	0.5	0.5	0.4	0.4	0.4
Non-Def	0.3	0.3	0.3	0.5	0.4	0.4	0.3	0.1	0.3	0.5	0.2	0.2	0.2	0.2	0.2	0.2
Defense	$5.8	$6.1	$6.3	$6.1	$6.4	$5.7	$5.3	$5.0	$5.2	$5.1	$5.2	$5.0	$5.0	$5.0	$4.9	$5.1

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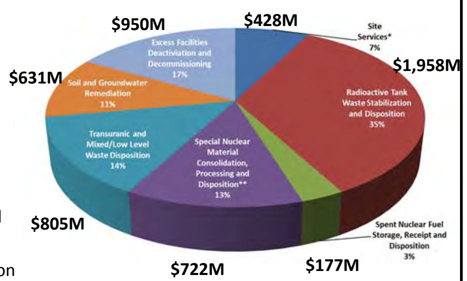
EM Program Priorities

- Maintain a safe, secure, and compliant posture in the EM complex
- Radioactive tank waste stabilization, treatment, and disposal
- Spent (used) nuclear fuel storage, receipt, and disposition
- Special nuclear material consolidation, processing, and disposition
- Transuranic and mixed/low-level waste disposition
- Soil and groundwater remediation
- Excess facilities deactivation and decommissioning (D&D)

FY 2013 Budget Request - $5.65B



* Includes Program Direction, Program Support, TDD, Post Closure Administration and Community and Regulatory Support

** Includes Safeguards and Security

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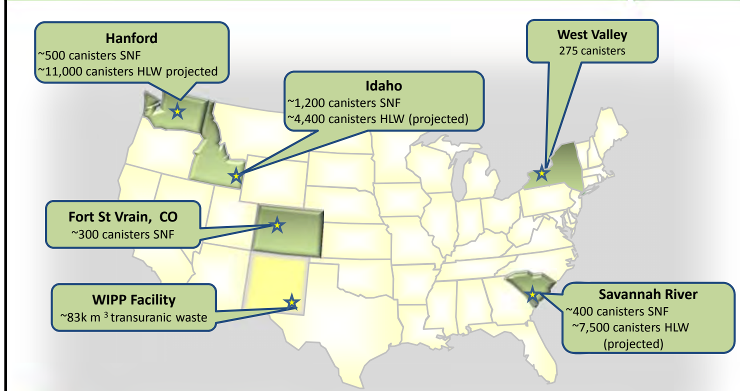
EM Manages Nuclear Materials and Waste at Numerous Locations



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BRC Delivered Recommendations in January 2012

- A new, consent-based approach to siting and development
- A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed
- Access to the funds that nuclear utility ratepayers are providing for the purpose of nuclear waste management
- Prompt efforts to develop one or more geologic disposal facilities
- Prompt efforts to develop one or more consolidated storage facilities
- Prompt efforts to prepare for the eventual large scale transport of spent nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available
- Support for continued U.S. innovation in nuclear energy technology and for workforce development
- Active U.S. leadership in international efforts to address safety, waste management, nonproliferation, and security concerns

DOE Response to BRC

- In response to the BRC Report issued in January 2012, the Secretary of Energy established a multi-tier DOE task force, the Management and Disposition Working Group (MDWG), to evaluate the BRC recommendation and develop a strategy.
- The MDWG was supported and accomplished through four integrated task teams:
  - Governance Framework and Funding
  - Consent-based Siting
  - System Design & Architecture (EM-led)
  - Transportation Routing, Safety, and Security
- DOE has been evaluating the recommendations of the BRC regarding long-term waste storage and disposal. DOE has been developing a potential strategy and action plan.
  - Repository and interim storage sites will be considered in accordance with a consent-based process as outlined by the BRC.
- Once the strategy is submitted to Congress, additional details regarding next steps will likely be available.

Implications for EM Program

- Pending more information on Congressional and stakeholder reaction to the BRC and Administration's response, EM's near-term efforts will be largely unchanged.
  - Continued focus on safe, effective management, retrieval, and treatment of our tank waste/high-level waste inventories
  - Continued R&D on alternatives to improve techniques, advance waste forms, and optimize disposition paths
  - Continued collaboration with Nuclear Energy on their ongoing generic repository evaluations
- There is no disposal path for much of EM's waste inventory - much effort is spent to safely store wastes.
- Responsibility to develop a geologic repository belongs to NE

WIPP: A Good Model

- EM has established strong relationships with New Mexico government and oversight agencies and Carlsbad elected officials.
- State and local support exists for a science-based expansion of WIPP.
  - September 2011 letter from New Mexico Governor Martinez to the Secretary of Energy
  - Consistent with several of the BRC recommendations (i.e., consent-based siting)
- Past studies at WIPP provide sound foundation for continuing research.
- Initial information indicates disposal at WIPP is a viable option for many DOE-owned wastes.
- Carlsbad, LANL, and SNL have developed detailed proposals for studying and demonstrating disposal of DOE waste forms in salt.
- Building on these elements, DOE could develop a strategy that positions WIPP for future missions.

Status of DOE's Collaborative Studies

- NE currently funding laboratory and modeling work
- DOE March 2012 workshop achieved consensus on technical objectives for R&D work
  - Participants from EM, NE, and SC
  - Agreement on laboratory and modeling efforts funded by NE
- New Mexico supports confirmatory field heater tests
  - Mining intiated to develop Underground Research Laboratory (URL) to conduct low thermal output heater test of in-drift emplacement concept for disposal of HLW
  - Additional funding for FY13 not yet identified

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Next Steps

- Path forward **will** be developed in concert with the State and local communities
- EM will continue to support NE in their efforts to site a repository
- Sources of funding are being sought for further R&D and field heater tests—success to be determined

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U.S. DEPARTMENT OF ENERGY | Nuclear Energy

The DOE-NE Used Fuel Disposition (R&D) Program

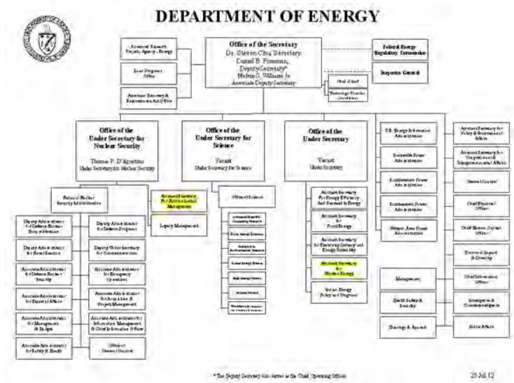
Timothy C. Gunter

Federal Program Manager, Disposal R&D
Office of Used Nuclear Fuel Disposition R&D
Fuel Cycle Technologies

3rd US/German Workshop on Salt Repository Research, Design and Operations
Albuquerque, NM
October 9, 2012

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

DOE Organization



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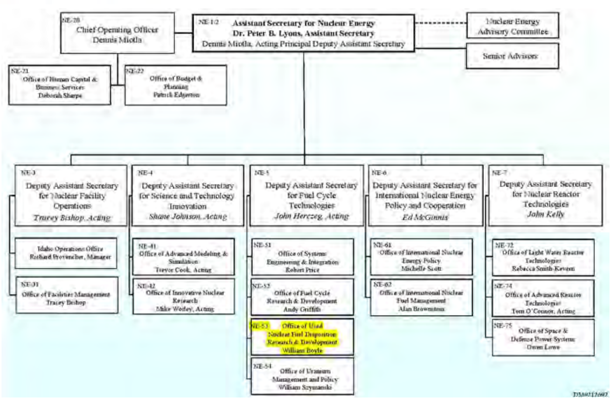
U.S. DEPARTMENT OF ENERGY | Nuclear Energy

DOE-NE Organization



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U.S. DEPARTMENT OF ENERGY | Nuclear Energy

DOE-NE Mission

- **The primary mission of the Office of Nuclear Energy, is to advance nuclear power as a resource capable of meeting the Nation's energy, environmental, and national security needs by resolving technical, cost, safety, proliferation resistance, and security barriers through research, development, and demonstration as appropriate.**
- **The mission of the Used Fuel Disposition Campaign is to identify alternatives and conduct scientific research and technology development to enable storage, transportation, and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles.**
- **Used Fuel Disposition R&D is focused in three areas**
  - Storage
  - Transportation
  - Disposal

4

U.S. DEPARTMENT OF ENERGY Nuclear Energy

Blue Ribbon Commission on America's Nuclear Future

- **Secretary of Energy established the Blue Ribbon Commission on America's Nuclear Future (BRC) in January 2010 to evaluate alternative approaches for managing spent nuclear fuel (SNF) and high-level radioactive waste (HLW) from commercial and defense activities**
- **BRC conducted a comprehensive review of policies for managing the back end of the nuclear fuel cycle**
- **BRC provided eight major recommendations (January 2012) for developing a safe long-term solution to managing the Nation's used nuclear fuel and nuclear waste**

5

U.S. DEPARTMENT OF ENERGY Nuclear Energy

Blue Ribbon Commission Recommendations

1. A new, consent-based approach to siting future nuclear waste management facilities.
2. A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed.
3. Access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management.
4. Prompt efforts to develop one or more geologic disposal facilities.
5. Prompt efforts to develop one or more consolidated storage facilities.
6. Prompt efforts to prepare for the eventual large-scale transport of spent nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available.
7. Support for continued U.S. innovation in nuclear energy technology and for workforce development.
8. Active U.S. leadership in international efforts to address safety, waste management, non-proliferation, and security concerns.

6

U.S. DEPARTMENT OF ENERGY Nuclear Energy

BRC Assessment of Current DOE-NE UFD Program

(Section 7.8 Near-Term Steps)

Confirms the importance for *"DOE to keep the program moving forward through non-site specific activities, including R&D on geological media and work to design improved engineered barriers"*

Recommends the continuation of activities currently conducted under the DOE-NE Used Nuclear Fuel Disposition Campaign

"Identify alternatives"

"R&D on transportation, storage, and disposal options for SNF from existing and future fuel cycles"

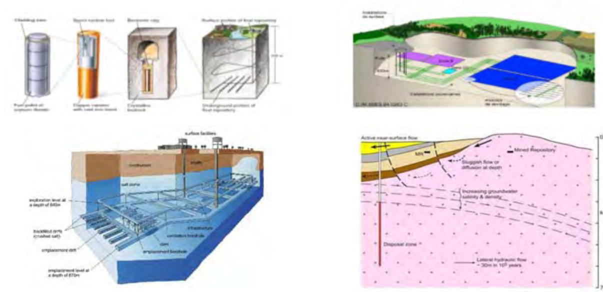
"Other non-site specific generic activities, such as support for and coordination with states and regional state government groups on transportation planning"

7

U.S. DEPARTMENT OF ENERGY Nuclear Energy

Disposal Options

- **Disposal R&D is focusing on four basic disposal options**
  - Three mined repository options (granitic rocks, clay/shale, and salt)
  - One geologic disposal alternative: deep boreholes in crystalline rocks



8

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

R&D Activities in Disposal

- **R&D on generic geological media**
  - Evaluating the performance of repositories in various geologic environments
  - Advanced understanding of various disposal concepts in geologic media
- **Work on geologic disposal will include:**
  - Initiating work to determine the best approaches for understanding the behavior of salt in response to heat producing radioactive waste
  - Working with industry to initiate the development of an RD&D plan and roadmap for the borehole disposal concept
  - Expanding work with our international partners for disposal in granite and clay rocks

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U.S. DEPARTMENT OF ENERGY
Nuclear Energy

R&D Activities in Salt

- **Salt R&D Workshop conducted in March, 2012, led by DOE Office of Nuclear Energy and Office of Environmental Management**
- **Result was the Salt R&D Study Plan which was a jointly agreed upon science-based scope of work**
- **Eighteen-month generic salt R&D program initiated in the summer of 2012**

10

Preliminary Safety Assessment for a Repository at the Gorleben Site

Wilhelm Bollingerfehr
DBE TECHNOLOGY GmbH, Peine, Germany

3rd US/German Workshop on Salt Repository Research, Design and Operation

Albuquerque/Carlsbad
October 8-10, 2012

Outline of Presentation

- Introductory Remarks
- Project VSG ("Vorläufige Sicherheitsanalyse Gorleben")
- Safety Concept
- Repository Design
- Demonstration of Repository Safety
- Conclusions and Summary

Introductory Remarks

- Reference disposal concept for SNF/HLW in a salt dome
- Exploration work at the Gorleben site was interrupted for 10 years, restarted in 2010, and will probably be interrupted again in 2013
- Safety requirements for HLW repository released in September 2010 (BMU)
- Political debate on new site selection process for HLW waste repository ongoing

Preliminary Safety Assessment Gorleben (VSG)

"Vorläufige Sicherheitsanalyse für den Standort Gorleben (VSG)"

Objectives
- Transparent evaluation of the suitability of the Gorleben site as a HLW repository
- Development of an optimized repository concept
- Derivation of further investigatory and exploratory needs

Project duration
- 33 months (July 2010 to March 2013)

Project leader
- GRS – Gesellschaft für Anlagen und Reaktorsicherheit, Cologne

Partners
- BGR, DBE TECHNOLOGY GmbH, IfG, ISTec, KIT-INE, nse, University Frankfurt, Aachen University, TU Clausthal (internal review)

VSG - Simplified Project Plan

Basics
- site characterisation and long-term prediction
- waste characterisation and waste quantities
- safety concept and demonstration concept

Repository design
- repository concept ⟷ repository design and optimisation

System analyses
- FEP catalogue, scenario development, process analyses (analyses of consequences)

Synthesis
- assessment of results ⟷ recommendations

source: GRS

Objectives of Safety Concept

- Rapid enclosure of waste containers by the rock salt
- Isolation rock zone – IRZ – remains preserved during demonstration period
- Inflow of only small quantities of solutions
- Radionuclide transport and release from the IRZ (chem./phys. processes)
- No criticality at any time

Basics

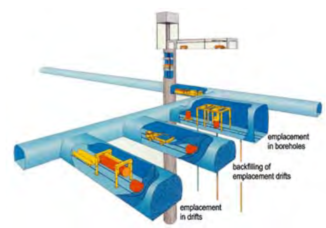
Data of the site:
- Site characterization of Gorleben; reports of BGR, Hannover (Gorleben Part I-III)
- Structure of geology of the entire salt dome according to a BGR working model (source: Bornemann 1989)
- Emplacement level: 870 m below surface

Waste data:
- Types and amounts of heat-generating radioactive waste and radioactive waste with negligible heat production

Regulatory requirements:
- Safety requirements governing the final disposal of heat generating radioactive waste (BMU, September 2010)
  - ✓ New: retrievability during operational phase
- Mining Act, Nuclear Energy Act, Radiation Protection Ordinance, etc.

Thermal boundary condition:
- max 200 ° C (interface: container/rock salt)

Disposal Concept and Site Characterization



German Reference Concept: Direct Disposal of Spent Fuel and HLW in Rock Salt Formations

- Deep geological disposal (depth: 870 m)
- Emplacement of HLW container in boreholes and spent fuel casks in drifts
- Backfill material: crushed salt

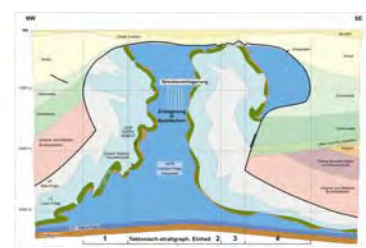
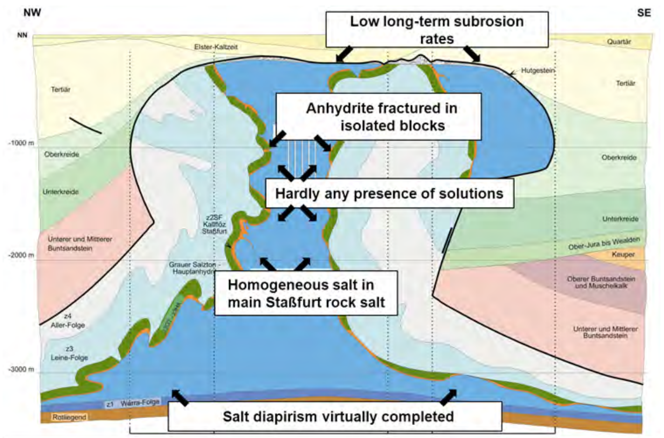


Illustration of the German repository reference concept. (Repository shown within a simplified geologic cross-section of the Gorleben salt dome)

Features of Gorleben Site



source: GRS

Prospective Waste Quantities

Source of Waste			Amounts of Waste			Waste Package	
				SF Elements	tHM	Type	Amount
Spent fuel		PWR	UO_2	12,450 FE	6,415	POLLUX-10	1,398
			MOX	1,530 FE	765		
		BWR	UO_2	14,350 FE	2,465		520
			MOX	1,250 FE	220		
		WWER-PWR	UO_2	5,050 FE	580		202
		Total	-	-	**10,445**		**2,120**
Waste from reprocessing	CSD-V	AREVA NC (F)	3,024 Canisters			POLLUX-9	336
	CSD-V	Sellafield Ltd. (UK)	565 Canister				63
	CSD-V	VEK (D)	140 Canisters				16
		Total	**3,729 Canisters**				**415**
	CSD-B	AREVA NC (F)	308 Canisters			POLLUX-9	**35**
	CSD-C	AREVA NC (F)	4,1404 Canisters			POLLUX-9	**456**
		Total	**8,141 Canisters**				**906**
Spent fuel of prototype and research reactors		AVR	250,000 Fuel Element (Pebbles)			CASTOR® THTR/AVR	152
		THTR	611,878 Fuel Element (Pebbles)				305
		KNK II	2,413 Fuel rods from 27 Fuel Elements			CASTOR® KNK	4
		Otto-Hahn	52 fuel rods				
		FRM II	approx. 120 - 150 MTR Fuel Elements			CASTOR® MTR 2	30
		BER II	approx. 120 MTR Fuel Elements				20
		Total	-			-	**511**
Structural components of SF		**Total**	-			MOSAIK	**2,620**

Repository Design

Objective: Development of a repository concept (surface and underground facilities) for heat-generating producing radioactive waste based on:

- Geologic conditions at the Gorleben site
- Expected types and amounts of radioactive waste

Repository design for two main emplacement variants:

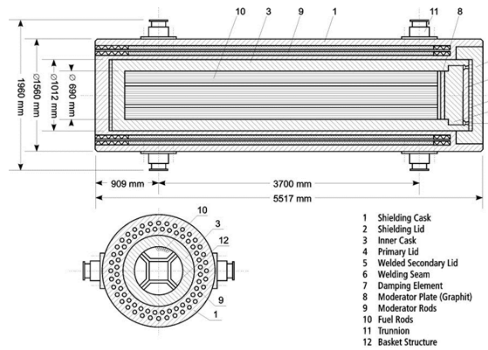
- Drift disposal: Emplacement of waste containers in horizontal drifts
- Borehole disposal: Emplacement of waste containers in vertical, up to 300 m deep boreholes

Implementation of Safety Concept

- **Containerization of radioactive waste**
  Disposal and/or transfer container
  (safe enclosure during operational phase and afterwards)
- **Excavation of mine openings in the centre of the salt dome at a depth > 800 m**
- **Backfilling of voids with compacted crushed salt**
- **Performance of high-quality drift and shaft seals**
- **Avoidance of unnecessary mining/drilling work in the IRZ**
- **Minimal moisture in the vicinity of waste container**
- **Restricted temperature increase**

Container for Drift Disposal Concept

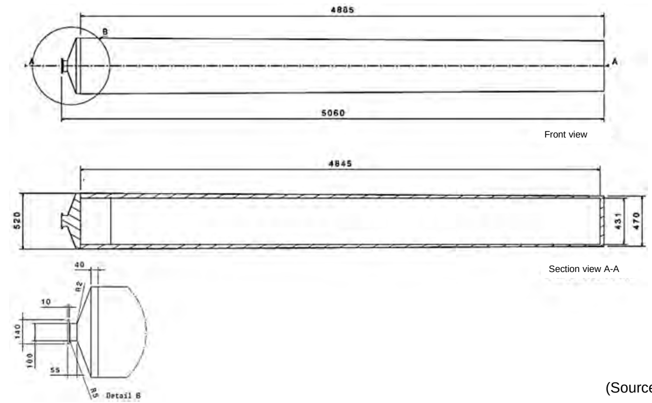
65 t POLLUX cask for max. 10 PWR spent fuel elements



(Source: GNS)

Container Type for Borehole Disposal Concept

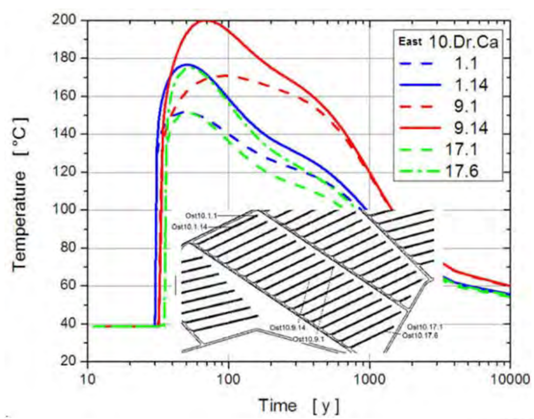
New design of a single container for HLW and SF



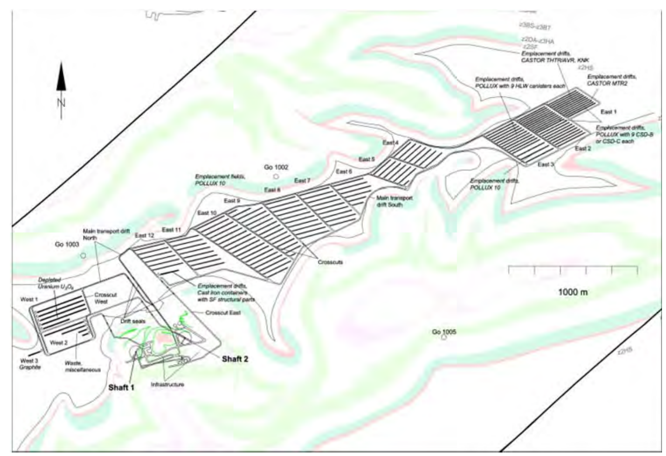
(Source: nse)

Main Design Parameter: Temperature

Temperature profile at specific points in an emplacement field for spent fuel



Design of the Entire Repository – Drift Disposal Concept



Backfilling and Sealing Concept

Backfilling of mine openings in the repository

- Dry crushed salt in emplacement drifts
- Wetted crushed salt (0.6 % Mas) in main drifts
- Backfill technique (blower, slinger, or dumping technique)

Backfilling of infrastructure openings

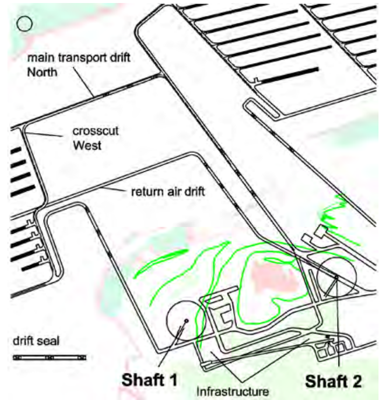
- gravel (providing buffer space)

Sealing measures

- Plugs (sorel concrete) to separate dry and wetted crushed salt
- Drift seals: sorel concrete
- Shaft seals (shaft 1 and 2)

Sealing of main drifts

Position of drift seals (870 m level = emplacement level)



Drift sealing concept and selection of suitable material according to experience gained from the Asse and Morsleben repository closure projects

System Analysis, Synthesis

- Based on repository design (type and amount of waste, layout of mine, geological environment, and backfilling and sealing concept):
- Development of an extended **FEP catalogue** and scenarios
  - (see presentation J. Wolf/GRS)
- **Process analysis** (consequences analysis) by GRS
  - in progress
- **Final step:** Assessment/results and recommendations
  - draft report end of the year 2012
  - final synthesis report March 2013

Conclusions and Summary

- A new concept to demonstrate safety is applied for the disposal of HLW in a repository in rock salt (example Gorleben)
- Primary focus is to demonstrate that releases of radionuclides from the IRZ into the surrounding rock are insignificant
- Repository design was adjusted to new safety requirements (including retrievability)
- Integrity of geologic and geotechnical barriers were investigated for likely evolutions of the repository system
  - Results are promising

DBE TECHNOLOGY GmbH

Thank you
for your attention.

Wilhelm Bollingerfehr /2012
3rd US/German Workshop
Albuquerque/Carlsbad; October 8-10, 2012

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GRS

FEP Catalogue and Scenario Development for a Repository in Salt

Jens Wolf
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH

GRS

ISIBEL → VSG: Status of Safety Assessment of Repositories for HLW in Salt

ISIBEL-I (2006-2010):

- safety concept and assessment strategy for HLW/SF repository
- in compliance with the German Safety Requirements
- financed by Federal Ministry of Economics and Technology (BMWi)
- BGR, DBE Technology, GRS
- FEP catalogue → scenario development

Preliminary Safety Analysis Gorleben (VSG) (2010 – 2012)

- application and advancement of the ISIBEL approach
- site: salt dome Gorleben
- BGR, DBETEC, GRS, IfG, INE (19 scientists)

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GRS

Objectives of the FEP-Catalogue and the Scenario Development

FEP-Catalogue

- identification of relevant features, events and processes (FEP)
- status of knowledge on the investigated site → basis of system analysis
- transparency and comprehensiveness

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GRS

Objectives of the FEP-Catalogue and the Scenario Development

FEP-Catalogue

- identification of relevant features, events and processes (FEP)
- status of knowledge on the investigated site → basis of system analysis
- transparency and comprehensiveness

Scer… development

- exa… volution of repository system cannot be forecasted in every single aspects → i… ification and description of possible scenarios
- 'po…' of derived scenarios is supposed to cover uncertainties regarding the real futu… f the repository system
- transparency und traceability

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Approach Scenario Development

- specifications in German Safety Requirements:
  - the comprehensive identification and analysis of safety-relevant scenarios and their allocation to probability categories:
    - – probable
    - – less probable
    - – improbable
- division of scenarios in
  - reference scenario = comprehensive set of probable FEP
  - alternative scenarios = probable and less probable alternatives to the reference

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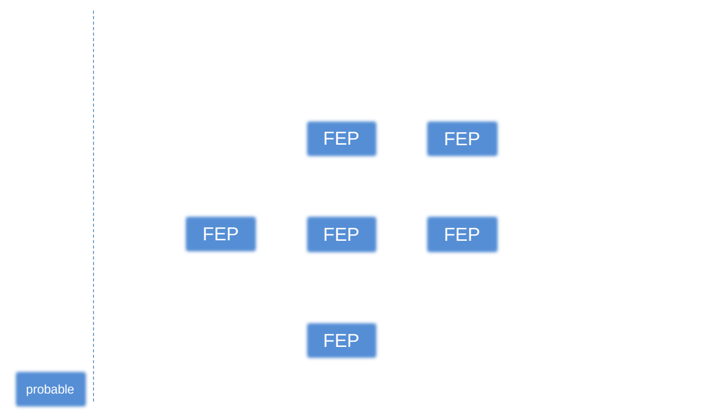
Specifications for FEP Descriptions (Reference Scenario)

- statement on probability



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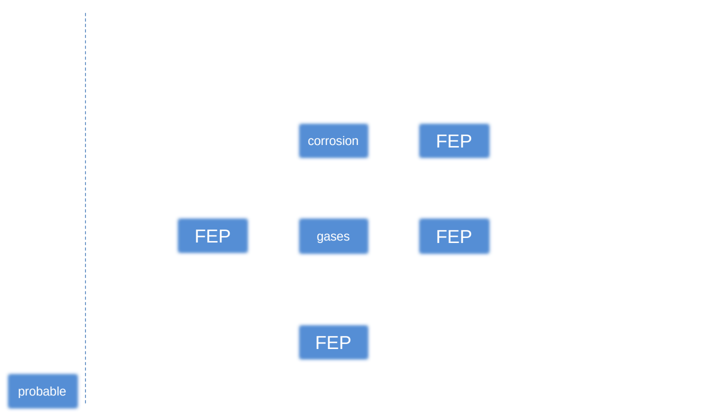

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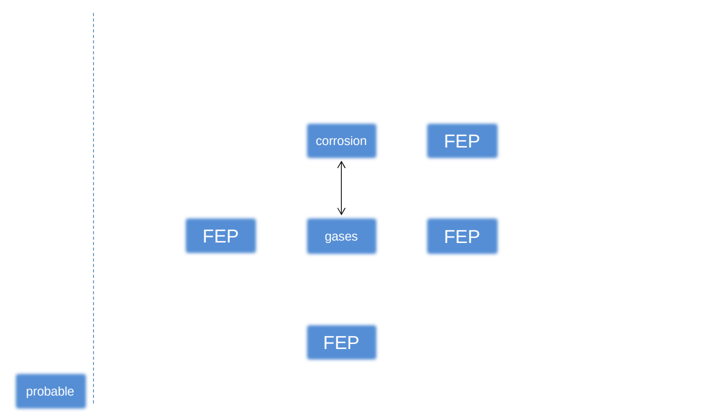

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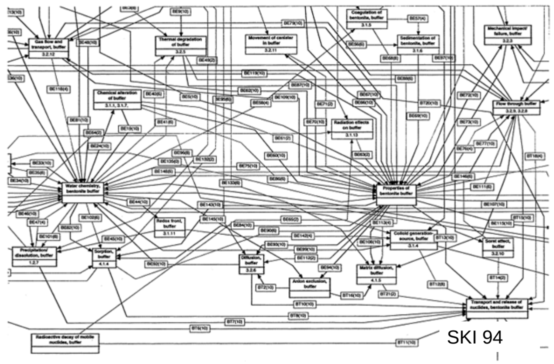
Specifications for FEP Descriptions (Reference Scenario)

- statement on probability
- interactions of FEP



probable

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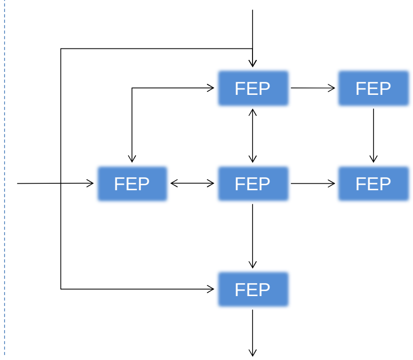

probable

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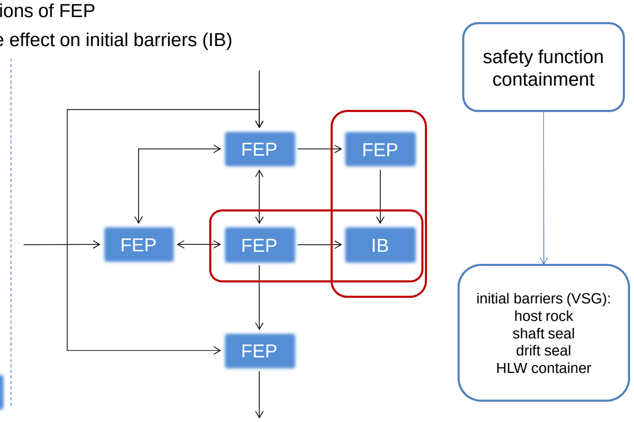
Specifications for FEP Descriptions (Reference Scenario)

- statement on probability
- interactions of FEP
- adverse effect on initial barriers (IB)



probable

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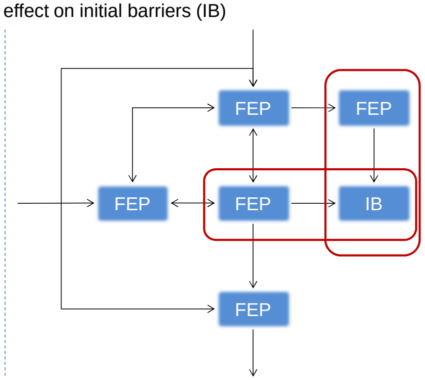

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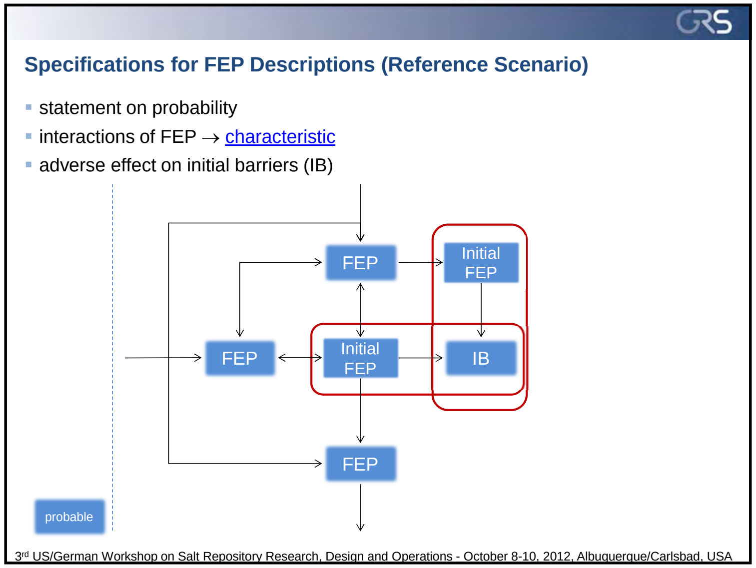
Specifications for FEP Descriptions (Reference Scenario)
statement on probability
interactions of FEP → characteristic
adverse effect on initial barriers (IB)
FEP
Initial FEP
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Initial FEP
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FEP
probable
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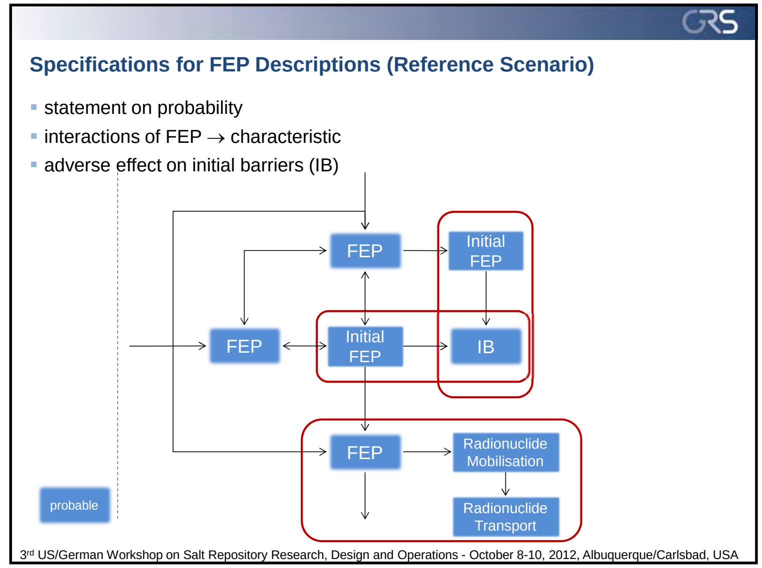
Specifications for FEP Descriptions (Reference Scenario)
statement on probability
interactions of FEP → characteristic
adverse effect on initial barriers (IB)
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Radionuclide Mobilisation
Radionuclide Transport
probable
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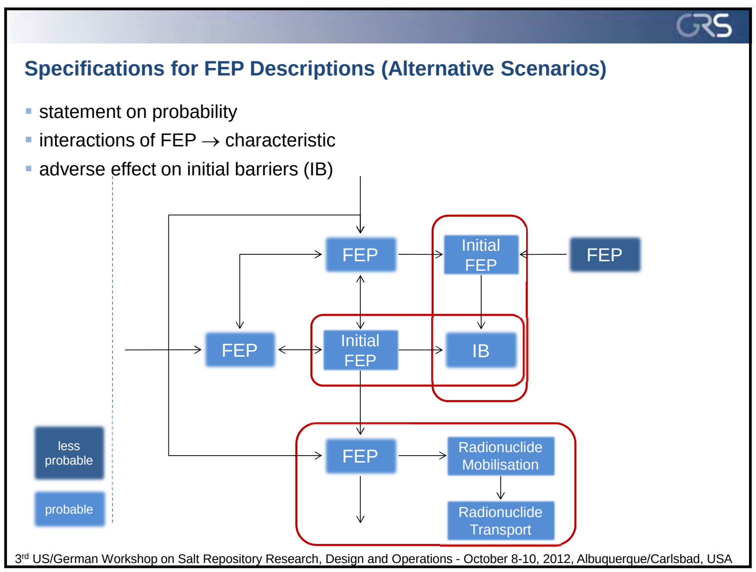
Specifications for FEP Descriptions (Alternative Scenarios)
statement on probability
interactions of FEP → characteristic
adverse effect on initial barriers (IB)
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FEP
FEP
Initial FEP
IB
FEP
Radionuclide Mobilisation
Radionuclide Transport
less probable
probable
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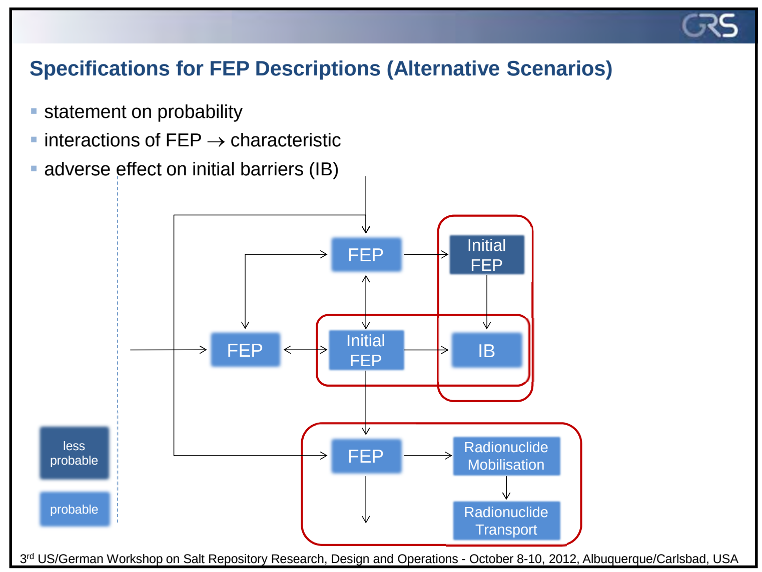
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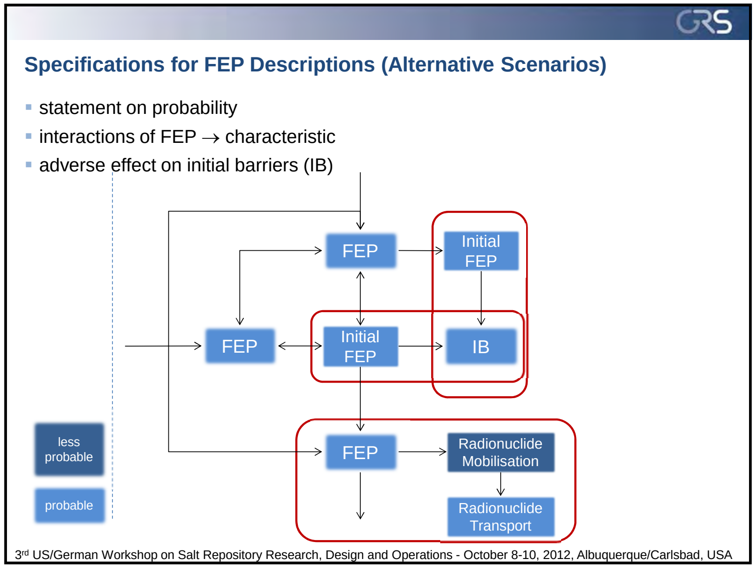
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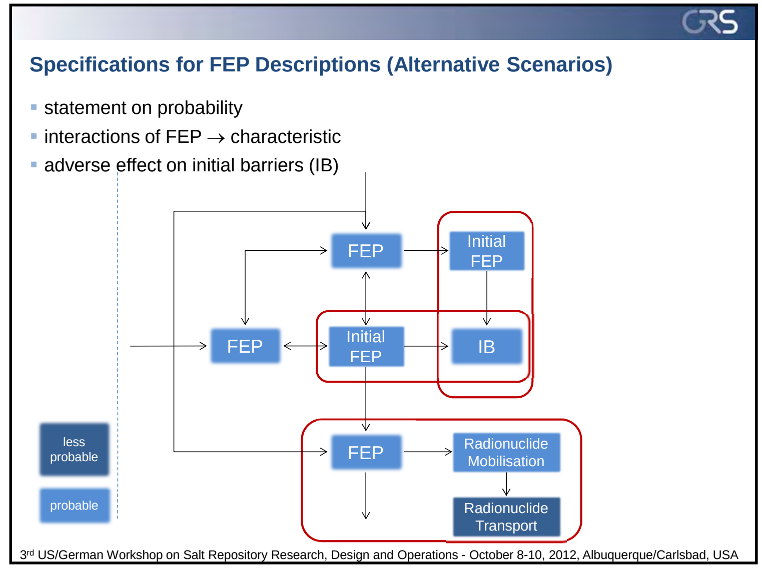
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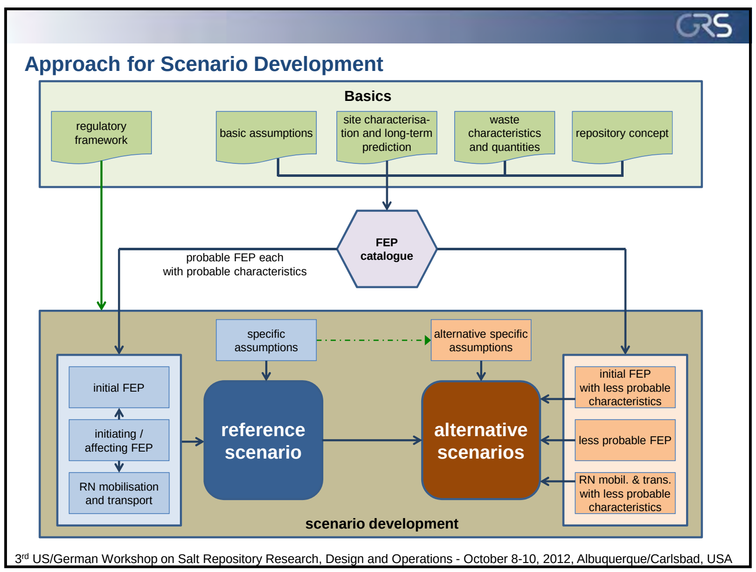
Approach for Scenario Development
Basics
regulatory framework
basic assumptions
site characterisa-tion and long-term prediction
waste characteristics and quantities
repository concept
FEP catalogue
probable FEP each with probable characteristics
specific assumptions
alternative specific assumptions
initial FEP
initiating / affecting FEP
RN mobilisation and transport
reference scenario
alternative scenarios
initial FEP with less probable characteristics
less probable FEP
RN mobil. & trans. with less probable characteristics
scenario development
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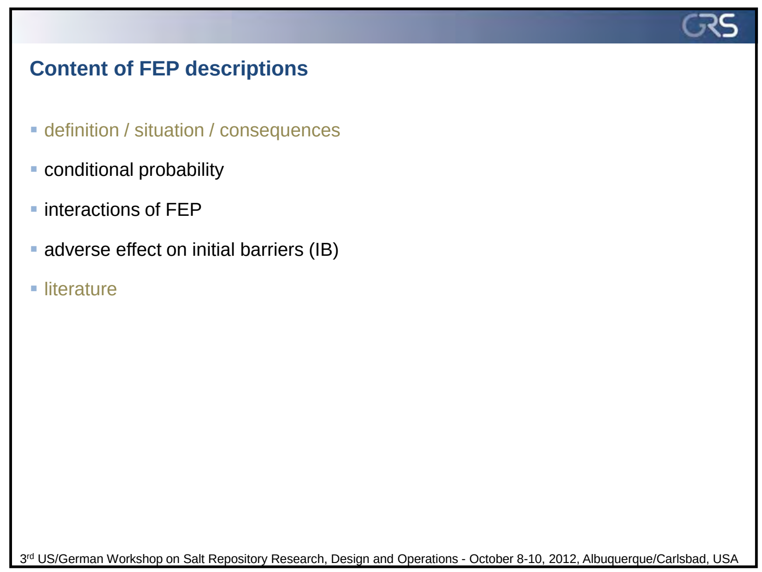
Content of FEP descriptions
definition / situation / consequences
conditional probability
interactions of FEP
adverse effect on initial barriers (IB)
literature
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Summary FEP Catalogue and Scenario Development VSG

- 115 FEPs, organised in a database
- statement on probability:
  probable: 98, less probable: 4, not to consider: 13
- FEP-Screening (II):
  6 probable FEP are classified as not relevant
- FEP list for scenario development:
  92 probable und 4 less probable FEP
- → 17 alternative szenarios (all less probable)

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Experiences

- tight linkage of FEP catalogue and scenario development is full of advantages:
  - transparency (subjective decisions are documented)
  - traceability (inside and outside)
  - consistency
  - redundancy
  - categorization of FEP to 'less probable' only possible technical components
- ISIBEL and VSG: all probable FEP in reference scenario
- there is no storyboard on FEP level
- not all information for the scenario development could be documented in FEP catalogue
- transfer scenarios → calculation?

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Outlook

- There is a great interest in the FEP Catalogue:
  - NEA IGSC → new NEA FEP database
  - Salt Club

→ translation of FEP catalogue and reports

→ international assessment

⇨ next iteration step

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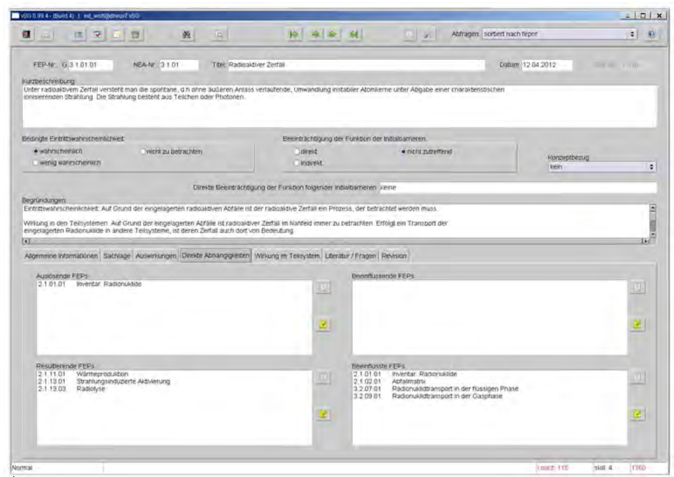
FEP Data Base



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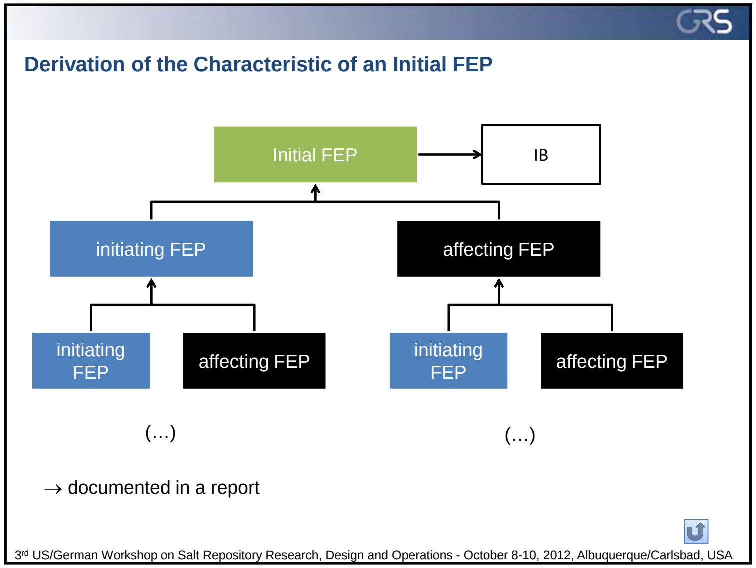
Derivation of the Characteristic of an Initial FEP
Initial FEP
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initiating FEP
affecting FEP
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(…)
(…)
→ documented in a report
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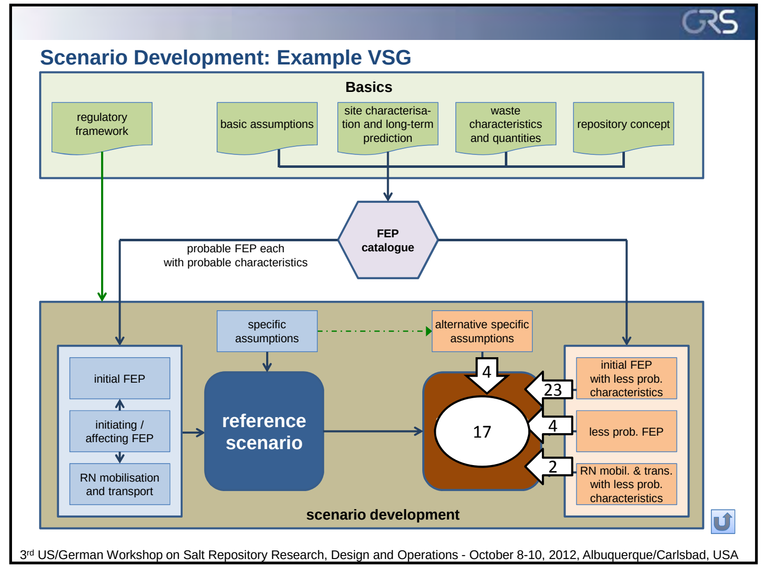
Scenario Development: Example VSG
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regulatory framework
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initial FEP with less prob. characteristics
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RN mobil. & trans. with less prob. characteristics
scenario development
3rd US/German Workshop on Salt Repository Research, Design and Operations - October 8-10, 2012, Albuquerque/Carlsbad, USA

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FEP Catalog for HLW/SNF Disposal in Salt

Christi D. Leigh

3rd US/German Workshop on
Salt Repository Research, Design and Operations
Albuquerque, NM, USA
October 9-10, 2012
SAND 2012-8033P

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Acknowledgements

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Outline

- Safety Assessment Methodology
- What are Features, Events and Processes
- Identification of FEPs for the Catalog
- Refinement of Generic FEPs for HLW/SNF Disposal in Salt
- Initial FEPs Screening for HLW/SNF Disposal in Salt
- Future FEPs Screening Activities for HLW/SNF Disposal in Salt

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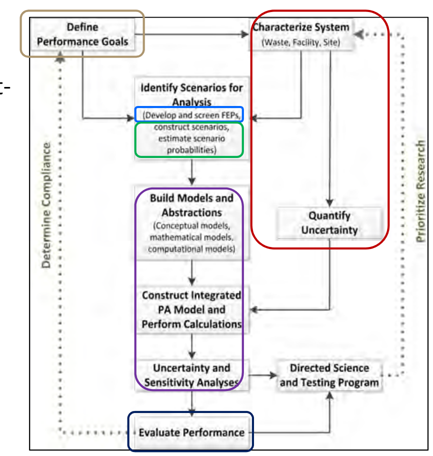
Safety Assessment Methodology

- Formal structure to guide iterative quantitative post-closure assessments
  - Application Objectives
  - Site Characterization
  - **FEP Analysis**
  - Scenario Development
  - PA Model Implementation
  - Assessment Results



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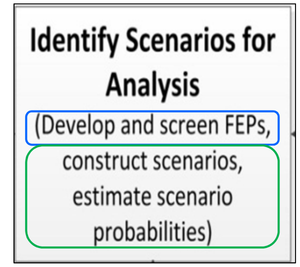
Features, Events, and Processes

- Feature(s)
  - An *object, structure, or condition* that has a potential to affect repository system performance (NRC 2003, Section 3)
- Event(s)
  - A natural or human-caused *phenomenon* that has a potential to affect repository system performance and that occurs during an interval that is short compared to the period of performance (NRC 2003, Section 3)
- Process(es)
  - A natural or human-caused *phenomenon* that has a potential to affect repository system performance and that occurs during all or a significant part of the period of performance (NRC 2003, Section 3)
- A "FEP" generally encompasses a single phenomenon
  - Typically a FEP is a *process* or *event* acting upon a *feature*

Development of a FEPs Catalog

- Formal FEP Analysis for PA consists of the systematic implementation of:
  - FEP Identification
  - FEP Screening
- FEP Analysis is performed iteratively with Scenario Development and PA Model Implementation
- References – FEP Analysis
  - NEA International FEP Database - (NEA 1999a, 2006)
  - US OCRWM - BSC (2005), SNL (2008)
  - US UFD - Freeze et al. (2010, 2011), Freeze and Swift (2010)



Identification of FEPs

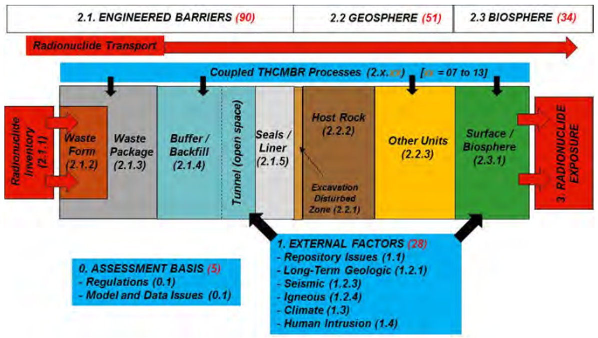
- NEA FEP Database is the basis for many FEP lists
  - comprehensive NEA FEP list (NEA 1999, 2006) contains ~2000 FEPs from 10 international programs in 6 countries
- Yucca Mountain Project (YMP) list = 374 FEPs
  - ~400 site- and design-specific phenomena considered in addition to ~2000 NEA FEPs (SNL 2008)
  - NEA list contains many duplicate or redundant FEPs – e.g., same FEP listed in each of the 10 programs
  - Categorization identified additional NEA FEPs that could be combined
- Preliminary UFD FEP list = 208 FEPs
  - Site- and design-specific YMP FEP list provides initial basis for generic UFD FEP list applicable to a range of disposal options
  - Focus on generic details results in smaller number of broader FEPs (Freeze et al. 2010, 2011)

Development of a FEPs Catalog for HLW/SNF Disposal in Salt

- Reviewed UFD generic FEPs list
  - Applicable to four different media
  - Used NEA hierarchical numbering system
- Modified the "Associated Processes" where Needed
  - more salt-specific for some FEPs
  - Cross-checked to WIPP FEPs catalogue
- Made Some Assumptions *(for initial salt FEPs screening)*:
  - Some early waste package failures are assumed to occur
  - The outer corrosion barrier of the waste package remains structurally intact and acts as a barrier to flow during the period up to the peak thermal pulse. However, the outer corrosion barrier is not a long-term hydrologic barrier after the peak thermal pulse
  - A "reference" salt design/site was developed *(for initial salt FEPs screening)*:

Reviewed UFD Generic FEPs List

- NEA hierarchical numbering system used to categorize 208 UFD FEPs by physical domains and features, THCMBR processes, and external factors/events



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Preliminary UFD FEPs - Example Listing for 1 of the 208 FEPs

Broad description of FEP provided in the "Description" column

Additional FEP detail provided in the "Associated Processes" column

Traceability and comprehensiveness provided by the "Related FEP Number" and "Domain" columns

Screening Decision is dependent on Disposal Option

UFD FEP Number	Description	Associated Processes	Related FEP Number	Domain	Disposal Options	Screening Decision
2.1.08.06	Alteration and Evolution of EBS Flow Pathways	- Drift collapse - Degradation/consolidation of EBS components - Plugging of flow pathways - Formation of corrosion products - Water ponding [see also Evolution of Flow Pathways in WPs in 2.1.03.08, Evolution of Backfill in 2.1.04.01, Drift Collapse in 2.1.07.02, and Mechanical Degradation of EBS in 2.1.07.10]	2.1.08.12.0A 2.1.08.15.0A 2.1.03.10.0A 2.1.03.11.0A 2.1.09.02.0A	EBS (FLOW)		

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UFD Generic FEPs Modified to be Salt-Specific

UFD FEP Number	Description	Associated Processes	Related FEP Number	Domain	Disposal Options	Screening Decision
2.1.07.03	Mechanical Effects of Backfill	- Protection of other EBS components from rockfall / drift collapse	2.1.04.04.0A	EBS	- Mined crystalline - Mined shale/clay - Mined salt - Deep borehole crystalline	

UFD FEP Number	Description	Associated Processes	Related FEP Number	Domain	Disposal Options	Screening Decision
2.1.07.03	Mechanical Effects of Backfill	- Crushed salt backfill should consolidate during room closure process - Static and dynamic loading on EBS structures - Restricts displacement of EBS components during ground motion and fault displacement - Protection of ~~other~~ EBS components from rockfall / drift collapse caused by ground motion and fault displacement	2.1.04.04.0A	EBS	- Mined salt	Included for quasi-static creep closure; Site Specific – direct fault displacement from a seismic event is highly site specific Excluded on low probability for seismic ground motion. The encapsulation process for a backfilled room should be completed by 500 years after closure of the repository, providing little time for major (low frequency) seismic ground motion to modify backfill. Excluded on low probability/low consequence from a volcanic event. The encapsulation process for a backfilled room should be completed by 500 years after closure of the repository, providing little time for major (low frequency) volcanic events to modify backfill.

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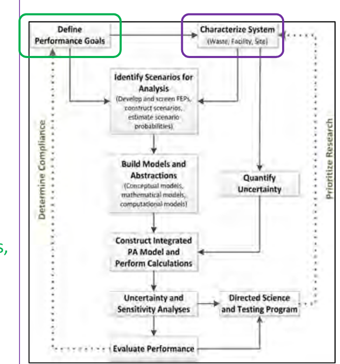
Salt Disposal Reference Case

- Bedded salt
- Crushed salt backfill will be emplaced
- Minimal ground support in emplacement drifts
- Use existing regulations (40 CFR 191) modified to include the risk-informed approach of 40 CFR 197:
  - 10,000-year screening of most FEPs, except 1,000,000 years for certain events, such as climate change (40 CFR 197)
  - Dose-based (40 CFR 197)
  - Waste recoverable for 300 years (40 CFR 191)



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FEP Screening for any Repository

- FEPs may be screened out (excluded from the PA model) by evaluation against the following screening criteria:
  - Low probability - probability of occurrence during the time period of concern is less than an established (regulatory) threshold
  - Low consequence - effect (quantitative or qualitative) on a specified performance measure (e.g., dose, subsystem measure) is not measureable/observable/significant during the time period of concern
  - Regulation - inconsistent or incompatible with the regulations
- Each FEP should be evaluated against the screening criteria
  - Screening criteria can be considered in any order
  - Screening need not be quantitative, but should have a technical basis
    - may be more qualitative and inclusive during early iterations
- If a FEP cannot be excluded, then it must be included
  - Err on side of inclusion – there is no downside to including a non-important FEP in a PA Model, other than computational / implementation cost

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FEP Screening Categories for a Generic Salt Repository

Categories are not necessarily mutually exclusive:

- Included. A FEP that is almost certain to be screened in to the generic salt disposal system models, independent of the type of salt site (bedded salt versus domal salt) or specific site characteristics. An example of an included FEP is FEP 2.2.08.02, Advective Flow, in the geosphere.
- Excluded – A FEP that is almost certain to be screened out of the generic salt disposal system models, independent of the specific salt site. An example of an excluded FEP is FEP 1.5.01.01, Meteorite Impact.
- Site-Specific – A FEP that requires a substantial amount of detailed information for a specific site. An example is FEP 1.4.02.01, Human Intrusion, which requires knowledge of the potential for mining and resource extraction activities to develop a detailed screening argument.
- Design-Specific – A FEP that requires detailed information for a specific repository design. Examples would be galvanic effects between dissimilar metals in a waste package, such as FEPs 2.1.09.09, Chemical Effects at EBS Component Interfaces, and FEP 2.1.09.11, Electrochemical Effects in EBS, which require knowledge of waste package design and EBS materials to formulate a screening argument.
- Evaluate – All other FEPs are candidates for screening calculations with the generic salt disposal system models. Some of these models may involve coupled processes, with the results providing guidance on which phenomena must be included in a salt disposal system model for the final licensing case

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Initial FEPs Screening for Generic Salt Repository (cont.)

Table A-1. Features, Events, and Processes (FEPs) Potentially Relevant to Disposal of UNF and HLW at a Generic Salt Site, based on Freeze et al. (2011). [Changes for a generic salt site are identified by a **reddish brown typeface**.]

UFD FEP Number	Description	Associated Processes	Screening Recommendation for a Generic Salt Site	Status & Crosswalk for WIPP	Status GDS Model
2.0.00.00	2. DISPOSAL SYSTEM FACTORS				
2.1.00.00	1. WASTES AND ENGINEERED FEATURES				
2.1.11.00	1.11. THERMAL PROCESSES				
2.1.11.08	Thermal-Mechanical Effects on Backfill	- Mechanical loads from room closure due to salt creep - Consolidation of backfill - Alteration - Cracking - Thermal expansion / stress - Movement of WP due to the negative buoyance	**Included** for the effects of quasi-static creep closure of the host rock and the resulting mechanical loading on and consolidation of crushed salt backfill.	W20 Salt Creep Incl. W31 Differing Thermal Expansion of Repository Components Excl. W35 Mechanical Effects of Backfill Excl.	Partially
2.1.11.10	Thermal Effects on Flow in EBS	- Altered influx/seepage - Altered saturation / relative humidity (dry-out, resaturation) - Condensation	**Evaluate** **Likely Included** to capture dryout and rewetting of the EBS	N28 Thermal Effects on Groundwater Flow Excl. W29 Thermal Effects on Material Properties Excl.	No
2.1.11.12	Thermally-Driven Buoyant Flow / Heat Pipes in EBS	- Vapor flow	**Evaluate** **Likely Excluded** after consolidation of crushed salt	N28 Thermal Effects on Groundwater Flow Excl. W43 Convection Excl. W89 Transport of Radioactive Gases Excl.	No
2.1.11.13	Thermal Effects on Chemistry and Microbial Activity in EBS		**Evaluate** **Evaluate** temperature dependence of solubility limits; **Excluded** for thermal effects on microbial activity because there is no organic material in the inventory.	W45 Effects of Temperature on Microbial Gas Generation Incl.	No

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Future Steps with FEPs Catalog

- Two primary issues are important for a FEPs Catalog: comprehensiveness and level of detail
- Comprehensiveness
  - Has already been addressed when modifying the UFD Generic FEPs list for a generic salt repository
  - Will need to be re-examined when a specific site and design are chosen
- Level of detail
  - No unique discretization, but must define FEPs broadly enough to produce a manageable number of FEPs (a few hundred), yet specific enough to provide the complexity required for screening and/or modeling
  - Initial screening of generic salt FEPs revealed issues:
    - A number of FEPs should be split into two or more FEPs because they are too broad in scope. For example, FEP 1.1.02.03, Thermal-Hydrologic Effects from Preclosure Operations, had both "include" and "exclude" aspects
    - FEPs sometimes seem to duplicate the same scope. For example, FEP 1.1.03.01, Climate Change, and FEP 1.1.04.01, Human Influences on Climate

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Safety Case for Salt Disposal of High-Level Waste (HLW) and Spent Nuclear Fuel (SNF)

Geoff Freeze

3rd US/German Workshop on
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Outline

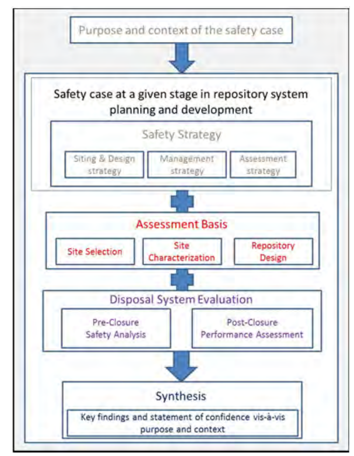
- Safety Case Elements
- Safety Case for salt disposal of HLW and SNF
  - Existing information relevant to the safety case elements
  - Information needs (gaps)

Safety Case - Definition

- "an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility" (NEA 2004, Section 1)
  - Quantitative information – calculated values for safety indicators, including uncertainty (e.g., a safety assessment)
  - Qualitative information – supporting evidence and reasoning that gives confidence in the quality of the underlying science and conclusions (e.g., relevant literature, natural analogs)
- References – Safety Case Elements
  - NEA (1999, 2002, 2004, 2008, 2009, *2012?*)
  - IAEA (2006, 2011)
  - Bailey et al. (2011), Van Luik et al. (2011)

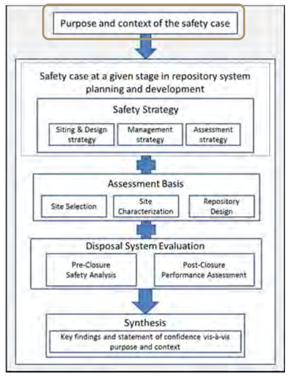
Safety Case – Elements

- Purpose and Context
- Safety Strategy
- Assessment Basis
  - Site Selection
  - Site Characterization
    - Natural Barriers
  - Repository Design
    - Disposal Concept
    - Waste Inventory
    - Engineered Barriers
- Disposal System Evaluation
  - Pre-Closure
  - Post-Closure
- Synthesis of Findings
  - Statement of Confidence



Purpose and Context

- Describes the current stage or decision point within the program
  - Repository planning
  - Site screening and selection
  - Site characterization and repository design
  - Licensing
  - Construction
  - Operation
  - Closure



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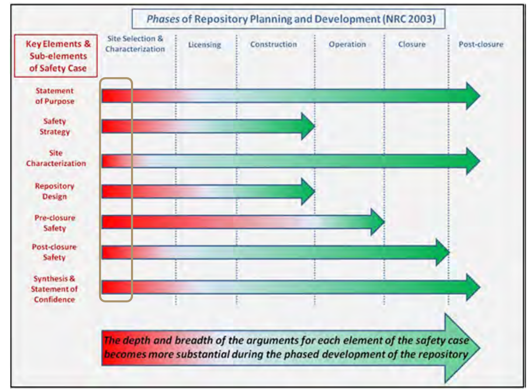
Purpose and Context

- U.S. is at an early stage – more qualitative and generic
  - Preliminary Salt Safety Cases - Vaughn et al. (2012), MacKinnon et al. (2012)



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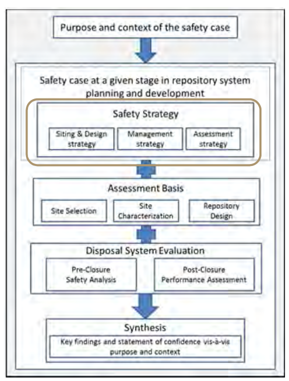
Safety Strategy

- High-level approach for achieving safe disposal
  - Siting and Design
  - Management
  - Assessment
- Key interfaces:
  - Alignment with legal and regulatory framework
    - Currently uncertain in U.S.
  - Public and stakeholder involvement



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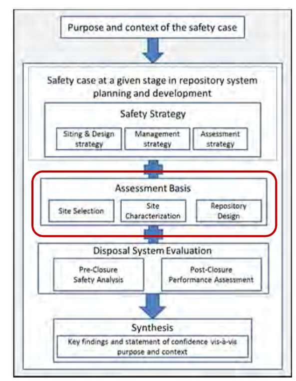
Assessment Basis

- Describe the primary characteristics and features of the disposal system
  - Location and layout of the repository
  - Waste inventory and waste forms (i.e., SNF and HLW)
  - Engineered barriers
  - Natural barriers
  - Biosphere
- Iterative with features, events, and processes (FEP) analysis and scenario development



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Assessment Basis - Site Selection

- Identification of potential sites
  - Several bedded and domal salt deposits in U.S.
- Preliminary site characterization information
  - thermal-hydrologic-chemical-mechanical-biological-radiological (THCMBR) properties
- Siting criteria
  - Geology – e.g., topography, stratigraphy, depth, lateral extent
  - Hydrology – e.g., subsurface flow and transport, surface waters, climate
  - Tectonic Stability – e.g., seismic activity, igneous activity, fracturing
  - Socio-economic – e.g., natural resources, population density, land jurisdiction, public acceptance

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Assessment Basis – Site Characterization and Repository Design

- Identify characteristics and features of the disposal system
  - Location and layout of the repository
  - Waste inventory and waste forms (i.e., SNF and HLW)
  - Engineered barriers
  - Natural barriers
  - Biosphere
- Conceptualize initial state and evolution of the disposal system
  - Undisturbed (nominal) and disturbed (e.g., human intrusion) evolution
    - THCMBR processes and properties governing disposal system performance
    - Spatial and temporal variability and uncertainty in the THCMBR properties and processes associated with the initial state of the disposal system and its evolution over 10,000 years or more

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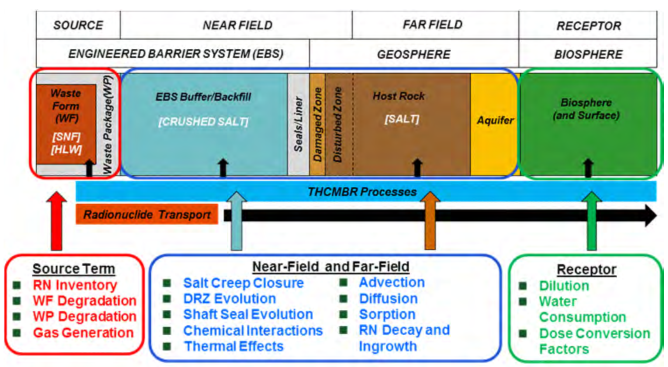
Assessment Basis - Undisturbed

- Schematic of "generic" components (features) and undisturbed (nominal) processes for a salt repository



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Assessment Basis - Undisturbed

- Salt is most promising method for HLW disposal (NRC 1957)
- Salt is essentially impermeable, self-sealing, and thermally conductive
  - Significant experience base from past studies (e.g., WIPP)
  - Ongoing Salt R&D Studies
- Thick and areally extensive salt formations exist
- Effects of heat-generating waste (i.e., FEPs) need further study
    - Waste package corrosion from acidic brine
    - Waste package buoyancy
    - Salt creep, disturbed rock zone (DRZ), and backfill evolution
    - Pressure buildup
    - Radionuclide solubility
    - Brine movement
    - Vapor-phase transport
    - Radiolysis of waste

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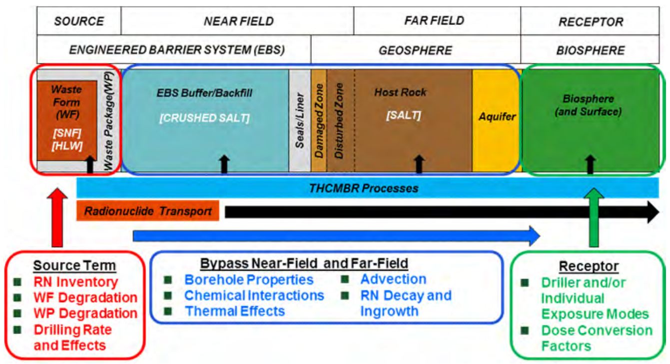
Assessment Basis - Disturbed

- Schematic of "generic" components (features) and disruptive events (human intrusion borehole) for a salt repository

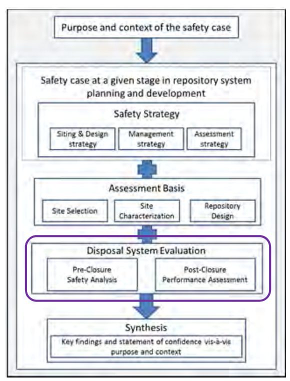


Assessment Basis - Disturbed

- Human intrusion tends to dominate dose calculations for salt repositories
  - No releases under undisturbed conditions
- Effects of human intrusion are influenced by:
  - Siting considerations
    - away from natural resources, where possible
  - Regulatory assumptions

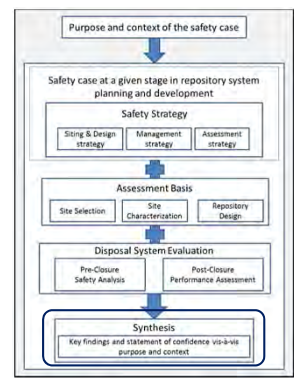
Disposal System Evaluation

- Pre-Closure Safety Analysis
  - Waste Transportation to Site
  - Surface and Subsurface Facilities
    - Construction
    - Operations
    - Closure
- Post-Closure Safety Assessment
  - Quantitative system and subsystem performance measures
    - Simplified analyses
      - Clayton et al. (2011), Vaughn et al. (2012)
    - Complex analyses
      - Ongoing Salt R&D Studies



Synthesis of Results

- Statement of confidence based on qualitative and quantitative information
  - Discuss completeness and open issues
  - Provide quality assurance (QA)
- Provides a structure for
  - Identification of important subsystem components and processes
  - Evaluation of evidence and gaps – to guide research and development (R&D)
    - Nutt (2011)
  - Discussion with stakeholders – address socio-political concerns



Synthesis of Results

- **Multiple Barriers Contribute to Safety Functions of Waste Isolation and Containment**
  - Natural Barriers
  - Slow diffusion-dominated transport with sorption
  - Long migration distance to receptor (undisturbed)
    - Host salt - very slow brine movement
    - Interbeds - absence of well-connected fractures

  Salt deposits are deep, thick and expansive

  Transport to an aquifer in an undisturbed case will not occur

  - Engineered Barriers
  - Slow waste dissolution due to reducing chemistry
  - Salt creep closure of repository and DRZ healing
    - Waste Package – performance credit not needed
    - Shaft Seals – effectiveness demonstrated at WIPP

  Extensive engineered barriers are not needed

- **Research ongoing to examine thermal effects and human intrusion**

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Exceptional service in the national interest

Sandia National Laboratories

Performance Assessment for HLW/SNF Disposal in Salt

S. David Sevougian

3rd US/German Workshop on Salt Repository Research, Design and Operations
Albuquerque, NM, USA
October 9-10, 2012
SAND 2012-8037P

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

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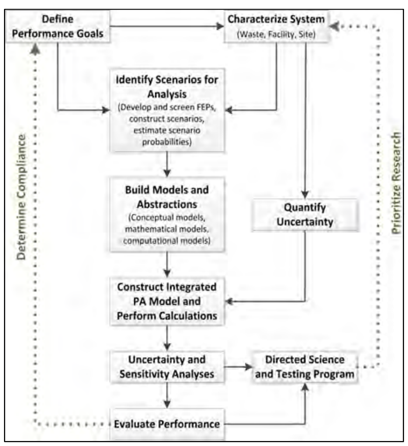
Outline

- General performance assessment (PA) methodology
- Past Sandia and U.S. Efforts in salt PA
- Current focus on "generic" disposal systems and geologic media
- HLW/SNF salt host rock TSPA model development methodology—scope for FY 2012
- Site/design reference case definition
- Sensitivity analyses to support FEPs exclusion
- Mapping of included FEPs to PA model components, by major process and domain
- Future work: model framework and computational framework design/requirements
- Possible areas for U.S.-German collaboration

2

Performance Assessment (PA) Methodology

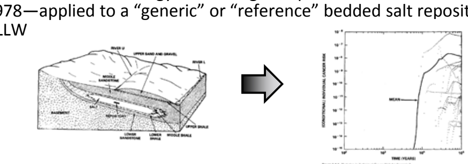
- Formal structure to guide **iterative** quantitative post-closure assessments:
  - Goals & site/design →
  - PA→
  - UA/SA →
  - R&D →
  - Site/design in next phase



3

Previous U.S. & Sandia Efforts in Salt PA

1) Sandia's "Risk Methodology for Geologic Disposal of Radioactive Waste," Campbell et al. 1978—applied to a "generic" or "reference" bedded salt repository for HLW, ILW, and LLW



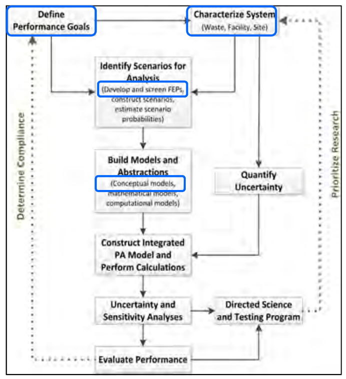
2) Salt Repository Project (SRP), Deaf Smith County, TX: "Postclosure performance assessment of the SCP (Site Characterization Plan) conceptual design for horizontal emplacement: Revision 1," ONWI (Office of Nuclear Waste Isolation) 1987b
3) Waste Isolation Pilot Plant (WIPP) for defense TRU waste, Compliance Certification Application (CCA) Performance Assessment, DOE 1996

- Initially sited – 1975
- Certified by the EPA – 1998
- First Waste Receipt – March 26, 1999
- First Recertification – March 2006
- Second Recertification – November 2010
- More than 10,000 shipments to date

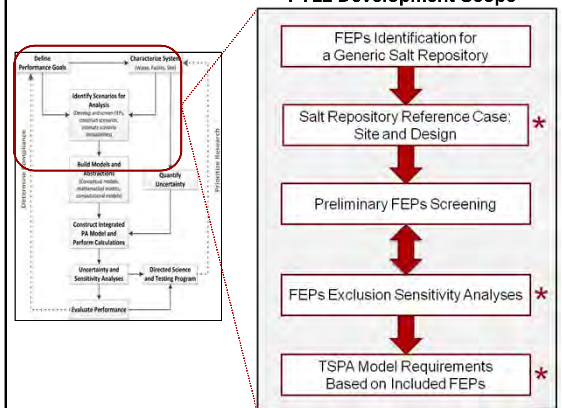
4

HLW/SNF Salt PA Model Activities in FY 12

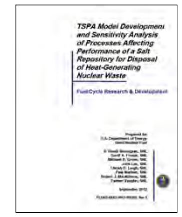
- Until new U.S. disposal policy is established, the DOE storage and disposal RD&D program will focus on "generic" repository systems in various media (granite, shale, salt)
- An generic salt PA model was designed (Clayton et al. 2011) but was isothermal, with limited process couplings
- New generic *salt* disposal PA model development is focusing on model requirements, using:
  - Generic performance standards
  - Generic site/design
  - FEP screening evaluations for a generic salt reference site/design
  - Methodology/requirements for ensuring key FEPs inclusion in component PA models, and key process couplings within and among component models



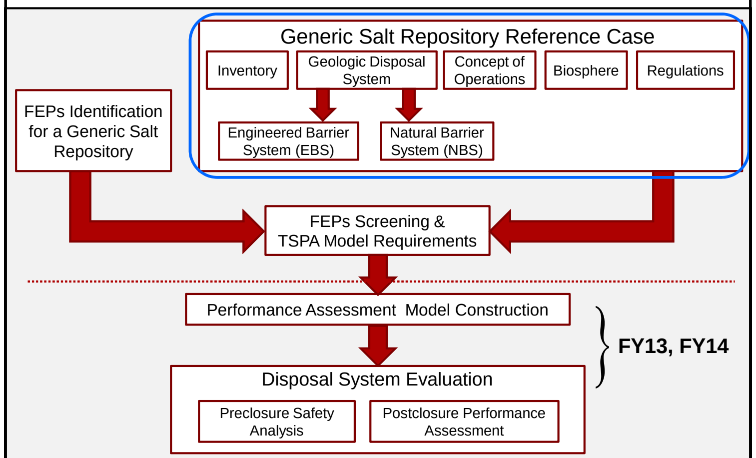
Methodology for Salt TSPA Model Development—Scope for FY 2012



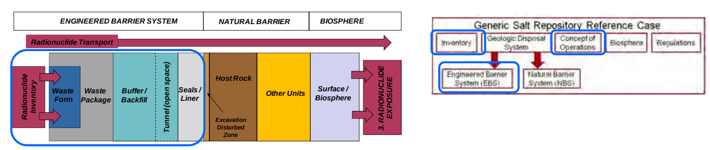
2012 Milestone Report



Generic Salt Repository Reference Case

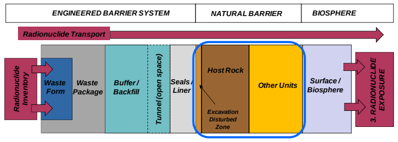


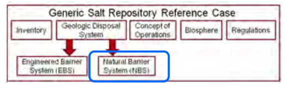
EBS Specification for Reference Case



- Waste form & inventory for "no replacement scenario": Carter et al. 2012a, 2012b
- Waste package overpack of carbon steel (A216 or A516): thick enough to be recovered after 300 years in 18 MPa lithostatic: ONWI 1987a, Hardin et al. 2012
- Repository layout and waste package emplacement in alcoves (hot waste) or on floor (cool waste): Hardin et al. 2012
- Thermal management such that 12-PWR SNF packages can be used (after sufficient decay storage) so as not to exceed 200°C at drift wall: Hardin et al. 2012
- Backfill of slightly compacted crushed salt (35% porosity): Rothfuchs et al. 2003
- Tunnels sufficient for 1.3 m by 5 m 12-PWR packages: Hardin et al. 2012
- Seal system similar to WIPP, with crushed salt for long-term and concrete/asphalt for short-term: DOE 2006

NBS Specification for Reference Case





- Geologic Setting such that bedded salt host formation could be found in any of five major depositional basins in the U.S.: see Pierce and Rich 1958, Pierce and Rich 1962, and Johnson and Gonzales 1978
- Excavation Disturbed Zone (EDZ): see Hansen and Leigh 2011 for likely evolution
- Host rock salt formation properties defined, including depth to top of salt, salt bed thickness, lateral extent of salt bed, stratigraphic dip, interbed thickness and location, and brine chemistry: Sevougian et al. 2012
- Other geologic units including overlying aquifer properties, and properties of an overpressure zone beneath salt bed (human intrusion scenario): Sevougian et al. 2012

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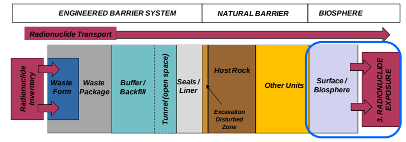
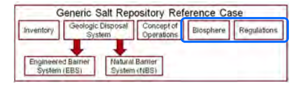
Biosphere/Regulations for Reference Case

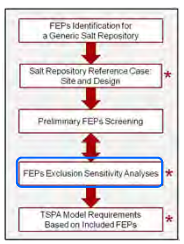




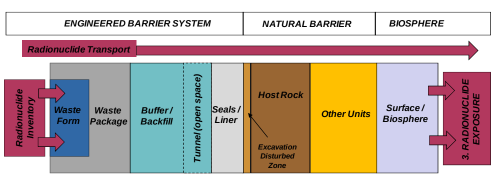
- Biosphere based on IAEA BIOMASS Example Reference Biosphere 1 (ERB1) dose model, and assumes certain other properties, including repository fluid discharge rate into an aquifer, aquifer dimensions and flow and transport properties, water well rate, water consumption rates, and ingestion dose coefficients: IAEA 2003
- Generic regulatory environment uses existing regulations (40 CFR 191) modified to include the risk-informed approach of 40 CFR 197:
  - 10,000-year screening of most FEPs, except 1,000,000 years for certain events, such as climate change (40 CFR 197)
  - Dose-based (40 CFR 197)
  - Waste recoverable for 300 years (40 CFR 191)

10

Qualitative or Quantitative Justification for Evaluate/Exclude FEPs



- Categorize the "evaluate" and "exclude" FEPs by major physical-chemical processes:* R-T-M-H-Tr-C-B
- Determine if "evaluate"/"exclude" categorization can be justified with a qualitative reasoned argument or whether a quantitative sensitivity analysis is required
- Classify sensitivity analyses by model feature/domain and by model/software type (e.g., existing THM process model, new THMC process model, existing TSPA model, enhanced existing TSPA model, or a bounding analysis)



*(R = Radiological Decay and Ingrowth; T = Thermal; M = Mechanical; H = Hydrological; Tr = Transport; C = Chemical; B = Biological)

11

Sensitivity Analyses Proposed for Justification of "Evaluate" or "Exclude" FEPs

UFD FEP Number	Description	Related Feature or Component	Screening Recommendation for a Generic Salt Site, Emphasizing FEPs Identified as "Evaluate" or "Likely Excluded" in Appendix A	Recommended Approach for Screening FEPs Identified as "Evaluate" or "Likely Excluded"	Relevant Process for Calculations						
					R	T	M	H	Tr	C	B
2.1.03.00	1.03. WASTE CONTAINER										
2.1.03.01	Early Failure of Waste Packages	- Waste Package	**Evaluate** impact of early waste package failures on chemistry of brine in backfill/tunnels and on early radionuclide releases from EBS	**EBS-5:** Thermal-Chemical Calculations for Chemistry of Brine in Waste Package, Backfill, and Tunnels After Waste Package Failure **Model**: Existing T-C process model		✓				✓	
2.1.08.00	1.08. HYDROLOGIC PROCESSES										
2.1.08.05	Flow Through Liner / Rock Reinforcement Materials in EBS	- Tunnel/Liner	**Likely Excluded**	Provide a **reasoned argument** that flow through these EBS components are not important, based on the use of minimal ground support in the emplacement drifts, per the salt disposal reference case.							
2.1.08.07	Condensation Forms in Repository - On Tunnel Roof / Walls - On EBS Components	- Waste Package - Buffer/Backfill - Tunnel - Seals - EDZ	**Evaluate**	**EBS-9:** Thermal-Hydrological-Chemical Calculations for Dryout and Rewetting of emplacement drifts **Model:** New coupled T-H-C process model		✓		✓		✓	

(R = Radiological Decay and Ingrowth; T = Thermal; M = Mechanical; H = Hydrological; Tr = Transport; C = Chemical; B = Biological)

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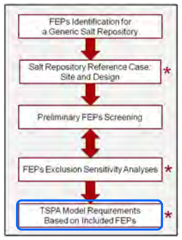
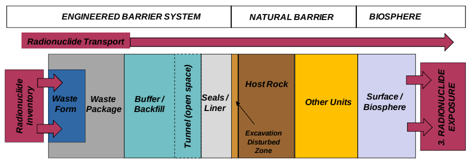
Mapping of Included FEPs to PA Feature/ Component Models (Spatial Domain)



- Define the major physical-chemical processes (T-H-M-C-R-Tr-B) to be included in each PA component model based on FEPs screening



- Review/analysis of included FEPs to decide how to include them in the PA component models (in FY 2013):
  - High-fidelity
  - "Lumped" = reduced dimensionality or simplified representation (limited multi-physics coupling)
  - Response surface

13

Mapping of Included FEPs to Waste Package Structural Response Model

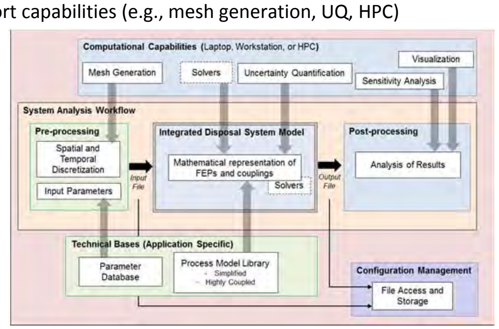
Table 3. Models for Structural Response of the Waste Package, Based on Included or Likely Included FEPs
(R = Radiological Decay and Ingrowth; T = Thermal; M = Mechanical; H = Hydrological; Tr = Transport; C = Chemical)

UFD FEP Number	FEP Description	Notes	R	T	M	H	Tr	C
CORE MODEL FOR STRUCTURAL RESPONSE OF THE WASTE PACKAGE:								
2.1.07.02	Drift Collapse			✓	✓			
2.1.07.03	Mechanical Effects of Backfill	Backfill consolidation around waste package		✓	✓			
2.1.07.05	Mechanical Response of Waste Packages				✓			
2.1.11.01	Heat Generation in EBS			✓				
2.1.11.03	Effects of Backfill on EBS Thermal Environment			✓	✓			
2.1.11.07	Thermal-Mechanical Effects on Waste Packages			✓	✓			
2.1.11.08	Thermal-Mechanical Effects on Backfill			✓	✓			
CORE MODEL FOR STRUCTURAL RESPONSE OF THE WASTE PACKAGE COUPLED WITH FLOW:								
2.1.08.03	Flow in Backfill	Determines brine availability during consolidation				✓		
2.1.08.08	Capillary Effects in EBS	Determines brine availability during consolidation				✓		
CORE MODEL FOR STRUCTURAL RESPONSE OF WASTE PACKAGE COUPLED WITH FLOW & CORROSION OF WASTE PACKAGE OVERPACK:								
2.1.03.02	General Corrosion of Waste Packages	Thickness of waste package overpack		✓		✓		✓
2.1.03.04	Localized Corrosion of Waste Packages	Integrity of overpack when pits/cracks form		✓		✓		✓

14

Future Design of Salt TSPA Model

- The TSPA model is comprised of two main components:
  - a generic multi-physics model framework that facilitates inclusion of conceptual and mathematical models of the key included FEPs
  - a computational framework that facilitates integration of system analysis workflow (e.g., pre-processing, numerical integration, post-processing) with support capabilities (e.g., mesh generation, UQ, HPC)



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Proposed Areas for Collaboration

- Methodology for determining what physical-chemical processes and process couplings are needed in a salt PA model:
  - How should T-H-M-C-R-B-Tr processes be represented in a system PA model that represents uncertainty with multiple realizations of system performance?
  - Three-dimensional T-M-H processes are clearly important at early times but can they simply be abstracted for representation in the system PA, and how?
- Methodology for R&D prioritization:
  - More formally define how to use the safety case to prioritize future R&D
  - Methods for using PA, and associated uncertainty/sensitivity analyses, for prioritizing R&D
  - Decision analysis models/methods/software have been used in other fields to prioritize R&D activities and R&D "portfolios" (or groups of activities), based on cost/benefit, and including constraints:
    - Can we adapt decision analysis techniques to develop a robust methodology to guide repository science and R&D?

16

Exceptional service in the national interest

Sandia National Laboratories

Uncertainty Treatment in Performance Assessment for a salt repository - the Sandia Approach

Cédric J. Sallaberry

3rd US/German Workshop on Salt Repository Research, Design and Operations

Albuquerque, NM, USA

October 9-10, 2012

SAND2012-8036P

Sandia National Laboratories DBE TEC PTKA ENERGY NNSA

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What's a performance Assessment

Every PA starts with the same four questions

- Q1: What can happen?
- Q2: How likely is it to happen?
- Q3: What are the consequences if it does happen?
- Q4: How much confidence do you have in the answers to the first three questions?

Basic concept (1/4)

From the question to the mathematical characterization

EN1: Probabilistic characterization of what can happen in the future

- Answers first two questions
- Provides formal characterization of aleatory uncertainty

EN2: Mathematical models for predicting consequences

- Answers third question

EN3: Probabilistic characterization of uncertainty in PA inputs

- Basis for answering fourth question
- Provides formal characterization of epistemic uncertainty

Basic concept (2/4)

from mathematical characterization to implementation

Sampling-Based approach

EN3 (steps 1–2):

1. Characterization of uncertainty in **e** (i.e., definition of D_1, D_2, …, D_{nE})
2. Generation of sample from **e** (i.e., generation of $\mathbf{e}_k$, $k = 1, 2, …, nS$, in consistency with D_1, D_2, …, D_{nE})

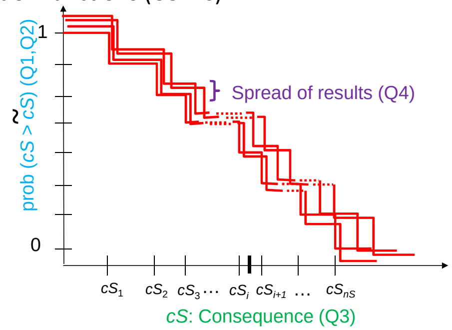
EN2 (step 3):

3. Propagation of sample through analysis (i.e., generation of mapping $[\mathbf{e}_k, \mathbf{y}(\mathbf{a}|\mathbf{e}_k)]$, $k = 1, 2, …, nS$) — *Defined in* **EN1**
4. Estimate of uncertain results and statistical (aka uncertainty) analysis (i.e., approximations to the distributions of the elements of **y** obtained from $\mathbf{y}(\mathbf{a}|\mathbf{e}_k)$, $k = 1, 2, …, nS$)
5. Determination of sensitivity analysis results (i.e., exploration of the mapping $[\mathbf{e}_k, \mathbf{y}(\mathbf{a}|\mathbf{e}_k)]$, $k = 1, 2, …, nS$)

Basic concept (3/4)

from implementation to results (uncertainty analysis)

- Risk expressed as a family of complementary cumulative distribution functions (CCDFs)



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Basic concept (4/4)

from implementation to results (sensitivity analysis)

- Involves exploration of mapping $[\mathbf{e}_k, \mathbf{y}(\mathbf{a}|\mathbf{e}_k)]$, $k = 1, 2, \ldots, nS$
- Available techniques for sensitivity analysis
  - Examination of scatterplots and cobweb plots
  - Correlation and partial correlation analysis
  - Stepwise regression analysis
  - Rank transforms to linearize monotonic relationships
  - Nonparametric regression: Loess, additive models, projection pursuit, recursive partitioning
  - ….

6

WIPP as an Example (1/4)

mathematical model

EN1

- Defined by probability space $(\mathcal{A}, \mathbb{A}, p_A)$,

  $\mathcal{A}$ = {**a**: **a** is a possible 10,000 yr sequence of occurrences at WIPP}
- Extensive review of possible disruptions at the WIPP led to drilling intrusions and potash mining being the only occurrences incorporated into the definition of $\mathcal{A}$

EN2

- Function **y** = **f**(**a**)
- Models represented by **f** include: Systems of algebraic equations, Systems of ordinary differential equations (ODEs), Systems of partial differential equations (PDEs), Algorithmic procedures
- Processes modeled include: Material deformation, Corrosion , Microbial gas generation, Two-phase fluid flow, Pressure-induced fracturing, Regional groundwater flow, Radionuclide transport in flowing groundwater

EN3

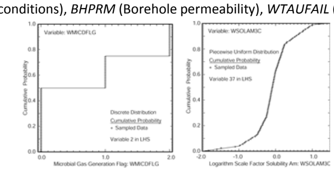
- Basic ideas underlying definition of EN3: Acceptable definitions for EN1 and EN2 result if appropriate values are assigned to quantities represented by $\mathbf{e}=[e_1,e_2,\ldots e_{NE}]$. Many possible values of varying levels of plausibility exist for **e.** Uncertainty in appropriate value to use for each e_j can be characterized by a distribution D_j
- EN3 defined by probability space $(\mathcal{E}, \mathbb{E}, p_E)$ derived from $D_1, D_2, \ldots, D_{nE}$

7

WIPP as an example (2/4)

implementation

- 57 uncertain quantities considered in WIPP 1996 PA, each associate with a distribution, including *WGRMICI* (Gas generation rate due to microbial degradation of cellulose under inundated conditions), *BHPRM* (Borehole permeability), *WTAUFAIL* (Shear strength of waste)…



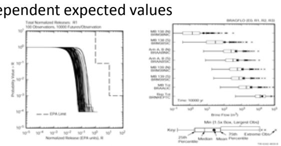
- Sample generated as 3 independent replicated samples of size 100 each
- Iman/Conover technique used to control correlations
- Of course, development of **f** , which is the most complex part.

8

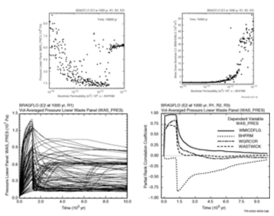
WIPP as an example (3/4)

uncertainty and sensitivity analyses

- WIPP Results as distributions of CCDFs or time dependent expected values
- Conditional results presented as Box plots



- Scatterplots, partial correlation coefficients, and stepwise regressions were used to analyze the influence of inputs uncertainty over selected outputs uncertainty.



Pressure at 10^4 yr

Step[a]	Variable[b]	SRC[c]	R^{2d}
1	*WMICDFLG*	0.718	0.508
2	*HALPOR*	0.466	0.732
3	*WGRCOR*	0.246	0.792
4	*ANHPRM*	0.129	0.809
5	*SHRGSSAT*	0.070	0.814
6	*SALPRES*	0.063	0.818

[a] Steps in stepwise analysis.
[b] Variables listed in the order of selection in regression analysis.
[c] Standardized regression coefficients (SRCs) for variables in final regression model.
[d] Cumulative R^2 value with entry of each variable into regression model.

9

WIPP as an example (4/4)

conclusion

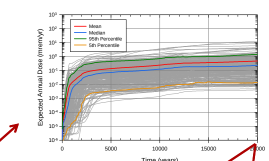
- Certification completed in 1996 (16 years ago)
- Most of the approaches used (sampling based method, rank regression …) are still valid today
- Remains a reference in term of Successful Probabilistic Assessment for underground repository
- But in order to remain an reference in radioactive waste disposal, Sandia (via center 6200) works into maintaining the past knowledge and improving or working on new concepts and techniques.
- Following slides will present Improved and new techniques successfully used at Sandia, complementing the original expertise

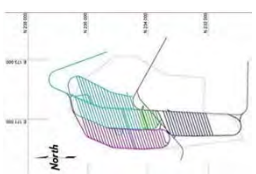
10

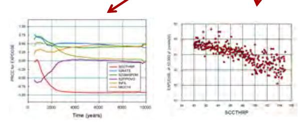
Different repository: same approach

the Yucca Mountain example

- Different repository concept (fractured media, high level waste, engineered barrier system with drip shield)
- Different regulatory requirements
- But same approach has been used with success to estimate uncertainty over expected doses and perform sensitivity analysis







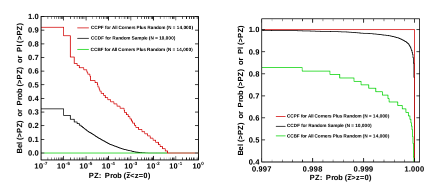
10 years after, we can still do it … and in color !

11

New approaches and methods

Alternative representations of (epistemic) uncertainty

- Sometimes, uncertainty is not well-enough defined to use probability without adding some subjectivity.
- Alternative representations of uncertainty (such as Evidence theory, Possibility theory, Fuzzy sets, Interval analysis) allow to relax some of the constraints inherent to probability theory and avoid such addition
- With current computational capabilities, Sandia showed that it is possible now to use in real-world problem such new representations
- CCDF over epistemic uncertainty are then defined with a range delimited by Plausibility (in red in graph below) and Belief (in green below)



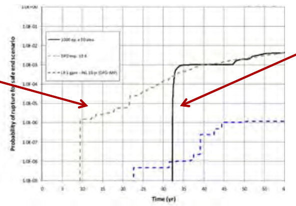
12

New approaches and methods

New sampling and optimizations techniques

- In term of sampling, LHS is still considered as the sampling of choice for many problem as it informs where most of the uncertainty has an effect
- The original code developed by Ron Iman in 1980 has been continually improved since
- **Sometimes, LHS may not be the method of choice**: when estimated probabilities are pretty low, when a particular area of interest needs to be oversampled …
- Other techniques such as **importance sampling and optimizations** are then more appropriate and efficient
- Sandia develops and maintain a freeware optimization toolkit that can be plug to external code and run optimization and/or sampling on the code. Its codename is DAKOTA

Importance sampling with same sample size is a lot more accurate for low probabilities events



Classical LHS missed low probability unless sample size is increased

Results from xLPR project for US-NRC

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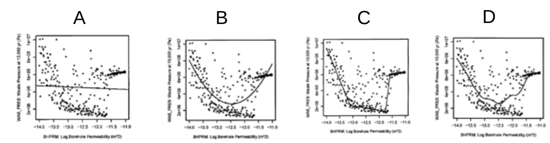
New approaches and methods

New regression techniques (1/2)

- Rank regression was a powerful technique that captured most of the uncertainty for WIPP and Yucca Mountain sensitivity Analysis
- However, it did not capture non monotonic influence (fig. A) and conjoint influence of two parameters
- New regression techniques, coupled with Sobol variance decomposition has been successfully used in order to capture more complex influence that sometimes happen in complex models and are hard to recognize. Techniques such as quadratic regression (fig. B), recursive partitioning (fig. C), MARS and ACOSSO (fig. D) have been used to capture more complex relationship between input and output.



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New approaches and methods

New regression techniques (2/2)

- These techniques have been also successfully used to capture conjoint influence that was missed by regression into additive models

	Rank Regression			Quadratic			Recursive Partitioning			MARS		
Final R^2	0.24			0.61			0.60			0.60		
Input	R^2 inc.	R^2 cont.	SRRC	S_i	T_i	p-val	S_i	T_i	p-val	S_i	T_i	p-val
CYSIGA.1..	0.04	0.04	-0.11	0.00	0.03	0.56	0.00	0.00	1.00	0.05	0.17	0.14
EFFTHR.1..	0.08	0.04	-0.11	0.06	0.13	0.26	0.06	0.09	0.23	0.00	0.48	0.00
GSHFAC.2..	0.11	0.03	0.11	0.01	0.24	0.02	0.00	0.13	0.04	0.02	0.11	0.25
SRVLAMB	0.13	0.03	-0.09	0.00	0.30	0.00	0.12	0.36	0.00	0.01	0.26	0.02
CWASH1.	0.16	0.03	0.08	0.00	0.86	0.00	0.26	0.91	0.00	0.13	0.34	0.14
SRVOAFRAC	0.18	0.02	-0.07	0.01	0.00	1.00	---	---	---	0.06	0.16	0.62
RRDOOR	0.19	0.01	0.10	0.00	0.00	1.00	---	---	---	0.01	0.32	0.00
PROTIN.2..	0.20	0.01	0.05	---	---	---	0.00	0.00	1.00	0.02	0.43	0.00
EFFTHR.2..	0.21	0.01	-0.05	---	---	---	0.00	0.30	0.00	0.02	0.00	1.00
CSFACT.3..	0.22	0.01	0.04	---	---	---	---	---	---	0.00	0.10	0.26
EIFACB.3..	0.22	0.01	-0.04	---	---	---	---	---	---	---	---	---
SC1131_2	0.23	0.01	0.03	---	---	---	0.03	0.15	0.05	0.00	0.20	0.03
DLTEVA.12..	0.23	0.01	-0.04	0.04	0.46	0.00	---	---	---	---	---	---
SRVFAILT	0.23	0.00	0.03	0.00	0.00	1.00	0.00	0.00	1.00	---	---	---
EITHRE.3..	0.24	0.00	-0.03	0.00	0.00	1.00	---	---	---	0.00	0.20	0.03
DLTEVA_5.2..	---	---	---	0.00	0.24	0.01	---	---	---	---	---	---
CSFACT.2..	---	---	---	0.00	0.27	0.09	0.00	0.48	0.00	0.02	0.02	0.56
PROTIN.3..	---	---	---	0.00	0.07	0.32	0.00	0.00	1.00	---	---	---
PROTIN.1..	---	---	---	0.01	0.00	1.00	---	---	---	0.01	0.00	1.00
VDEPOS.1..	---	---	---	0.00	0.00	1.00	0.04	0.09	0.07	---	---	---
DLTEVA_5.11..	---	---	---	---	---	---	0.02	0.00	1.00	---	---	---
EFFACB.1..	---	---	---	---	---	---	0.01	0.00	1.00	---	---	---
DLTEVA.13..	---	---	---	---	---	---	0.00	0.00	1.00	---	---	---
GSHFAC.3..	---	---	---	---	---	---	---	---	---	0.00	0.00	1.00
	---	---	---	---	---	---	---	---	---	---	---	---
	---	---	---	---	---	---	---	---	---	---	---	---
	---	---	---	---	---	---	---	---	---	---	---	---

In this example, the conjoint influence of variable CWASH1 was completely missed by Rank Regression

Examples results from SOARCA UA project for US-NRC

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Conclusion

- Sandia has shown capability to complete a complex PA for certification of radioactive waste repository in Salt in the past
- The expertise in the area has been maintained as many of the techniques used are still valid and powerful
- Since then, Sandia has built upon this basis to expand its expertise and bring new and improved techniques to enrich its capabilities
- These techniques are not only theoretical but **used** in **real** projects with success in other activities.
- Our desire is now to regroup all these techniques and apply them again on Repository science to demonstrate their advantages

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Investigations on Sensitivity Analysis of Complex Final Repository Models

Dirk-Alexander Becker, GRS

October 9, 2012

3rd US-German Workshop on Salt Research, Design and Operations

Albuquerque, New Mexico, USA

Introduction

Modeling of long-term safety of repository systems

- representation of a repository system using a numerical model
- various physical and chemical effects to be taken into account
- numerous input parameters
- calculation of adequate output values for assessing long-term safety (safety indicators)

Uncertainties

- scenario uncertainties: *what will happen?*
- model uncertainties: *how can the relevant effects be described?*
- parameter uncertainties: *which are the correct input values?*
  - aleatory: random-influenced
  - epistemic: due to lack of knowledge

2

Handling of Uncertainties

Conservatism: use of pessimistic assumptions and parameter values

- must not go too far, otherwise meaningless results
- not always possible because of nonlinear model behavior

Consideration of alternative scenarios or models

- if in doubt, consider all possibilities

Uncertainty analysis: a number of model runs with distributed parameter values

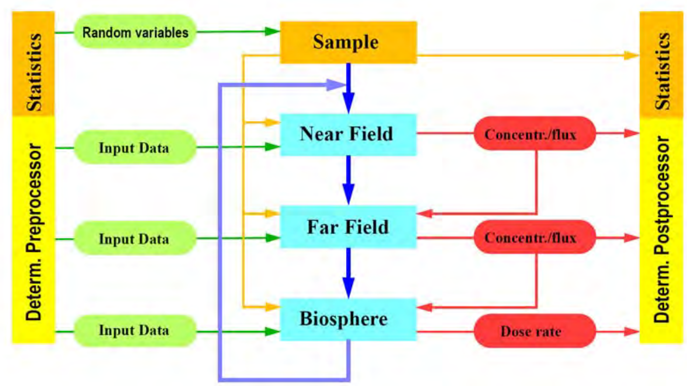
- adequate probability density functions
- analysis of output distribution (maximum, mean, quantiles, …)

Sensitivity analysis: identification of most influential parameters

- probabilistic methods required
- demanding task!

3

Scheme of Calculation



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Sensitivity Analysis

Graphical methods
- presentation of input/output: scatterplots, cobweb plots, CSM and CSV plots, …
- very illustrative and helpful!

Correlation- or regression- based methods
- calculation of regression or correlation coefficients
- information on direction of influence
- work best on systems with a (nearly) linear behavior
- rank transformation can improve performance on *monotonic*, nonlinear systems, leading to loss of quantitative information

Non-parametric methods
- two sample tests: Smirnov, Mann-Whitney, …
- sometimes helpful, but hard to interpret/understand

5

Sensitivity Analysis

Variance-based methods
- decomposition of model output variance according to individual parameters or parameter combinations
- Sobol's sensitivity indices of 1st (2nd, 3rd, …) and total order
- quantitative measure; first-order indices sum up to 1
- numerous methods for calculation (Sobol, FAST/EFAST, RBD, EASI, …)
- neither linearity nor monotonicity required
- require a high number of model runs
- no information on direction of influence
- work best on a linear scale

$$\frac{\mathrm{Var}_{X_j}[E(Y)|X_j]}{\mathrm{Var}(Y)}$$

Metamodel methods (emulator methods)
- original model behavior is simulated by a simplified metamodel
- metamodel is calibrated by a number of original model runs
- sensitivity analysis is performed using the metamodel
- different methods available (SDP, Gaussian emulator, …)

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Repository Systems in Rock Salt

Existing LLW/ILW repository
- erected in a former salt production mine
- made in view of effective production
- many chambers and drifts
- multiple interconnections
- complex, irregular geometry
- different salt types and qualities
- brine intrusion possible
- unknown geochemical conditions
- geotechnical measures to inhibit brine flow
- failure of seals possible

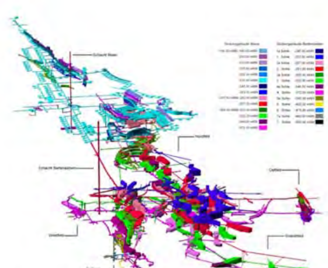


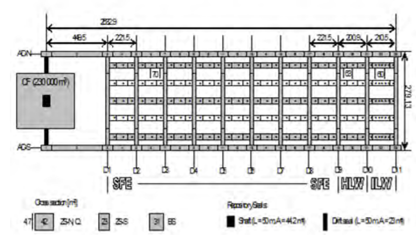
Abbildung 2.1-3: Grubengebäude, Ansicht von Süd nach Nord

Particularities of the Model
- essential simplification necessary
- interaction of various physical and chemical effects
- seal failure can cause significant changes of flow conditions and contaminant release
- highly nonlinear behavior, sometimes even discontinuous ➡
- output is spread over several orders of magnitude ➡

7

Repository Systems in Rock Salt

Generic HLW repository
- to be erected specifically as a repository
- homogeneous, well-explored rock salt formation
- well-planned repository design
- clear structure of chambers and drifts
- designed to prevent brine inflow
- fast inclusion of wastes expected



Particularities of the Model
- model is relatively close to reality
- nonlinear model behavior
- low probability of contaminant release: most scenarios yield zero output
- non-zero output is spread over several orders of magnitude

8

Specific Difficulties with Sensitivity Analysis

- Non-linear model behavior
  - low performance or failure of regression/correlation methods
- Non-monotonic model behavior
  - low performance or failure of rank regression/correlation methods
- Non-continuous model behavior
  - low performance of trajectory-based methods like FAST/EFAST
  - problematic for metamodel methods
  - high number of model runs needed ➡
- Correlated input parameters
  - some methods not applicable to systems with correlated parameters
  - interpretation of results difficult
- Non-normal distribution of model output
  - mean and, even more, variance can be dominated by a few outliers ➡
  - low robustness of all numerical methods
  - output transformation can improve the analysis ➡

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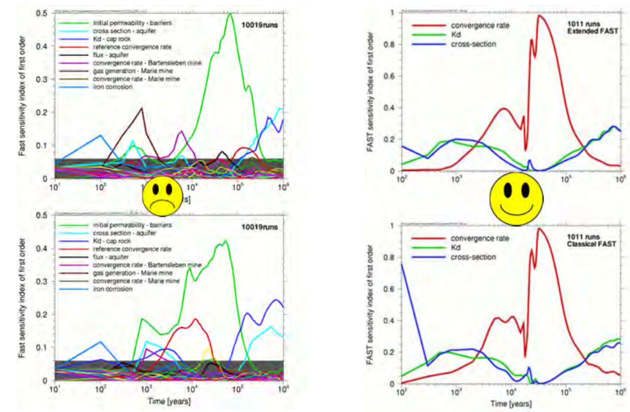
with "quasi-discrete" parameter

without "quasi-discrete" parameter



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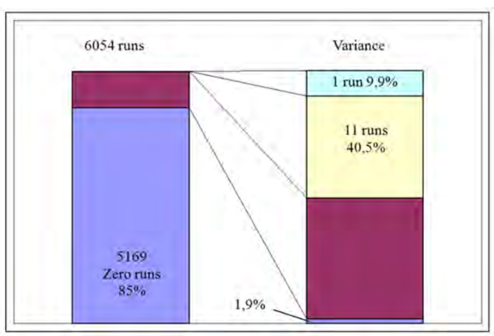

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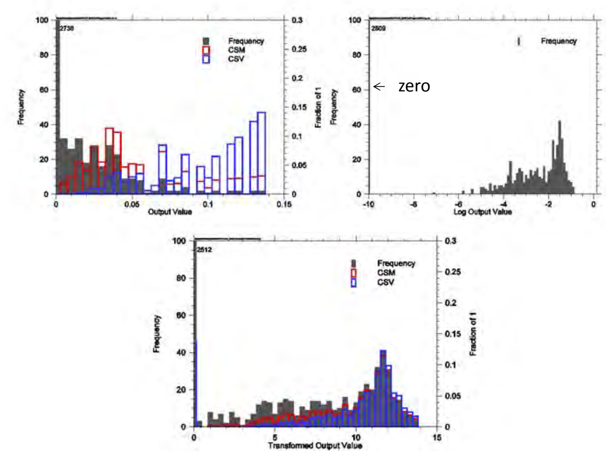

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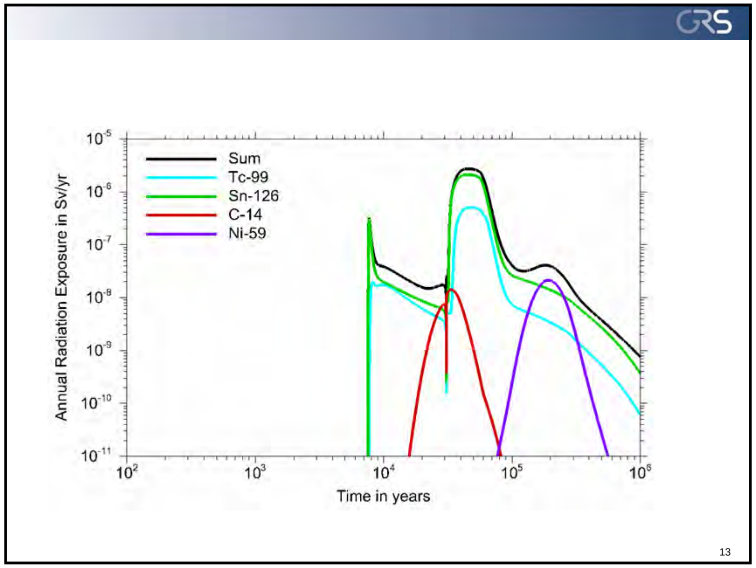
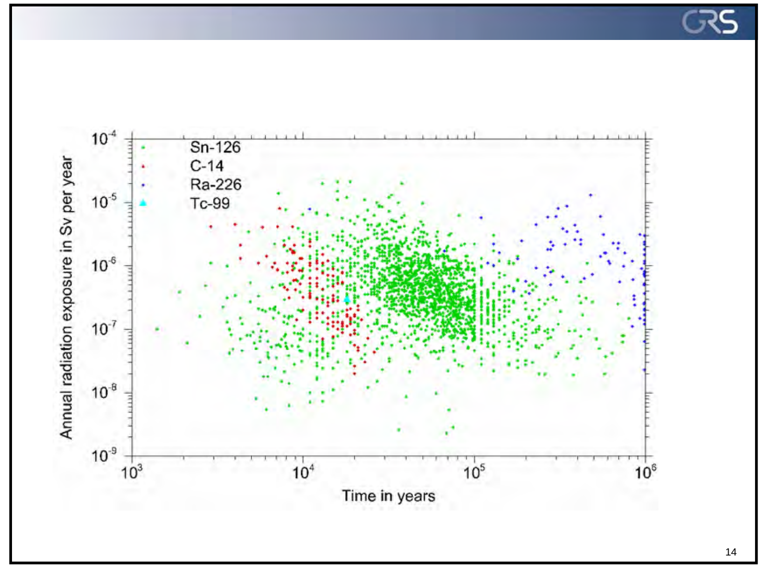

GRS
Annual Radiation Exposure in Sv/yr
Sum
Tc-99
Sn-126
C-14
Ni-59
Time in years
13


GRS
Annual radiation exposure in Sv per year
Sn-126
C-14
Ra-226
Tc-99
Time in years
14

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Methods for assessing the long-term performance of geotechnical seals in a repository in rock salt

J. Orzechowski, **E. Plischke**, K.-J. Röhlig, X. Li (TUC)
J. Krone, N. Müller-Hoeppe (DBE TEC)

3rd US/German Workshop on Salt Repository Research, Design & Operations
Albuquerque, October 9, 2012

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The problem

- Primary safety function for a drift seal (dam) in a HLW/SNF repository in rock salt: Preventing liquid inflow
- Dams are to be constructed according to existing engineering standards (e.g. „Eurocodes"), …
  - which provide a methodology for ensuring sufficient reliability (using mostly semi-probabilistic methods),
  - but proved for relatively short timeframes (design working life up to 100 a)
- Objectives:
  - Aim at consistency between construction and long-term safety assessment
  - Adapt engineering standards in order to support long-term safety case

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Engineering standards (Eurocodes)

- Aim: demonstrate that, **with sufficient confidence (likelihood)**, actions (e.g. load) remain smaller than resistances over demonstration timeframe
- Assume probability distributions for actions and resistances (mostly used: Gaussian)
- Derive „safety index" based on these distributions: index value corresponds to accepted maximal likelihood of failure
- Choose „characteristic values" (nominal, means, quantiles, …) of these distributions: CW_{load}, $CW_{resistance}$ (F_k, R_k)
- Define „partial safety factors" for characteristic values of load and resistance based on safety index: PSF_{load}, $PSF_{resistance}$ (γ_F, γ_M)

- Conclude that, if $CW_{load} * PSF_{load} < CW_{resistance} / PSF_{resistance}$, the above demonstration counts as achieved
- Specify construction requirements accordingly

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Challenges

- Choice of probability distributions:
  - Lack of experience
  - Sparse data
  - Complex THMC relationships between impacts (FEPs), load and resistance
- Safety index:
  - Role of demonstration timeframe – variation of entities over time
  - Role of component as part of overall system
- Choice of characteristic values (dependent on variation coefficients and temporal behaviour of entities considered)

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Work content: Two „lines of attack“

- Probability distributions: Can they be derived from existing data?
- Addressing FEP of long-term relevance and their interactions in terms of engineering approaches (actions and resistances)

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Part I:

Probability distributions: Can they be derived from existing data?

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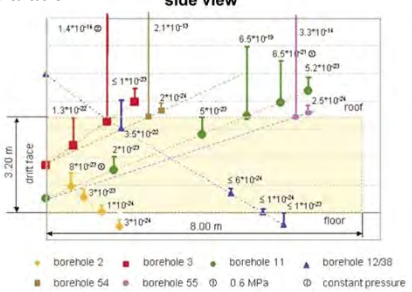
The data set

- In 1991/92, a pilot dam made out of salt concrete was built in the Asse mine as part of a study of a geotechnical barrier system.
- For modeling the permeability of the dam, 34 measurements from 12 drill holes are available.



Source: Final Report Übersicht Project, DBE 2009

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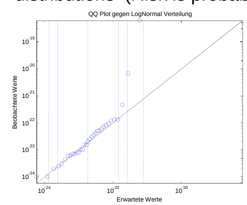
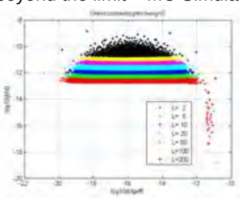
Sampling-based derivation of failure probabilities

- Derive „cautios estimates“ for permeabilities of dam core, contact zone and, excavation damaged zone/rock salt
- From Darcy's law: Limit State Function
- Alternative full-probabilistic approach: Simulate according to derived distributions (Risk is probability mass beyond the limit – MC Simulation)



Graphical test of probability assumption: expected vs. observed values



Failure domain: Dependence on barrier length

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Sampling: Accounting for spatial variability

- Approach presented before assumes each sample as representative for the whole dam structure
- In reality, though, all samples come from one and the same dam and represent hydraulic conductivity at different locations of this dam.
- Question: How to „upscale“ these data (packer scale 10 cm) in order to derive conclusions for the whole dam?
- Geostatistical approach:
  - Consider „true“ dam (the one the data come from) as one realisation of a location-dependent random variable („random function“)
  - Derive conclusions about pdf and spatial behaviour of the random function from the data („variography“, central: „assumption of stationarity“)
  - Sample realisations of the so described random variable (one realisation corresponds with one „possible dam“)
  - Calculate hydraulic flow (for given pressure gradient) for each and calculate effective conductivity
  - Perform statistics for these effective conductivities

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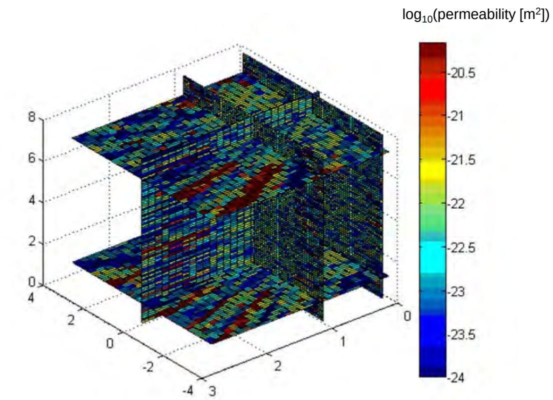
One realisation



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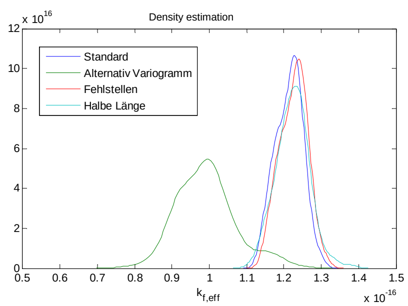
Statistics for effective conductivity (different model assumptions)



Conclusion: For a dam which is correctly described by the underlying assumptions, the effective conductivity is with a likelihood of 1/10.000 smaller than 1,3·10^{-23} m^2 (statistical confidence 95 %).

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Part II:

Addressing time relevant relationships between FEP, impacts (actions) and resistances

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- Development of a concept combining the engineering approach (demonstration of safety function <=100a) with FEP/scenario based methods for the long-time safety analysis (safety case >>100a)
- Highest priority to long-term impacts and their interactions
- Long-time design requires knowledge regarding time frame, mode of occurrence and intensity of impact (action)

  Problem: High degree of interaction between FEPs, uncertainty about varying intensities and time-dependent occurrence
- Goal: Preservation of safety function in the defined time frame (extended life expectancy compared to conventional engineering)

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Concept:

- Step 1: separate examination of the requirements from the long-term safety analysis and the engineering requirements
  - identification of FEP-interactions (determination of requirements for long-lived dam structure)
- Step 2: Alignment of the requirements from long-term safety analysis and the current engineering requirements
  - Derivation of additional requirements and safety criteria
- Step 3: Design of the dam structure complying with limiting/bounding values
  - Approximate dimensioning within the basic engineering design (first iteration loop)
- Step 4: Long-term safety case
- Step 5: Evaluation of the long-term safety case
  - If necessary: formulation of requirements for amending the design (second iteration loop)

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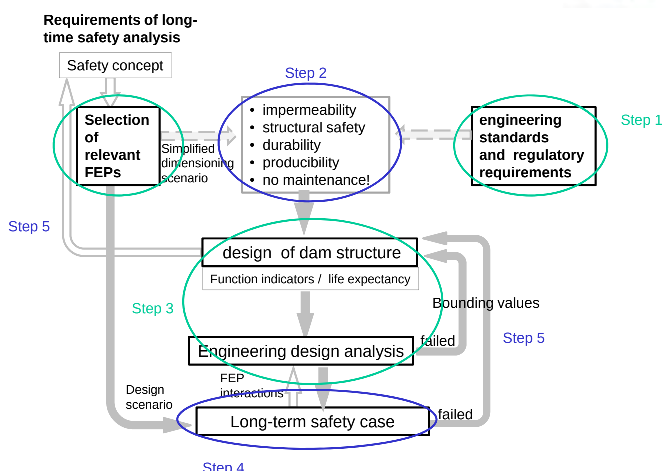

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- Selection of FEPs
  - Relevance towards safety functions (function indicators) and life expectancy
  - dimensioning-scenario
    - Classification in categories
      - Dependence (identification of high-level activating FEPs)
      - Time frames (in operation, transient, monotone/stationary, cyclic)
      - Uncertainties: Time of occurrence, intensity, safety relevance
      - Interactions
  - Most complicated impact due to its interaction: heat production of radioactive waste → Changes in geochemistry and mechanics → Changes in actions and resistance
- Influence on indicators for proof of the structural safety and the integrity of barrier
- Determination of the indicator values
  1. separate calculation of temperature, geochemical environment, mechanical stresses and, hydraulic pressures (in dimensioning)
  2. Calculation of coupled processes (e. g. THMC) focusing on FEP of long-term relevance

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Conclusions and perspectives (evtl. auf 2 Folien aufteilen)

- Geostatistics-based methodology for deriving **global** reliability statements (for the whole structure) from **local** measurements
- Reliability increases with increasing length of dam
- Monte Carlo simulations enhance confidence in calculations with cautious estimates
- However: Reliable variography would require more data (than achievable / affordable?)

- Can Eurocode methodology be applied for long timeframes?
  - Analysis of FEP evolution with time leads to identification of a **limited number of decisive FEPs**
  - In particular: FEP resulting from **heat production** and their interactions were identified as the most complicated impact on the structure and its resistance
  - Further aspects regarding partial safety factors to be investigated
- Additional considerations are needed:
  - Effects resulting from FEP-interactions in the case of THMC couplings
  - Alternatively: Avoiding complicated FEP interactions by an engineering design well adjusted

- It seems to be possible to map safety function indicators to indicators/criteria describing the resistance of a structure

Full Scale Demonstration of Plugs and Seals

- DOPAS -

Michael Jobmann

DBE TECHNOLOGY GmbH, Eschenstraße 55, 31224 Peine, Germany

DOPAS Partners

Full Scale Demonstration of Plugs and Seals

4 years Collaborative Project
Start: October 2012
Requested EC funding: 8.7 mill €

DOPAS is a project addressing a key priority identified and defined by the IGD-TP (Implementing Geological Disposal – Technology Platform) in its Strategic Research Agenda (SRA).

1	POSIVA	7	RAWRA
2	ANDRA	8	SKB
3	DBE TECHNOLOGY	9	CTU
4	GRS	10	NRG
5	NAGRA	11	GSL
6	NDA	12	BTECH

DOPAS

- WP1 Project Management and Coordination (Posiva)
- WP2 Definition of requirements and design basis of plugs and seals (SKB)
- WP3 Design and technical construction feasibility of plugs and seals (Andra)
- WP4 Appraisal of plugs and seals system´s function (NDA)
- WP5 Performance assessment of the plugs and seals systems (GRS)
- WP6 Integrative analysis of results (Posiva)
- WP7 Dissemination (Posiva)

- Experiment 1: FSS (BURE/FR) ANDRA & NAGRA
- Experiment 2: EPSP (URC Josef, CZ) RAWRA, CTU
- Experiment 3: DOMPLU (Äspö, SE) SKB, POSIVA
- Experiment 4: POPLU (ONKALO, FI) POSIVA, SKB, BTECH
- Experiment 5: ELSA, (tbd, DE) DBETEC, GRS, NRG

DOPAS

DOPAS addresses three candidate host rocks feasible for geological disposal in Europe i.e. salt, clay and crystalline rock.

The different types of plugs and seals under experimentation or under planned experimentation include

1. Full-scale deposition tunnel end plug (a hydro-mechanical plug) for the clay disposal environment (FSS demonstration experiment)
2. Half-scale experimental pressure and sealing plug (a hydro-mechanical plug) for tunnels in the crystalline disposal environment (EPSP experiment)
3. Full-scale deposition tunnel end plug (a hydro-mechanical plug) for the crystalline rock (SKB dome plug DOMPLU experiment)
4. Full-scale deposition tunnel end plug (a hydro-mechanical plug) for the crystalline rock (POPLU experiment)
5. Large-scale deep shaft seal experiment in salt dome environment (ELSA experiment).

DOPAS

WP2 - Definition of requirements and design basis of the plugs and seals to be demonstrated

DOPAS will develop a complete design basis for the engaged waste management programs. The prepared design basis will form the guidance for developing reference designs (i.e. designs which have the objective of performing in compliance to robust interpretation of results from the assessment of repository long-term safety).

Establishing the strategies for demonstrating compliance of designs to the design basis is expected to guide future work on the development of plugs and seals.

The main objectives are to:

- compile the design basis for the on-going and planned five demonstration experiment in DOPAS.
- develop reference designs for the same experiments.
- establish strategies for demonstrating the compliance of the reference designs to the design basis.

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WP3 - Design and technical construction feasibility of the plugs and seals

In DOPAS new and advanced designs will be developed and the WP3 includes the use of materials and machines in both new combinations for producing and installing the plugs' and seals' components.

These combinations are going to be tested in different ways, from computer simulations to full-scale *in-situ* demonstration.

The main objectives are to:

- (further) develop a comprehensive design basis for the in-situ demonstration experiments planned in the Czech Republic, Finland and France
- to carry out large/full-scale tests (EPSP, FSS) in URLs or mock-up drifts, and URCF ONKALO **(POPLU-Experiment)**
- to monitor full-scale demonstration **(DOMPLU-Experiment)** at Äspö HRL; and
- to address seal plug materials with respect to long-term behaviour, providing experimental data needed for numerical simulations in order to demonstrate material suitability.

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DOPAS

WP4 - Appraisal of plug and seal systems

Following construction and installation, monitoring systems will generate on-line data and planned experiment dismantling activities will supplement the knowledge base on plugs' and seals' initial state and evolution.
Data and other achievements will be used in evaluation of the observed performance against the predicted performance.

The objective of this Work Package is to assess and evaluate:

- the construction methodologies and technologies for plugs and seals (WP3)
- the results of the subsequent monitoring phase and the outcome of the dismantling activities to evaluate the predictions against the actual measured performance
- summarise the achievements made in design and the industrial scale implementation construction in the light of the specified required performance of plugs and seals as defined in WP2
- And to provide a basis and direct input for PA related activities carried out in WP5.

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WP5 – Performance assessment of the plugs and seals systems

The long-term safety assessment methodologies will be further developed. The results of this work package are cross-cutting to all of the experiment in their nature.

The objectives are defined as follows:

- process modelling of the experiments performed in WP3 to gain process understanding
- identify the main processes that are relevant and thus to be considered for predicting the short and long-term behaviour of the plug and sealing systems
- identify remaining uncertainties and their influence on performance assessment
- development and justification of conceptual models of plugs and seals for the different disposal concepts and geological environments
- simulation of processes and their evolution within individual sealing components
- further develop and apply the PA methodology and PA models for analysing the system behaviour.

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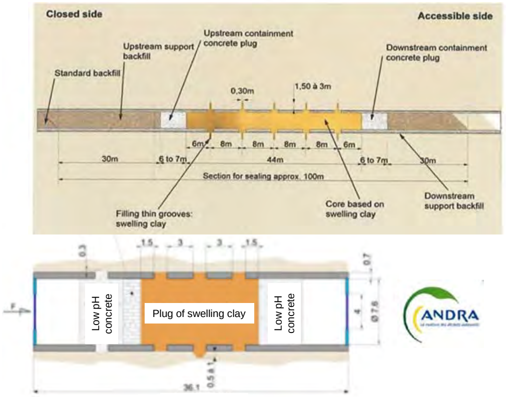
FSS - Experiment 1

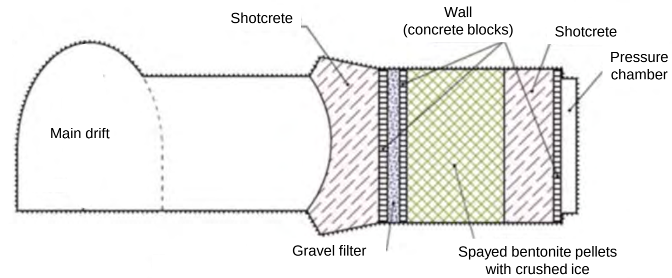
Andra's Full Scale Seal (FSS) project will be built inside a pre-existing drift or (more likely) inside a drift specifically excavated and prepared for the purpose.



Section BB

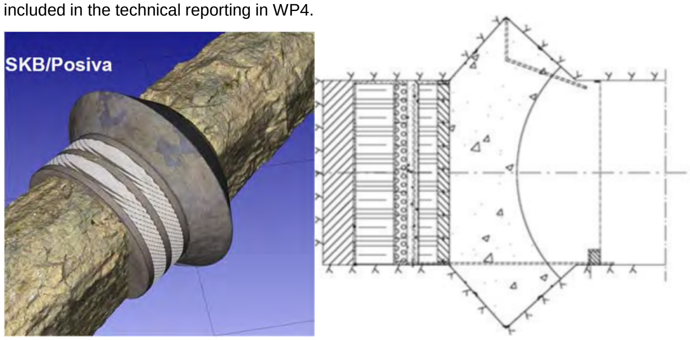
FSS - Experiment 2

Experimental Pressure and Sealing Plug (EPSP) Demonstrator will be constructed and operated in a small niche of the Josef Underground Laboratory. In the Czech reference concept, bentonite from Czech deposits and new developed low pH–concretes are foreseen. (RAWRA + CTU)



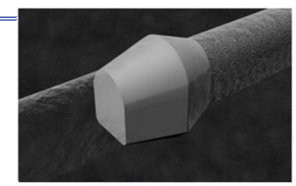
DOMPLU - Experiment 3

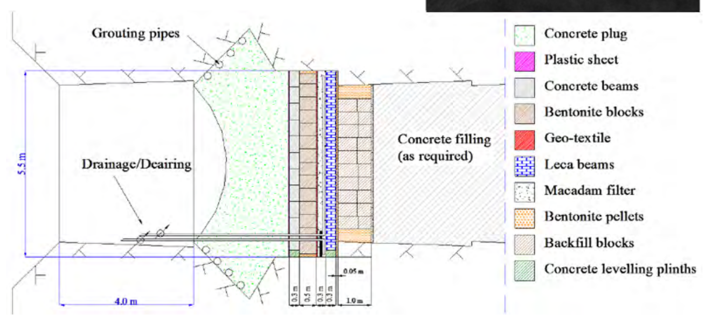
The design of the Swedish full-scale deposition tunnel end plug test was completed during 2011. The SKB full-scale dome-shaped plug demonstration (**DOMPLU**) with sealing parts takes place at the Äspö Hard Rock Laboratory (Oskarshamn, Sweden).
The installation already started in April, 2012. Consequently the installation of **DOMPLU** is not part of DOPAS, but SKB's experiences from installation and monitoring phases will be included in the technical reporting in WP4.



POPLU - Experiment 4

The primary objective of Posiva is the construction of a full-scale deposition tunnel plug experiment (**POPLU**) in ONKALO demonstration area including an installing of a monitoring system for studying the plug performance.





ELSA (Phase 3) - Experiment 5

Phase 1: (running)	Development of a safety assessment concept Identification of requirements, boundary conditions etc.
Phase 2: IGD-TP	Development of a technical shaft seal concept (Clay) Optimization of the preliminary shaft seal concept (Salt) Material development/selection and characterization (Lab tests) Further development and (in-situ) test of - compaction procedures or prefabricated blocks - injection procedures (EDZ) - accelerated buffer saturation Process level modelling to increase process understanding
Phase 3: IGD-TP	Large scale in-situ demonstration tests of individual functional components (sealing modules or supporting modules)

DOPAS

WP6 – Integrating analysis including cross-review of each other's work

This work package comprises a formal peer review to enhance the quality assurance of the outcomes and their integration for a wider use and knowledge building beyond the individual demonstrations.

The objectives are:
- to review the project results and ensure that the quality of the results are assured
- to provide possibility for expert staff exchange and enhance the integration between experiments
- to compile the lessons learned and experiences useful for implementing plugs and seals in various disposal concepts and high-lighting the future open questions related to plugs and seals

Conclusions

DOPAS - A project for full scale demonstration of plugs and seals

- is a collaborative EC-funded project of 12 European partners
- Start: October 2012
- End: September 2016

- DOPAS is part of a larger work area aimed at RD&D development of all IGD-TP plugs and seals components in an iterative manner. These components cover the needs in boreholes, shafts, ramps and tunnels for all types of candidate host rocks in IGD-TP's participants' countries.

- The aim in the RD&D development is that all future plugs and seals components can be developed to comply with the developed systematic manner and are based on the common know-how.

- The first end-user to apply these results beyond the on-going demonstrations is the ELSA experiment in its work phase 3.

Many thanks !

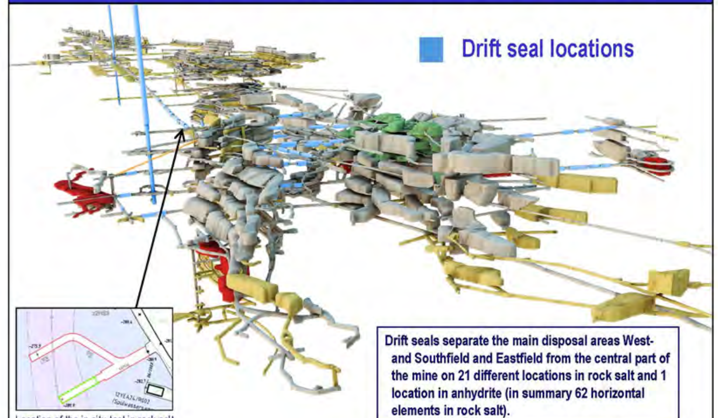
3rd US-German Workshop on Salt Repository Research, Design, and Operation - October 9 – 11, 2012, Albuquerque and Carlsbad, New Mexico, USA

In Situ Investigation of the Morsleben Drift Seal – Operating Experience and Preliminary Results[1)]

Ralf Mauke
Bundesamt für Strahlenschutz (BfS), Salzgitter
Federal Office for Radiation Protection
Department Safety of Nuclear Waste Management

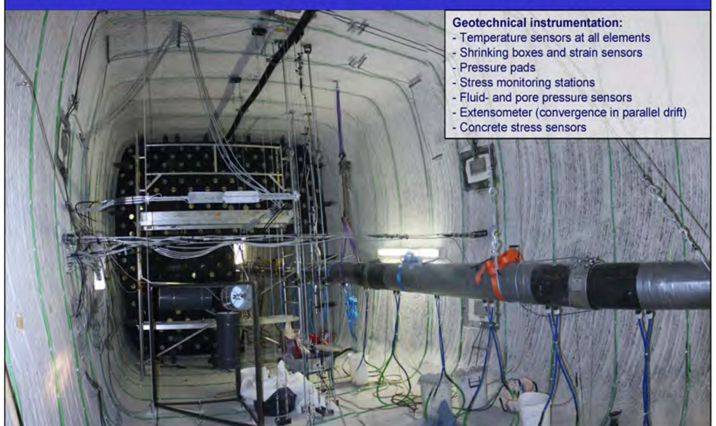
1) Continuation of presentation for 2nd US-German Workshop in Peine

Morsleben repository – closure concept and sealing measures



Location of the in situ-test in rock salt

In-situ Test - Impressions of Construction - Instrumentation



Geotechnical instrumentation:
- Temperature sensors at all elements
- Shrinking boxes and strain sensors
- Pressure pads
- Stress monitoring stations
- Fluid- and pore pressure sensors
- Extensometer (convergence in parallel drift)
- Concrete stress sensors

In-Situ Test – Current View of the Construction (09/2012)

Dimension of the construction: height: 4 to 5m, width: 4,5m, length: 25m
(This real full scale experiment represent a typical drift seal profile.)

Focal points reported on 2nd US/German workshop in Peine:

- Requirements on the drift seals in rock salt / objectives of the test
- Construction design and geotechnical measurements
- Site investigation program
- Operating experience of the instrumentation and the full-scale construction including grouting of the contact zone
- First preliminary results (i. a. temperature, deformation, stress measurement, permeability contact zone, pneumatic pre-Tests)

Main statement: Successful production of the in-situ test structure proofs its technical feasibility.

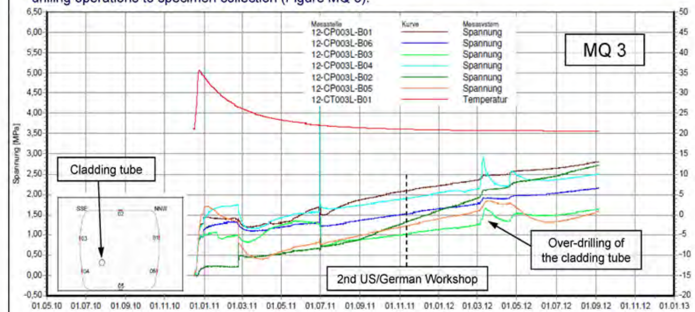
Further Investigation – since last presentation at 2nd Workshop

- **Continuation of the geotechnical measurements** – ongoing
- **Over-drilling and sealing of the cladding tube** – completed
- **Digital drill core imaging of the contact zone (core scanning)** – completed
- **Micro-section or thin section of core sample** – ongoing
- **Investigation program on core sample and in bore holes** – ongoing
- **Hydraulic pre-test** (24th February to 13th March 2012) – completed
- **Hydraulic main-test** (first period from 14th May to 22th August 2012) – ongoing
- **Numerical calculations to evaluate the overall functional tests and measurements** – ongoing

in situ Experiment - Continuation of the Stress Measurement

Stress Measurements - total of 22 Pressure Pads in the Contact Zone)

The current increase of the normal stresses in the contact zone are between 0.3 MPa and 2.6 MPa at MQ1 and MQ2 (near the pressure chamber), between 1.6 MPa and 2.8 MPa near the middle of the structure (MQ3) and between 3.3 MPa and 5.4 MPa at MQ4 (MP4 near the air-side is largely determined by stress redistributions due to the cross-sectional expansion of the drift for necessary drilling operations to specimen collection (Figure MQ 3).



Over-Drilling of the Cladding Tube

1st Step (see pictures above): Complete over-drilling of the injection tubes inside the cladding tube (successful execution)

2nd Step (see other pictures): over-drilling of the cladding tube made of steel (several trials required):

- 4 different drill bit constructions in use
- With a special milling crown (see below) the over-drilling of the steel tube could be executed to approx. 16.4 m

Consequence for further planning: replace steel pipe by better millable material (possibly using only temporary tube during the installation of injection tubes)

Sealing of the over-drilled Cladding Tube

Material: modified salt concrete (slightly modified additives e.g. barite powder to avoid autogenous shrinkage)

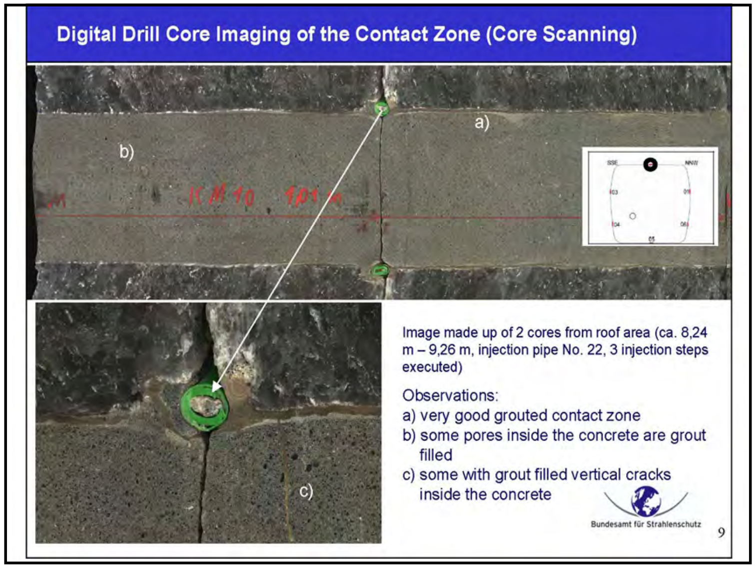
Backfilling: (see pictures above):

- Pumping with tremie method (first each 1,5m than each 3m)
- Continuous filling at the end with 6 bar overpressure

Observations:

Obviously the cladding tube bore hole has been sealed very good.

Additional investigations are ongoing (mechanical properties, permeability).


Digital Drill Core Imaging of the Contact Zone (Core Scanning)
a)
b)
c)
Image made up of 2 cores from roof area (ca. 8,24 m – 9,26 m, injection pipe No. 22, 3 injection steps executed)
Observations:
a) very good grouted contact zone
b) some pores inside the concrete are grout filled
c) some with grout filled vertical cracks inside the concrete
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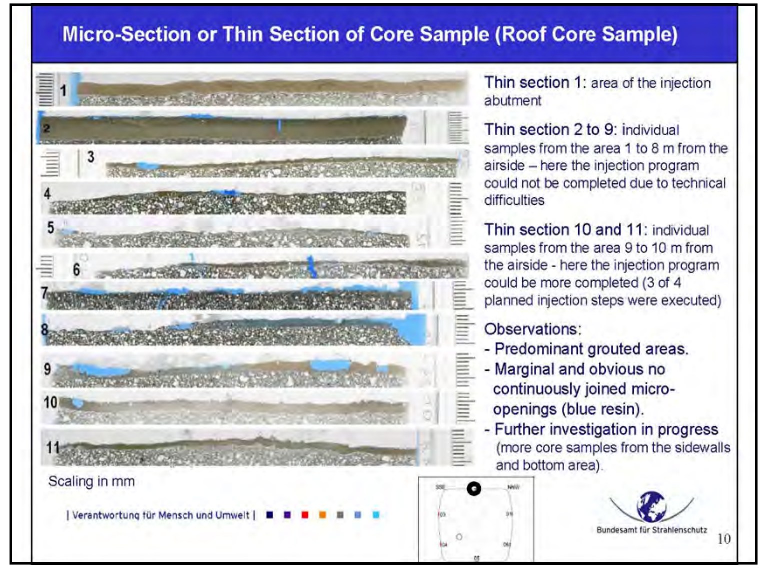
Micro-Section or Thin Section of Core Sample (Roof Core Sample)
1
2
3
4
5
6
7
8
9
10
11
Scaling in mm
Thin section 1: area of the injection abutment
Thin section 2 to 9: individual samples from the area 1 to 8 m from the airside – here the injection program could not be completed due to technical difficulties
Thin section 10 and 11: individual samples from the area 9 to 10 m from the airside - here the injection program could be more completed (3 of 4 planned injection steps were executed)
Observations:
- Predominant grouted areas.
- Marginal and obvious no continuously joined micro-openings (blue resin).
- Further investigation in progress (more core samples from the sidewalls and bottom area).
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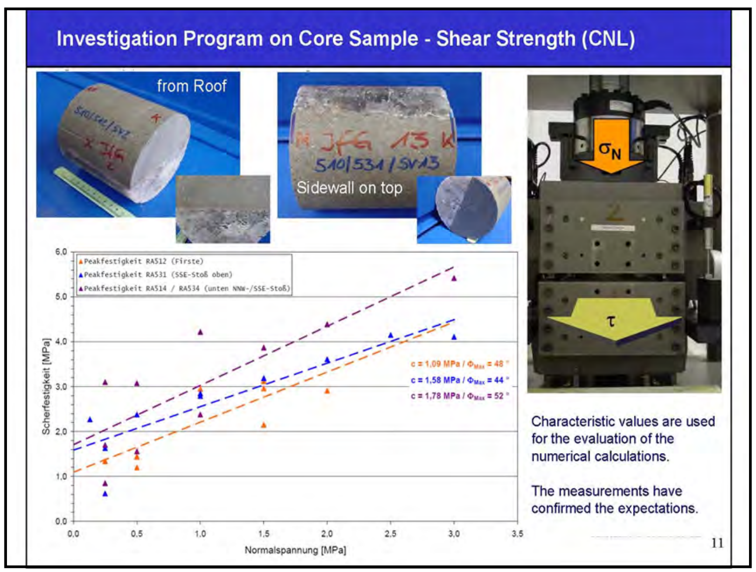
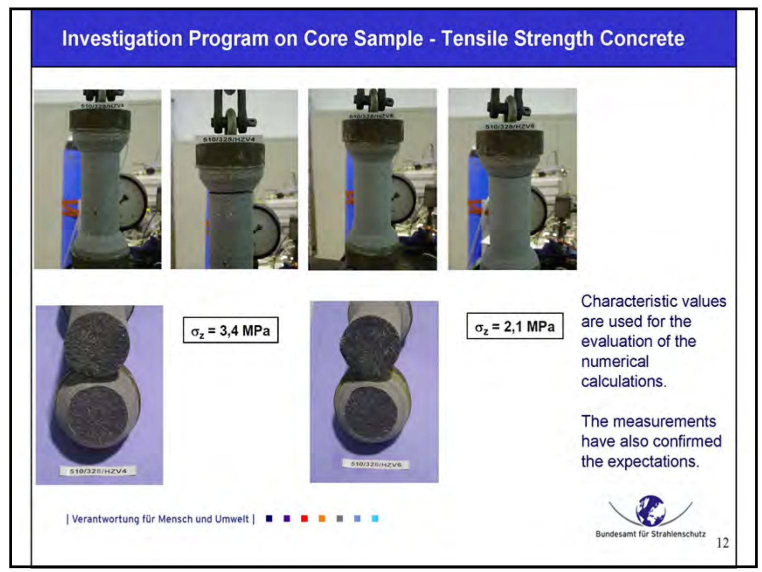

Investigation Program on Core Sample - Shear Strength (CNL)
from Roof
Sidewall on top
σ_N
τ
Scherfestigkeit [MPa]
Normalspannung [MPa]
c = 1,09 MPa / Φ_{Max} = 48 °
c = 1,58 MPa / Φ_{Max} = 44 °
c = 1,78 MPa / Φ_{Max} = 52 °
Characteristic values are used for the evaluation of the numerical calculations.
The measurements have confirmed the expectations.
11


Investigation Program on Core Sample - Tensile Strength Concrete
σ_z = 3,4 MPa
σ_z = 2,1 MPa
Characteristic values are used for the evaluation of the numerical calculations.
The measurements have also confirmed the expectations.
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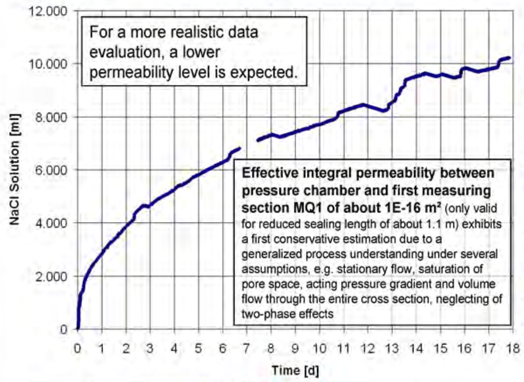
in situ Experiment - Hydraulic Pre-Test

Preliminary results of hydraulic pre-tests (24th February to 13th March 2012)
Main objectives: Start of saturation process and study of process performance



Constant pressure test: 0.1 MPa (at top of pressure chamber):

Decreasing flow rate at level below 1 ml / min.

Results:
- Adjustment of test equipment
- Evaluation of ongoing transient saturation and brine flow process
-Confirmation of volume estimation for the pressure chamber and the evaluation concept

The main test must be able to deal with low permeabilities !

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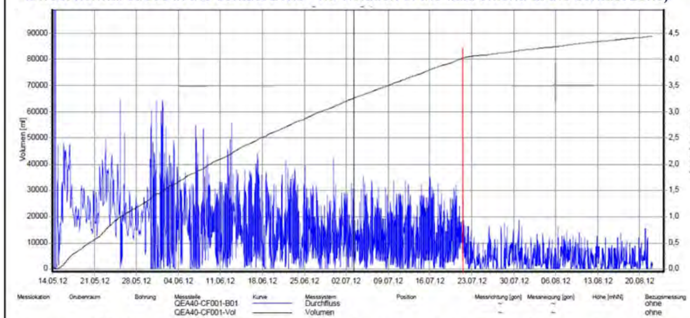
in situ Experiment - Hydraulic Main-Test (first period)

Main objectives: Investigation of the integral permeability (pressure level comparable with the lowest normal stress in the contact zone - no violation of the fluid criteria at the contact zone)



Increasing of fluid pressure to 0.3 MPa at the bottom of pressure chamber (70 days) then constant pressure test (duration: 1 month)

Observations: Decreasing flow rate at level below 0.5 ml / min (more sophisticated data evaluation including instationary flow processes is still pending)

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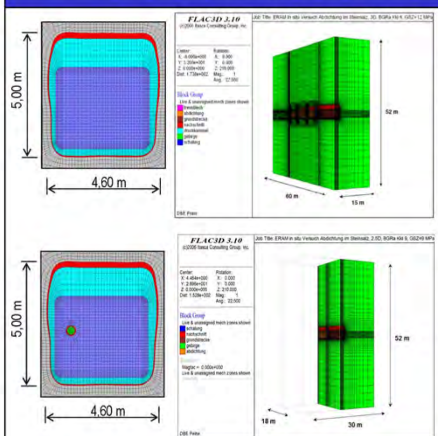
Numerical Calculations to Evaluate the Overall Functional Tests



Back-Analysis & Variations, Investigation of certain problems such as crack propagation

Extensive numerical calculation were carried out using different 3d and 2,5d models.

Procedure in the context of adaptation the in situ experiment:

1. Adaptation the thermal behavior
2. Adaptation the stress buildup on the contour and pressure loading rates – long term creeping
3. Adaptation the "early phase" of the salt concrete behavior (autogenous shrinkage with short-term creep - comparison with shrinkage boxes)
4. Adaptation other observations (e. g. crack evolution - Drucker-Prager bilinear, tensile bond strength, post-failure behavior)

Evaluation of the implemented constitutive model effects.

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Summary and Outlook

Successful production of the in-situ test structure proofs its technical Feasibility (see presentation of 2nd Workshop)

Some marginal technical improvements were identified (e. g. Replacing cladding tube material, using of more powerful injection pumps)

Low levels of integral permeability ≤ 1E-16 m² give evidence for required functionality (assumption from the concept design work was 1E-18 m²)

Next Steps:

- Preparation and evaluation of the overall functional tests and measurements until the end of 2012 (including documents for the licensing authority).
- The ongoing main permeability test is planned to be continued (possibly with higher pressures and over longer periods – some months or years)
- Review of tests results with the requirements on drift seals in rock salt
- If necessary re-evaluation of the long term safety assessments for the closure concept of the Morsleben repository (with the real reachable hydraulically properties of the drift seals)

Thank You for Your Attention !!!

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Exceptional service in the national interest

Sandia National Laboratories

FCT UFD Crushed Salt Mechanical Testing Results to Date

Frank Hansen
Scott Broome
Steve Bauer
Alex Urquhart

3rd US/German Workshop on Salt Repository Research, Design and Operations

Albuquerque, NM, USA

October 9-10, 2012

SAND 2012-8029P

Sandia National Laboratories | DBE TEC | PTKA | ENERGY | NNSA

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. SAND NO. 2012-XXXXP

Motivation for Studies

- Reconsolidation of crushed salt is an important physical phenomenon when backfilling or sealing nuclear waste repositories in salt.
- There is a renewed national and international interest in salt reconsolidation at elevated temperature, particularly as applied to disposal of heat-generating nuclear waste.
- Most salt reconsolidation studies have been at room temperature, with a few tests at elevated temperatures up to 100°C.
- Test Plan presents an experimental procedure for a laboratory study of reconsolidation of crushed salt, emphasizing testing at elevated temperature.

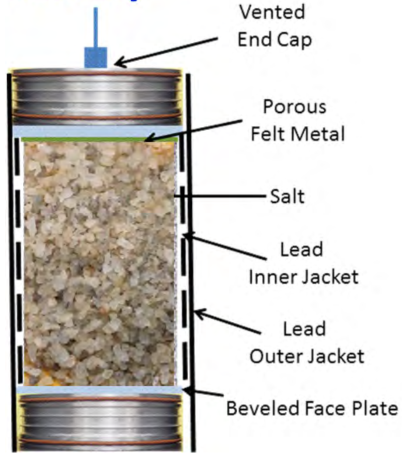
Approach

- Experiments designed to quantitatively evaluate consolidation as a f (σ. T).
- Determination of deformational processes by which the salt reconsolidates equally important.
- Laboratory studies intended to provide data representing consolidation behavior as a f (σ. T)up to 250˚C.
- The deformational processes are determined by optical and scanning electron microscopic examination of the deformed substructures.

Approach (Test Matrix)

Test Number	Test Type	T (°C)	Maximum Confining Pressure (MPa)	Stress Difference (MPa)	Axial Stress (MPa)	Mean Stress (MPa)	Description
7	Isostatic	250	20.0	0.0	20.0	20.0	Quasistatic
8/9	Isostatic/Shear	250	10.0	10.0	20.0	13.33	Quasistatic
1/10-16	Isostatic/Shear	100	2.5	2.50/5.0	5.0/7.5	3.33/4.17	Quasistatic-Creep
2/11-17	Isostatic/Shear	100	5.0	2.50/5.0	7.5/10.0	5.83/6.67	Quasistatic-Creep
3/12-18	Isostatic/Shear	175	2.5	2.50/5.0	5.0/7.5	3.33/4.17	Quasistatic-Creep
4/13-19	Isostatic/Shear	175	5.0	2.50/5.0	7.5/10.0	5.83/6.67	Quasistatic-Creep
5/14-20	Isostatic/Shear	250	2.5	2.50/5.0	5.0/7.5	3.33/4.17	Quasistatic-Creep
6/15-21	Isostatic/Shear	250	5.0	2.50/5.0	7.5/10.0	5.83/6.67	Quasistatic-Creep

Sample Assembly

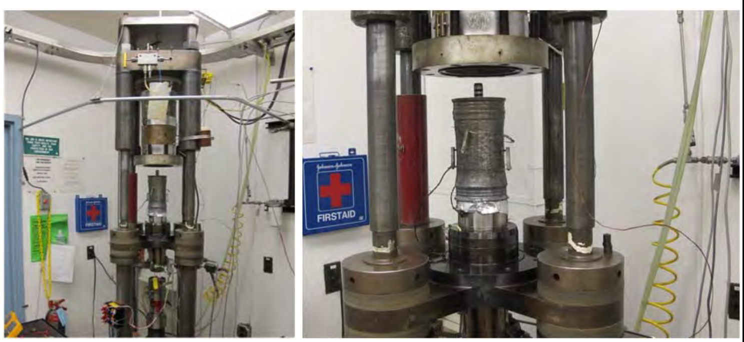


Experimental Setup

Pretest

Post test

Experimental Setup



Challenges and Observations

- Jacket leaks were problematic at 250˚C
- Intermediate thin copper shim (0.005") used as a soft barrier between lead jackets

Challenges and Observations

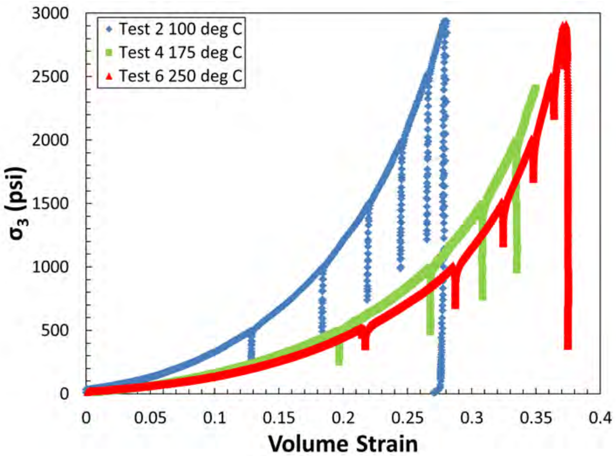
- Water was observed existing sample vent hole on 250˚C tests during heating
- This observation begs the question of the potential for a dry environment for high level waste disposal in (this) bedded salt

Summary of Tests Completed to Date

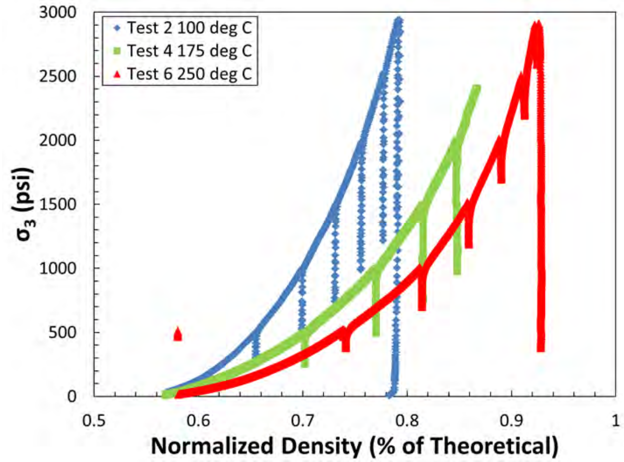
Test number (Scientific Notebook number sequence)	Date of test	Sample ID	Total ε_V (%)	Normalized Density (% of theoretical)	Confining pressure obtained (psi)	Tests satisfied from test matrix
2	6/28/2011	FCT-CS-HQ-100-02	28	79	2900	1,2
3	7/6/2011	FCT-CS-HQ-250-01	29, Leak	78, Leak	800	5,6
4	7/12/2011	FCT-CS-HQ-175-01	35	87	2400	3,4
5	1/19/2012	FCT-CS-HQ-175-02	N/A piston contacted sample early			None
6	3/15/2012	FCT-CS-HQ-250-02	37	93	2900	5,6,7,8
7	4/4/2012	FCT-CS-SQ-250-01	31,σ_C*	84,σ_C*	1450	8
8	5/1/2012	FCT-CS-SQ-250-02	37	93	1450	9
9	5/8/2012	FCT-CS-CR-250-01	33	86	363	14,20
10	5/23/2012	FCT-CS-CR-250-02				None (leak)
11	6/19/2012	FCT-CS-CR-250-03				None (leak)
12	6/27/2012	FCT-CS-CR-250-04				None (leak)
13	7/3/2012	FCT-CS-CR-175-01	31	86	363	12,18
14	7/11/2012	FCT-CS-CR-175-02	32	85	725	13,19
15	7/23/2012	FCT-CS-CR-100-01	19	73	363	10,16 second stage creep not run
16	7/24/2012	FCT-CS-CR-250-05	40	94	725	15,21
17	7/27/2012	FCT-CS-CR-100-02	26	77	363	10,16
18	8/9/2012	FCT-CS-CR-100-03	33	86	725	11,17

*Values obtained after hydrostatic compaction and are not available after the shear stage.

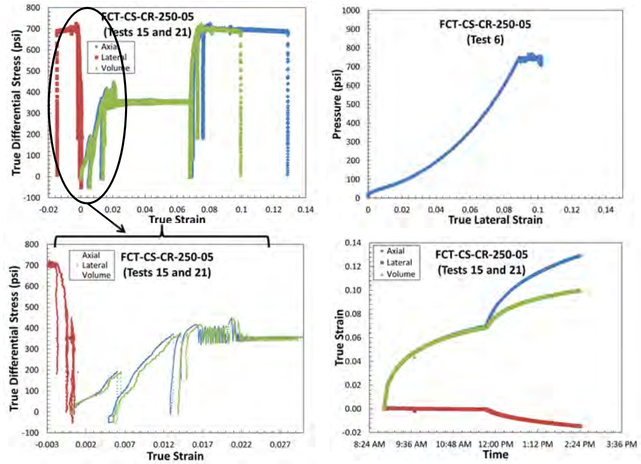
Pressure versus Volume Strain



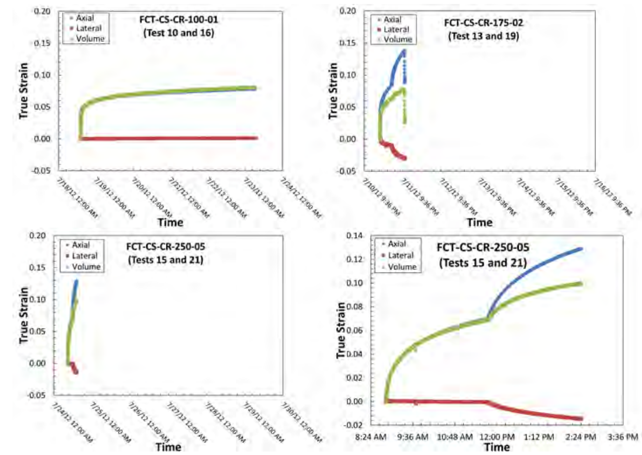
Pressure versus Fractional Density



250˚C Staged Test Results



ε_V versus time; staged tests



Microprocesses of Reconsolidation

- Samples cut in half, then quartered with a low damage wire saw
- "Thick" optical slides were made for most material
- Freshly broken faces were coated and examined in the SEM
- Individual crystals were cleaved and etched in some cases

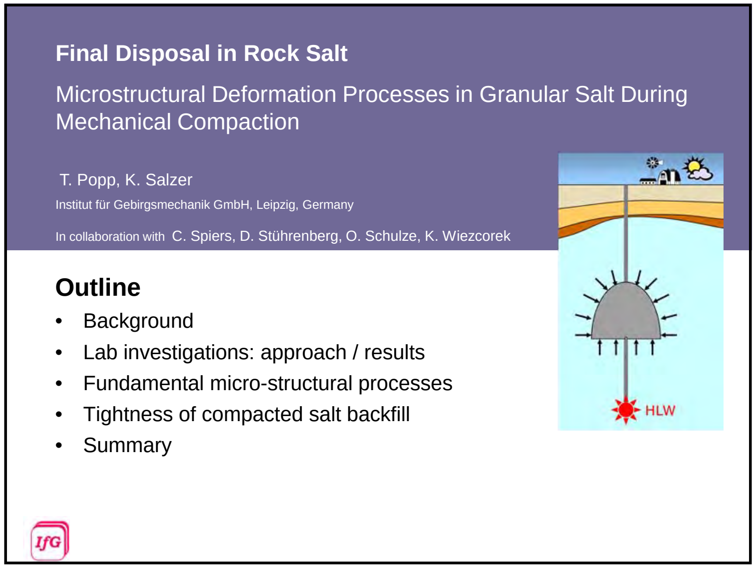
100ºC 250ºC

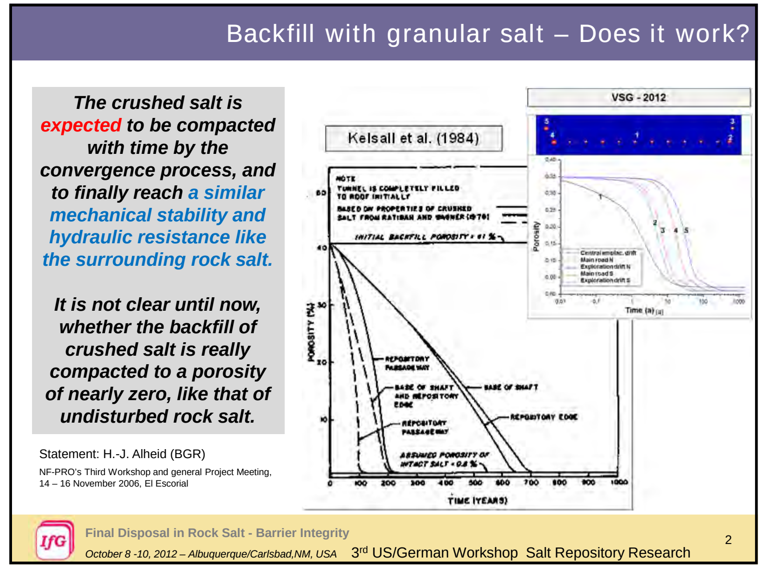
Conclusions

- Hydrostatic tests
- Pressure versus εV
- Pressure versus Fractional Density
- Multistage hydrostatic and shear (quasistatic and creep) tests completed
- Differential stress versus strain

- Final εV and fractional density linked to post test microscopy
- Data will be fit to the Callahan model

- Experimental work is ongoing


Final Disposal in Rock Salt
Microstructural Deformation Processes in Granular Salt During Mechanical Compaction
T. Popp, K. Salzer
Institut für Gebirgsmechanik GmbH, Leipzig, Germany
In collaboration with C. Spiers, D. Stührenberg, O. Schulze, K. Wiezcorek
Outline
• Background
• Lab investigations: approach / results
• Fundamental micro-structural processes
• Tightness of compacted salt backfill
• Summary
HLW
IfG


Backfill with granular salt – Does it work?
The crushed salt is expected to be compacted with time by the convergence process, and to finally reach a similar mechanical stability and hydraulic resistance like the surrounding rock salt.
It is not clear until now, whether the backfill of crushed salt is really compacted to a porosity of nearly zero, like that of undisturbed rock salt.
Statement: H.-J. Alheid (BGR)
NF-PRO's Third Workshop and general Project Meeting, 14 – 16 November 2006, El Escorial
Kelsall et al. (1984)
VSG - 2012
POROSITY (%)
TIME (YEARS)
Porosity
Time (a)
IfG
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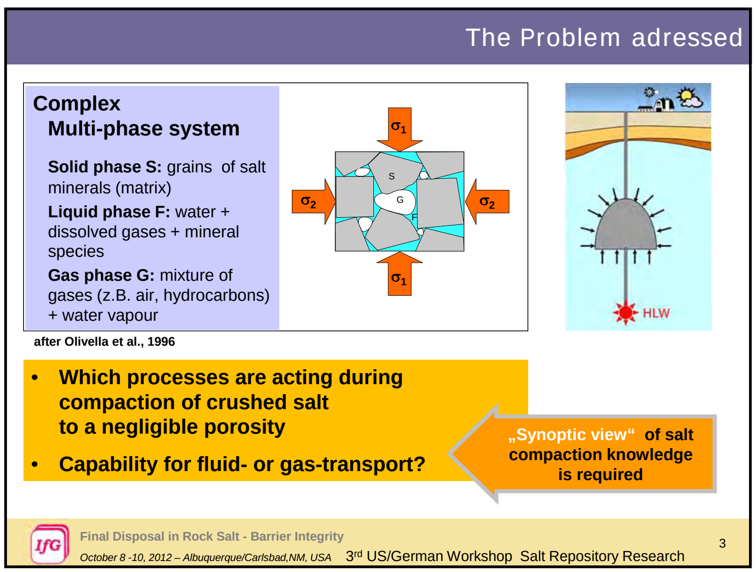
2


The Problem adressed
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
σ1
σ2
σ2
σ1
S
G
F
HLW
after Olivella et al., 1996
• 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
IfG
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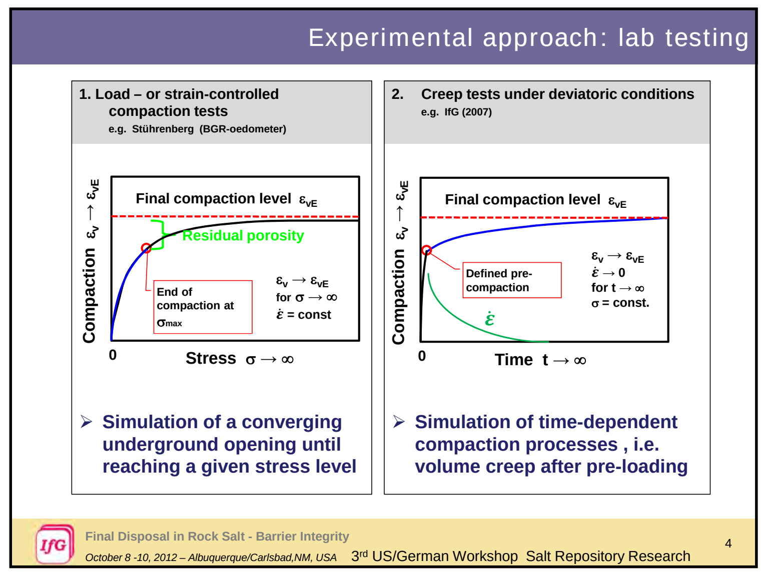
Experimental approach: lab testing
1. Load – or strain-controlled compaction tests
e.g. Stührenberg (BGR-oedometer)
2. Creep tests under deviatoric conditions
e.g. IfG (2007)
Final compaction level εvE
Residual porosity
End of compaction at σmax
εv → εvE for σ → ∞ ε̇ = const
Compaction εv → εvE
0
Stress σ → ∞
Final compaction level εvE
Defined pre-compaction
εv → εvE ε̇ → 0 for t → ∞ σ = const.
ε̇
Compaction εv → εvE
0
Time t → ∞
➢ Simulation of a converging underground opening until reaching a given stress level
➢ Simulation of time-dependent compaction processes , i.e. volume creep after pre-loading
IfG
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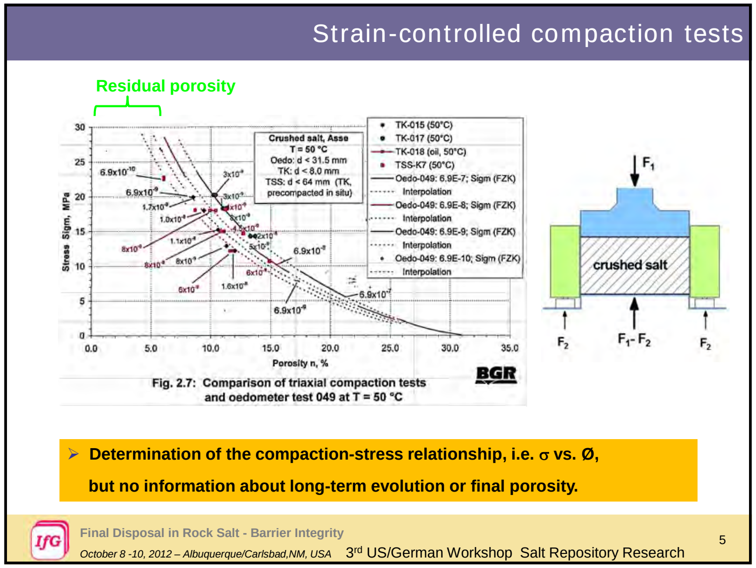
4


Strain-controlled compaction tests
Residual porosity
crushed salt
Fig. 2.7: Comparison of triaxial compaction tests and oedometer test 049 at T = 50 °C
BGR
Determination of the compaction-stress relationship, i.e. σ vs. Ø, but no information about long-term evolution or final porosity.
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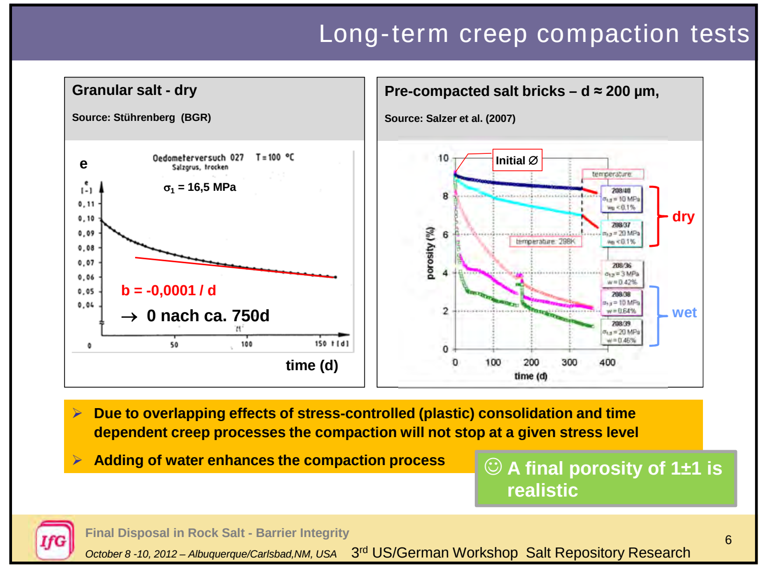
Long-term creep compaction tests
Granular salt - dry
Source: Stührenberg (BGR)
b = -0,0001 / d
→ 0 nach ca. 750d
time (d)
Pre-compacted salt bricks – d ≈ 200 µm,
Source: Salzer et al. (2007)
Initial Ø
dry
wet
Due to overlapping effects of stress-controlled (plastic) consolidation and time dependent creep processes the compaction will not stop at a given stress level
Adding of water enhances the compaction process
☺ A final porosity of 1±1 is realistic
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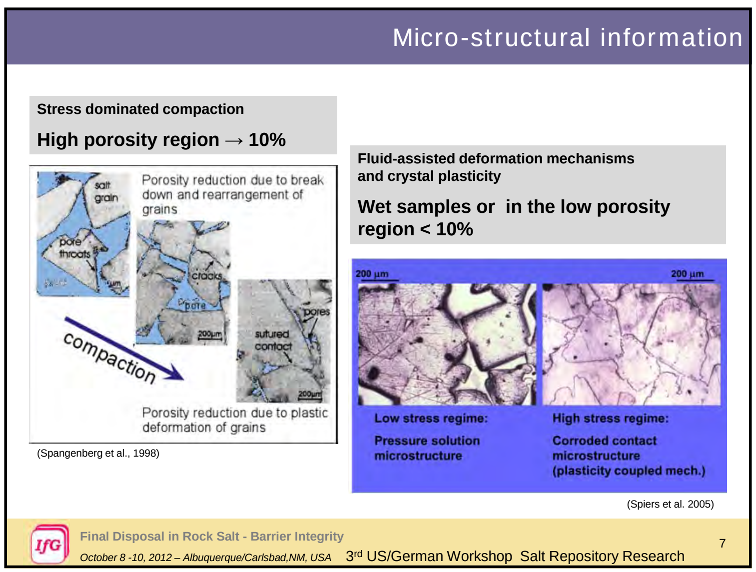
Micro-structural information
Stress dominated compaction
High porosity region → 10%
Porosity reduction due to break down and rearrangement of grains
compaction
Porosity reduction due to plastic deformation of grains
(Spangenberg et al., 1998)
Fluid-assisted deformation mechanisms and crystal plasticity
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)
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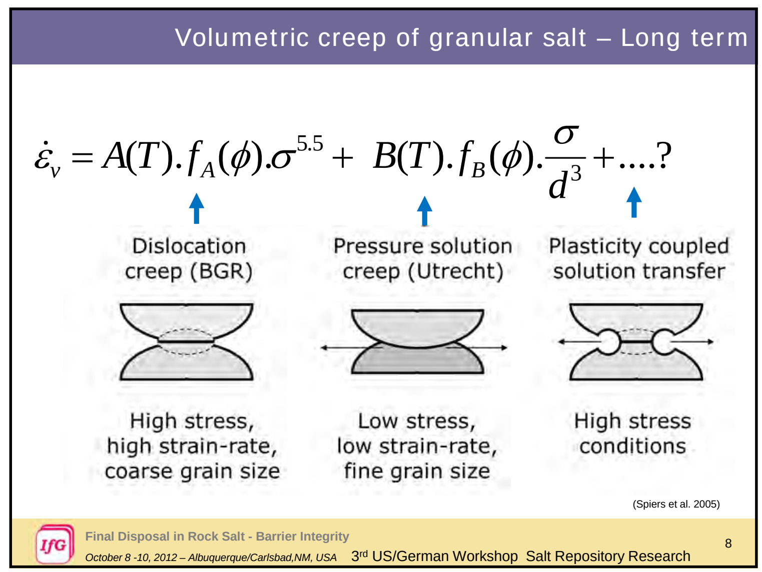
Volumetric creep of granular salt – Long term
$\dot{\varepsilon}_v = A(T).f_A(\phi).\sigma^{5.5} + B(T).f_B(\phi).\frac{\sigma}{d^3} + ...?$
Dislocation creep (BGR)
Pressure solution creep (Utrecht)
Plasticity coupled solution transfer
High stress, high strain-rate, coarse grain size
Low stress, low strain-rate, fine grain size
High stress conditions
(Spiers et al. 2005)
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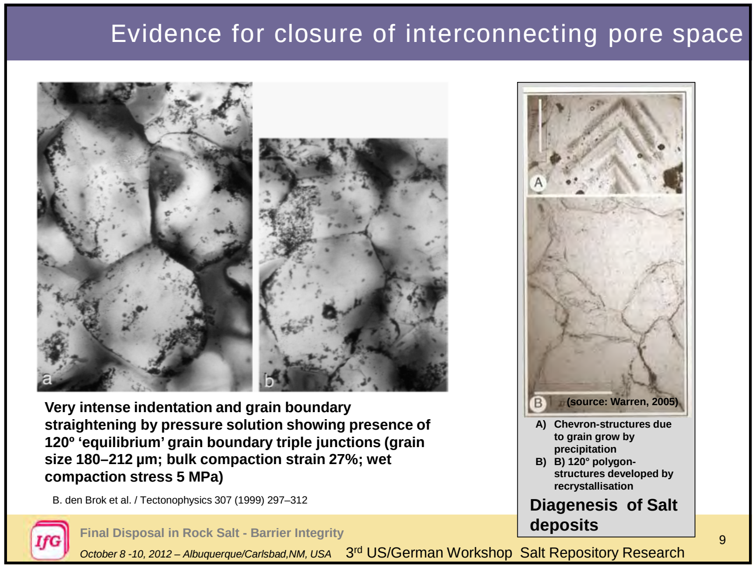
Evidence for closure of interconnecting pore space
Very intense indentation and grain boundary straightening by pressure solution showing presence of 120° 'equilibrium' grain boundary triple junctions (grain size 180–212 µm; bulk compaction strain 27%; wet compaction stress 5 MPa)
B. den Brok et al. / Tectonophysics 307 (1999) 297–312
(source: Warren, 2005)
A) Chevron-structures due to grain grow by precipitation
B) B) 120° polygon-structures developed by recrystallisation
Diagenesis of Salt deposits
Final Disposal in Rock Salt - Barrier Integrity
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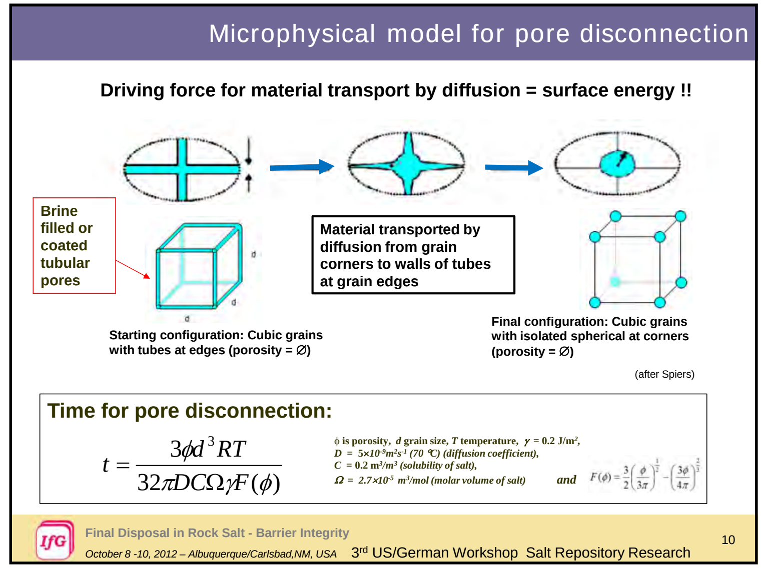
Microphysical model for pore disconnection
Driving force for material transport by diffusion = surface energy !!
Brine filled or coated tubular pores
Material transported by diffusion from grain corners to walls of tubes at grain edges
Starting configuration: Cubic grains with tubes at edges (porosity = ∅)
Final configuration: Cubic grains with isolated spherical at corners (porosity = ∅)
(after Spiers)
Time for pore disconnection:
$t = \frac{3\phi d^3 RT}{32\pi DC\Omega\gamma F(\phi)}$
ϕ is porosity, d grain size, T temperature, γ = 0.2 J/m²,
D = 5x10⁻⁹m²s⁻¹ (70 °C) (diffusion coefficient),
C = 0.2 m³/m³ (solubility of salt),
Ω = 2.7x10⁻⁵ m³/mol (molar volume of salt)
and
Final Disposal in Rock Salt - Barrier Integrity
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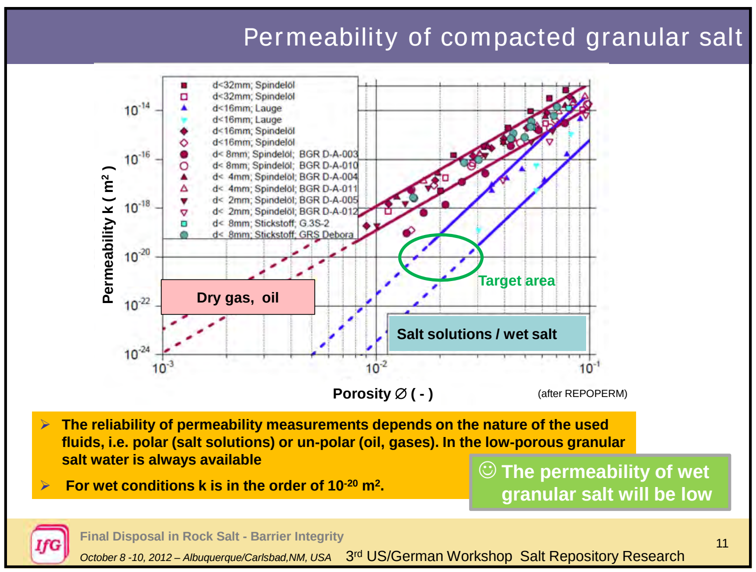
Permeability of compacted granular salt
Permeability k (m²)
Porosity ∅ (-)
(after REPOPERM)
Target area
Dry gas, oil
Salt solutions / wet salt
The reliability of permeability measurements depends on the nature of the used fluids, i.e. polar (salt solutions) or un-polar (oil, gases). In the low-porous granular salt water is always available
For wet conditions k is in the order of 10⁻²⁰ m².
☺ The permeability of wet granular salt will be low
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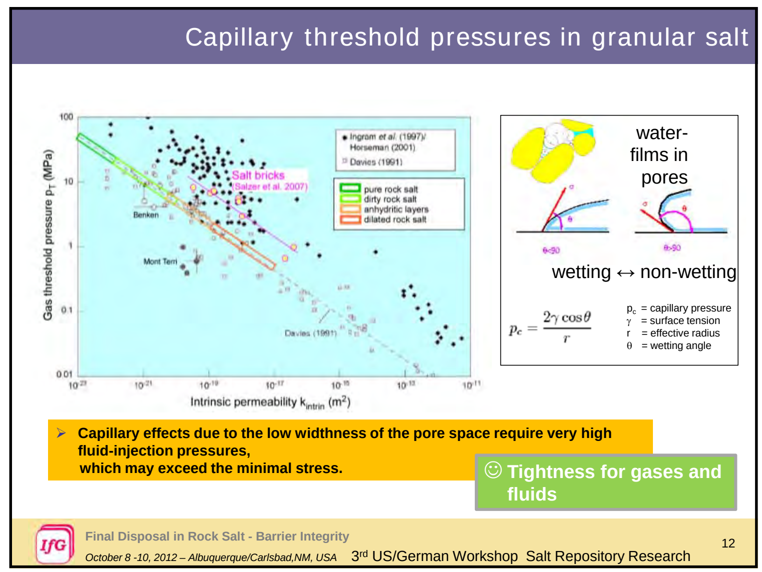
Capillary threshold pressures in granular salt
Gas threshold pressure p_T (MPa)
Intrinsic permeability k_intrin (m²)
Salt bricks
pure rock salt
dirty rock salt
anhydritic layers
dilated rock salt
water-films in pores
wetting ↔ non-wetting
$p_c = \frac{2\gamma\cos\theta}{r}$
p_c = capillary pressure
γ = surface tension
r = effective radius
θ = wetting angle
Capillary effects due to the low widthness of the pore space require very high fluid-injection pressures, which may exceed the minimal stress.
☺ Tightness for gases and fluids
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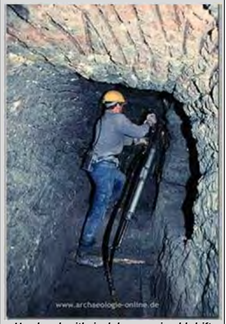
Natural analogues



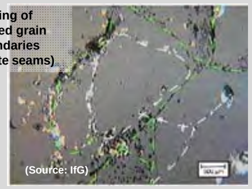
Headwork with jack-hammer in old-drifts in the salt mine Dürnberg (A)

Bronze age rock salt mining in Austria

„Heidengebirge“ 6. - 4. B.C.

Convergence of old back-filled drifts

Healing of dilated grain boundaries (white seams)



Healing of damage / EDZ (Ø = some few %)

A) Chevron-structures due to grain grow by precipitation
B) B) 120° polygon-structures developed by recrystallisation

Diagenesis of Salt deposits

Lessons learned

The actual knowledge gives confidence,

that granular salt

- **will compact to a final porosity in the order of $1^{\pm 1}$ % within less than 1000 a**
- **will be tight against gases and fluids**

☺ Time-dependent volumetric creep (enhanced by water) results in a fast porosity reduction (e.g. due to dislocation or pressure-solution creep)

→ **comprehensive understanding of the acting micro-structural deformation mechanisms** (benefitted mostly from the work of Spiers, Urai)

☺ The permeability, measured with brine on highly compacted samples is low and, in addition, capillary threshold effects will prevent fluid mobility

☺ **Natural analogues** exist (e.g. diagenesis of salt deposits, healing of damage)

But as the remaining challenge,

it is important that the mechanistic understanding and empirical data gained to date lead to a consensus on constitutive models for compaction that can be reliably extrapolated to in-situ conditions

BGR GRS

Recent Experimental and Modeling Results on Crushed Salt Consolidation

Klaus Wieczorek, Oliver Czaikowski, Chun-Liang Zhang, GRS
Dieter Stührenberg, BGR

3rd US/German Workshop on Salt Repository Research, Design and Operations
Albuquerque and Carlsbad, New Mexico, USA
October 8-10, 2012

BGR GRS

Introduction

Crushed salt backfill is expected to take an important barrier function in a salt repository in the long term. After compaction, we expect that the porosity and permeability of the backfill will be low enough to take the barrier role. An immediate question is

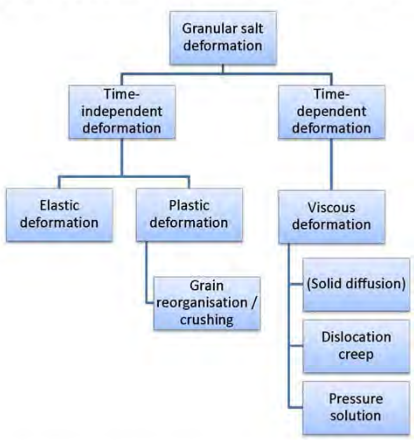
- Is the required low-permeability state reached, and how long does it take to reach it? What is the corresponding porosity range?

Presentation Structure

- Deformation mechanisms and controlling factors
- Experiment types
- Recent results of deformation rate controlled tests
- Load controlled tests and model calibration
- Summary of current state

BGR GRS

Deformation mechanisms of granular salt



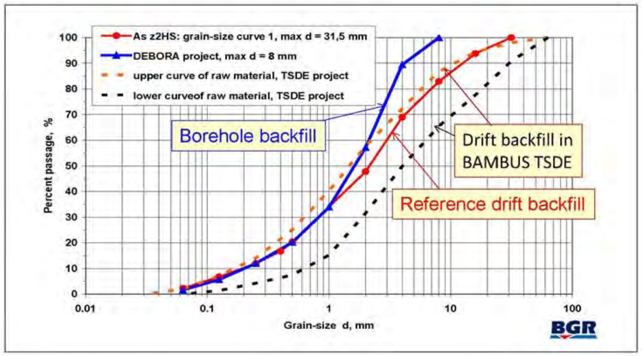
Controlling factors:

- Stress/strain state
- Temperature
- Material composition (Grain size distribution)
- Solution content

Simplified after: Popp, T.; Salzer, K.; Schulze, O.; Stührenberg, D.; Hydro-mechanische Eigenschaften von Salzgrusversatz – Synoptischen Prozessverständnis und Datenbasis, Memorandum IFG –BGR, 30.05.2012.

BGR GRS

Grain size distributions of investigated backfill samples



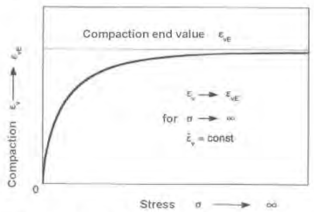
Compaction experiment types

Experiments can be classified by the type of load application

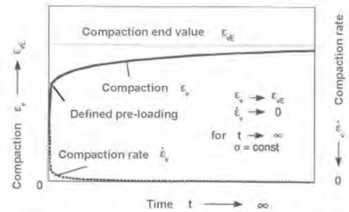
- Triaxial tests – well defined stress state, complicated
- Oedometer (inhibited lateral strain) tests – less complicated, stress uncertainty

Or by experiment control

- Deformation rate controlled tests (BGR)
- Load controlled tests (GRS)



Deformation rate controlled tests



Load controlled tests

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Experimental philosophy and evaluation procedure

- Deformation rate controlled tests:
  - Determination of backfill resistance (stress build-up in the backfill) at different compaction rates possible in the lab and extrapolation to lower (in situ) rates
  - Estimation of compaction rates at in situ stress as a function of compaction state
- Load controlled tests (creep tests):
  - Evolution of compaction rate at constant load (different load steps)
  - Calibration of compaction models
- Special issues of both types of test:
  - Time required to reach low porosity at relevant compaction rates / loads
  - Uncertainty of porosity determination (deriving from density uncertainty)

Note: In situ behavior involves both changing deformation rate and stress:

- *Early phase, high porosity: compaction will be governed by convergence rate (deformation rate control)*
- *Later phase, lower porosity: compaction will be governed by effective stress*

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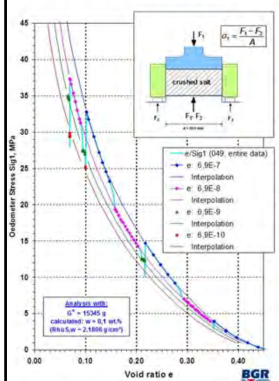
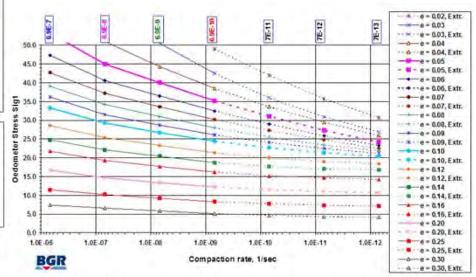
Evaluation example for a deformation rate controlled test



Oedometer stress as a function of void ratio



Oedometer stress as a function of compaction rate for different void ratios

Oedometer test 049, T = 50 °C, crushed salt Asse z2HS, d_{max} = 31.5 mm

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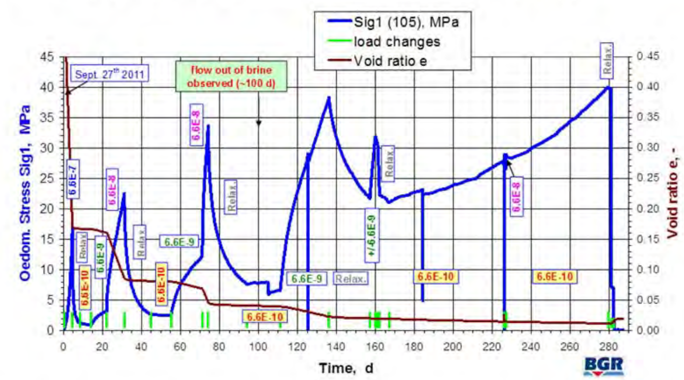
Test history of a new oedometer test with 1 wt.% solution content



Oedometer test 105, T = 33 °C, $\sigma_1 = f(t)$, crushed salt Asse z2HS-SP + 1 wt.% saturated brine, d_{max} = 8.0 mm

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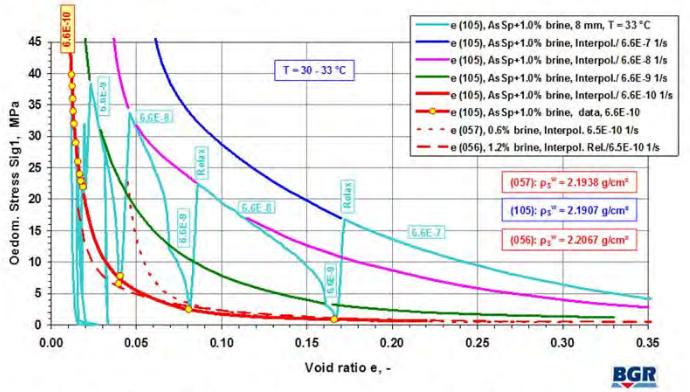
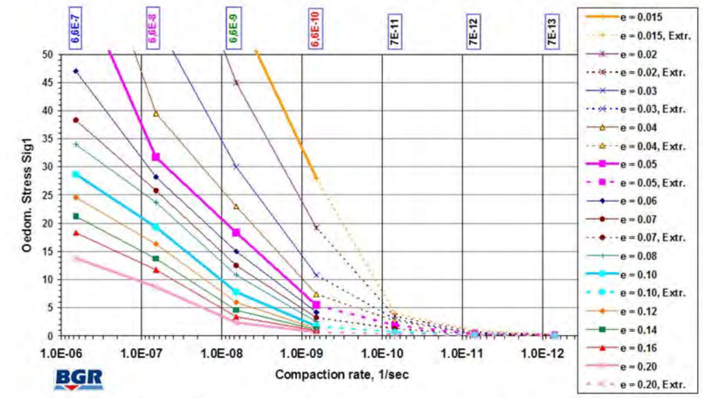
Test evaluation in terms of backfill resistance as a function of void ratio



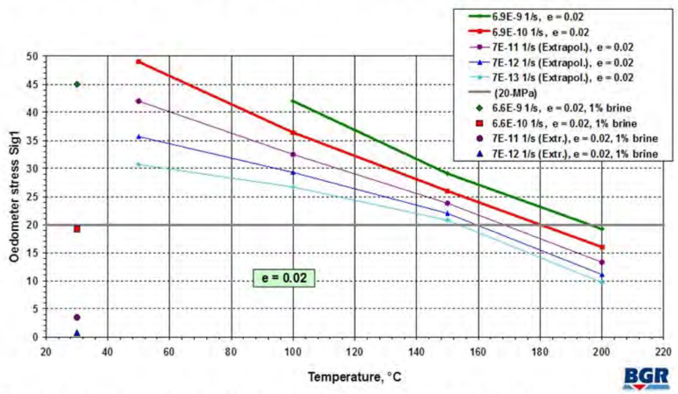
Oedometer test 105, T = 33 °C, $\sigma_1 = f(e)$, crushed salt Asse z2HS-SP + 1 wt.% saturated brine, d_{max} = 8.0 mm

Extrapolation of backfill resistance for lower compaction rates



Oedometer test 105, T = 33 °C, $\sigma_1 = f(\dot{\varepsilon})$, crushed salt Asse z2HS-SP + 1 wt.% saturated brine, d_{max} = 8.0 mm

Influence of temperature on backfill resistance for different void ratios



Different Oedometer tests, $\sigma_1 = f(T)$, crushed salt Asse z2HS dry / Asse z2HS-SP + 1 wt.% saturated brine, d_{max} = 31.5 mm / d_{max} = 8.0 mm

Load controlled tests and model calibration

- Load controlled tests appear more suitable for model calibration, because they allow the distinction between time-independent and viscous behavior, especially for multistep loading

  Problem: Time needed to achieve low porosity at relevant stress states

- Recent material models for crushed salt behavior
  - WIPP model
  - Hein's model
  - Zhang's model (empirical creep compaction model)
  - CODE_BRIGHT model (combination of elasticity, visco-plasticity, dislocation creep, and fluid assisted diffusional transfer)

Zhang's model (1993)

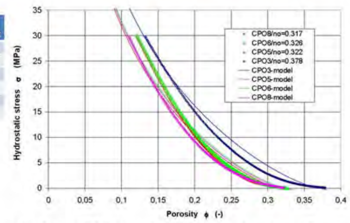
- Relates the volumetric strain rate to compaction pressure and compaction state

$$\dot{\varepsilon}_v = A \exp\left(\frac{-Q}{RT}\right)\left(\frac{P_o}{P_a}\right)^n \left[\ln\left(\frac{\phi_o}{\phi_o - \varepsilon_v}\right)\right]^{-m}$$

- Was first calibrated on moist dump salt, other parameter sets for different types of crushed salt

Test type	GRS triaxial test	GRS triaxial test	BGR oedometer test	BGR oedometer test
Grain size d	< 2 mm	< 8 mm	< 31 mm	< 0.125 mm
ϕ_o	0.26 – 0.32	0.32 – 0.37	0.31	0.48
A (1/s)	$2*10^{-6}$	$2*10^{-5}$	1.4	$3.3*10^{-5}$
Q (kJ/mole)	96	96	156	133
n	13	13	14.3	15
m	17	17	17	21.7

- Minimum porosities in the experiments for calibration always above 10 %



Calibration example from GRS triaxial tests, grain size < 8 mm

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CODE_BRIGHT model (currently in calibration)

CODE_BRIGHT – COupled DEformation of BRIne Gas and Heat Transport (UPC)

- 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 behavior
  - Elastic stiffness increases with decreasing porosity
- Dislocation creep
  - 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
  - Viscoplastic deformation of the grain aggregate (grain re-organisation & crushing)
    - In CODE_BRIGHT, a time-dependent approach is used
- Fluid assisted diffusional transfer (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)*

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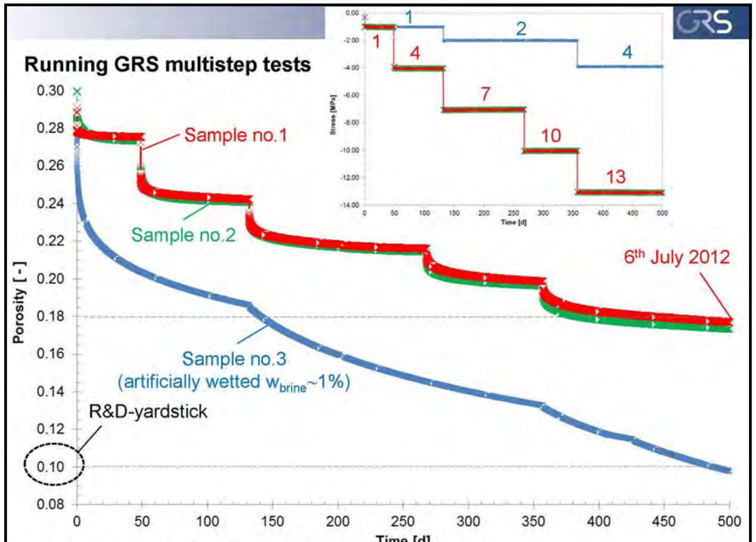
Running GRS multistep tests



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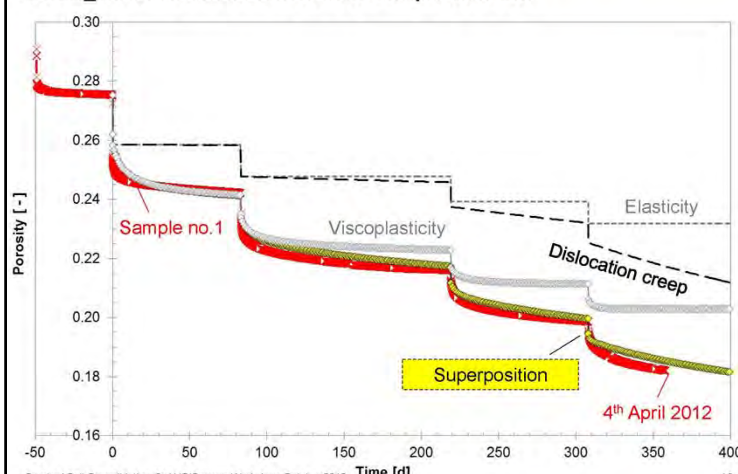
CODE_BRIGHT simulation of dried sample behavior



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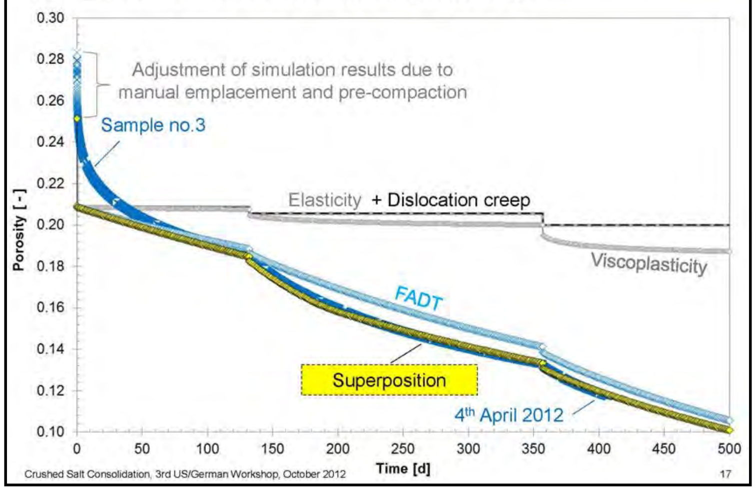
CODE_BRIGHT simulation of dried sample behavior



Summary of current state

Results from compaction rate controlled testing

- With dry crushed salt at ambient temperature, compaction rates in situ may become so small that sufficient compaction may not be reached within a reasonable time scale.
- Elevated temperature reduces backfill resistance, increasing compaction rates.
- A small solution content in the range of 1 wt.% is even more effective for reducing backfill resistance.

Results from load controlled testing and model calibration

- Zhang's model and CODE_BRIGHT have been or are currently calibrated, but the calibration is not (yet) confirmed for porosities below 10 %.
- Additional calibration work (besides low porosity) is needed to capture temperature effects and variations in grain size distribution.

Remaining Issues

- Uncertainty in porosity determination
- Assessment of permeability / porosity relation of crushed salt compacted under relevant conditions

The presented work was funded by the German Federal Ministry of Economics and Technology (BMWi) under the contracts no. 02E10477 and 02E10740 (REPOPERM), parts also by BMWi (02E9269) and EC (FIKW-CT-2000-00051) in BAMBUS-II.

DBE TEC DBE TECHNOLOGY GmbH | Sandia National Laboratories | Projektträger Karlsruhe

Crushed Salt Model Regions of Influence

Gary Callahan, PhD, PE
3rd US/German Workshop on Salt Repository Research, Design, and Operations
SAND2013-1230C

Albuquerque and Carlsbad, New Mexico, USA, October 8 - 10, 2012

ENERGY NNSA

Deformation Evolution

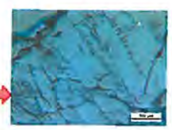
- Crushed Salt Used as Repository Shaft Seal Material and/or Room Backfill Material

→ *Crushed Salt* → *Granular Salt* → *Disaggregated Salt* → *Salt Particles* → *Mine Run Salt*	*Stress* *Temperature* *Time*	→ *Intact Salt* → *Solid Salt* → *Rock Salt* → *Reconsolidated*
Volumetric	*Volumetric + Shear*	*Shear*
$D=\frac{\rho_0}{\rho_f}=0.60$	$D=\frac{\rho}{\rho_f}$	$D=\frac{\rho_f}{\rho_f}=1.0$
$\phi=1-D=0.40$	$\phi=1-D$	$\phi=1-D=0.0$

Crushed Salt Deformation Mechanisms

- Particle Rearrangement
  - Time-Independent Sliding, Breaking, Crushing
  - Nonlinear elastic model
  - BAMBUS II (20.7% Porosity, K = 4.17e-13 m^2)

- Dislocation Creep
  - Well Established for Intact Salt
  - M-D Model [Munson et al., 1989]
  - Inclusion Motion Distorted by Dislocation Creep (250°C, Shear Consolidation, ε_v=37%)



- Grain Boundary Diffusional Pressure Solution
  - Fluid Phase Must be Present
  - Pressure Solution [Spiers and Brzesowsky, 1993]
  - Moisture Added, Rampant Pressure Solution (3% Porosity, K = 1.0E-19 m^2)

Granular Salt Reconsolidation Model

- Model is Well Documented in a Series of Papers and Reports
- Experimental Database for Parameter Values Includes
  - 40 Isostatic Consolidation Tests
  - 18 Shear Consolidation Tests
  - Database Predominately at Room Temperature or Short-Term Elevated Temperatures
- Current Elevated Temperature Test Program Underway at Sandia National Laboratories
  - Temperatures from 100°C to 250°C
  - Isostatic and Shear Consolidation Tests Included
  - Unload/Reload Cycles for Elastic Properties

Probe Model Using A Simple Hypothetical Shaft Analyses

- Examine Three Depths, Which Gives Us a Range in Stress and Temperature
- Use the Nonlinear Elastic/Combined Mechanism Crushed Salt Model to Produce the Baseline Results $\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^c$
- Comparative Analyses and Constitutive Model Variations
  - Empty Shaft with No Crushed Salt
  - Nonlinear Elastic Portion of the Model Only
  - Empty Shaft for a Number of Years then Backfilled with
    - Baseline Model at Fractional Density Computed in Baseline Analysis
    - Same as Above with Linear Elasticity Replacing Nonlinear Elastic Model
  - Assume Granular Salt is Dry (Turn Off Pressure Solution)

Shaft Seal Analyses

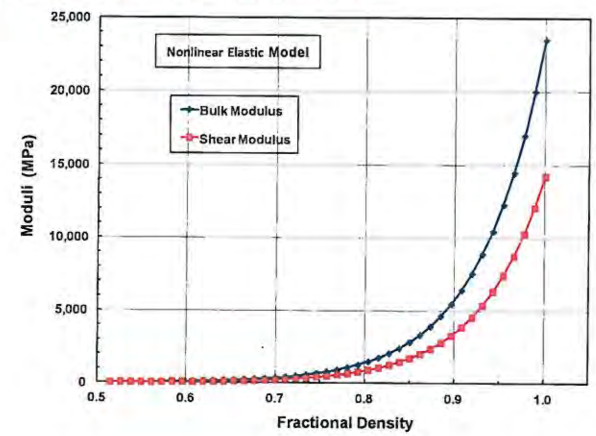
- Shaft Assumed to Contain Granulated Salt at Time = 0 yr
- Granulated Salt Assumed to Have an Initial D=0.75
- Finite Element Analyses in Axisymmetry
- Plane Strain Axial Direction
- 1,000-Year Analyses
- Combined Shear and Isostatic Test Database Parameters Used in Simulations
- Granulated Salt Model Examined by Inclusion and Exclusion of Model Components

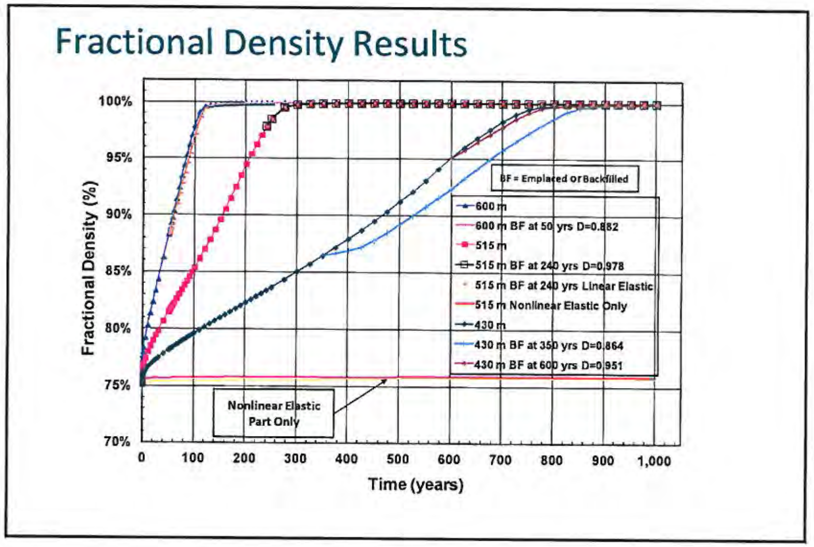
Shaft Analyses

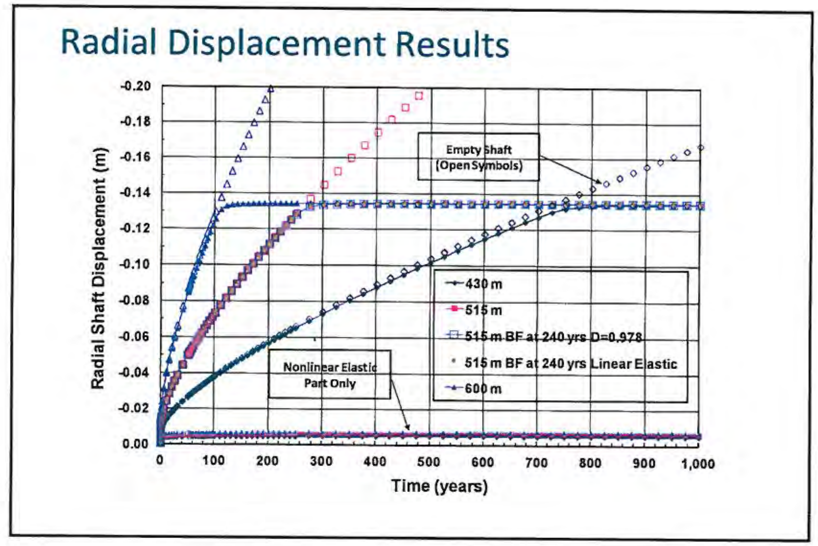
Three Depths Analyzed

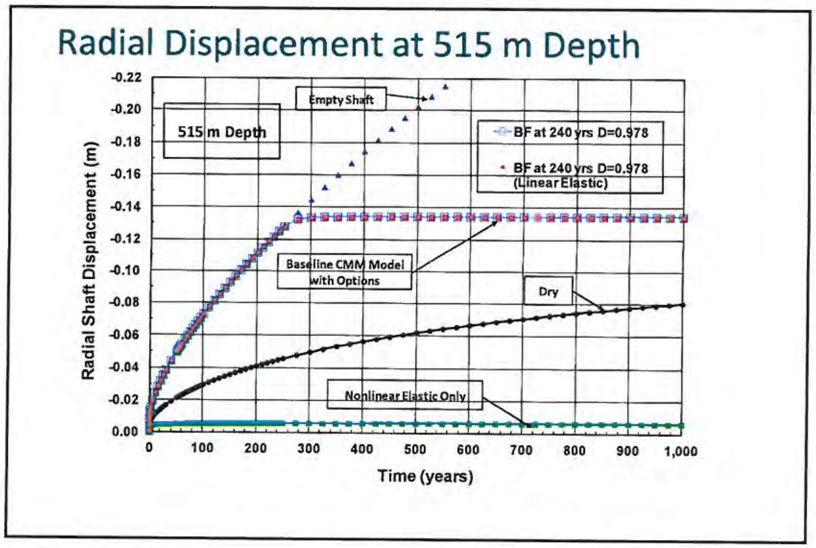
Depth (m)	Temperature (°C)	Isostatic In Situ Stress (MPa)
430	24.80	9.85
515	25.65	11.76
600	26.50	13.68

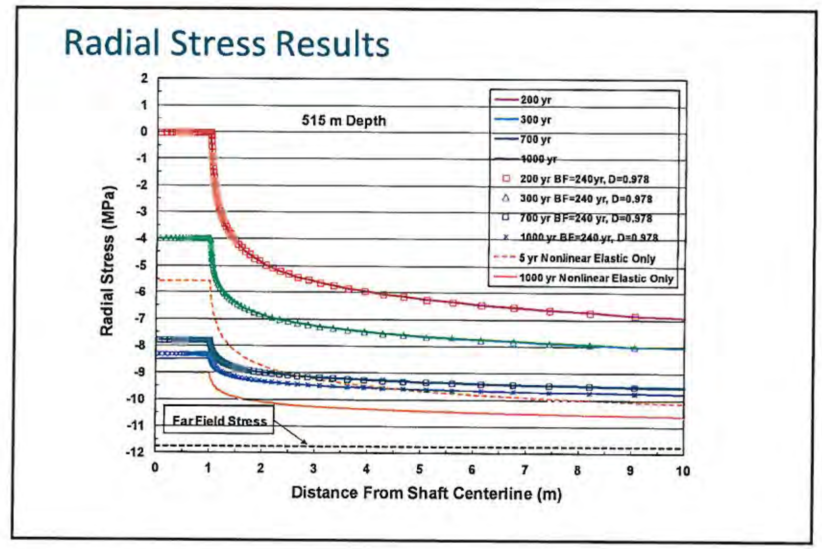
Nonlinear Elastic Model



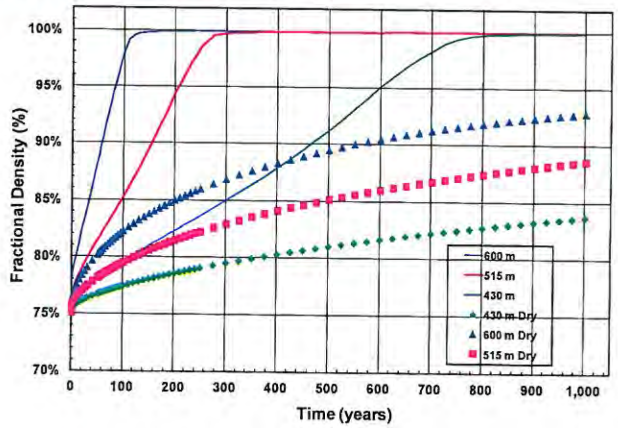

Fractional Density Results
Fractional Density (%)
100%
95%
90%
85%
80%
75%
70%
0 100 200 300 400 500 600 700 800 900 1,000
Time (years)
BF = Emplaced or Backfilled
600 m
600 m BF at 50 yrs D=0.882
515 m
515 m BF at 240 yrs D=0.978
515 m BF at 240 yrs Linear Elastic
515 m Nonlinear Elastic Only
430 m
430 m BF at 350 yrs D=0.864
430 m BF at 600 yrs D=0.951
Nonlinear Elastic Part Only


Radial Displacement Results
Radial Shaft Displacement (m)
-0.20
-0.18
-0.16
-0.14
-0.12
-0.10
-0.08
-0.06
-0.04
-0.02
0.00
0 100 200 300 400 500 600 700 800 900 1,000
Time (years)
Empty Shaft (Open Symbols)
430 m
515 m
515 m BF at 240 yrs D=0.978
515 m BF at 240 yrs Linear Elastic
600 m
Nonlinear Elastic Part Only


Radial Displacement at 515 m Depth
Radial Shaft Displacement (m)
-0.22
-0.20
-0.18
-0.16
-0.14
-0.12
-0.10
-0.08
-0.06
-0.04
-0.02
0.00
0 100 200 300 400 500 600 700 800 900 1,000
Time (years)
515 m Depth
Empty Shaft
BF at 240 yrs D=0.978
BF at 240 yrs D=0.978 (Linear Elastic)
Baseline CMM Model with Options
Dry
Nonlinear Elastic Only


Radial Stress Results
Radial Stress (MPa)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
0 1 2 3 4 5 6 7 8 9 10
Distance From Shaft Centerline (m)
515 m Depth
200 yr
300 yr
700 yr
1000 yr
200 yr BF=240yr, D=0.978
300 yr BF=240 yr, D=0.978
700 yr BF=240 yr, D=0.978
1000 yr BF=240 yr, D=0.978
5 yr Nonlinear Elastic Only
1000 yr Nonlinear Elastic Only
Far Field Stress

Importance of Moisture



Conclusions

- From a Mechanical Standpoint, the Granular Salt Reconsolidation Model Apparently Does Not Have to be Very Robust in the High Porosity Region (e.g. $0.55 \leq D \leq 0.85$) as Long as the Representation is not Overly Stiff.
- Although the Above Point May Be True for Mechanical Processes, it Probably Does not Hold For Fluid Flow and Thermal Analyses.
- The Analyses Assumed to be Dry Keenly Illustrates the Known Fact that the Presence of Moisture Significantly Accelerates the Deformation and Shows How the Constitutive Model Captures It.
- Current Work Explores the Model's Ability to Represent Granular Salt Consolidation at Elevated Temperatures. Decrepitation of the Granular Salt at Temperatures Around 280°C with Steam Release Will Require Further Consideration.

Exceptional service in the national interest

Sandia National Laboratories

Perspectives on Granular Salt Reconsolidation

Frank Hansen PhD PE

3rd US/German Workshop on Salt Repository Research, Design and Operations

Albuquerque, NM, USA

October 9-10, 2012

SAND 2012-8034P

Sandia National Laboratories | DBE TEC | PTKA | U.S. Department of Energy | NNSA

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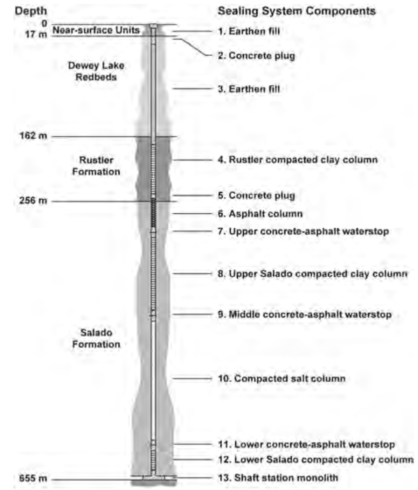
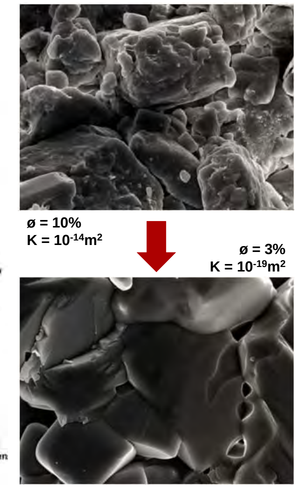
Shaft Sealing System

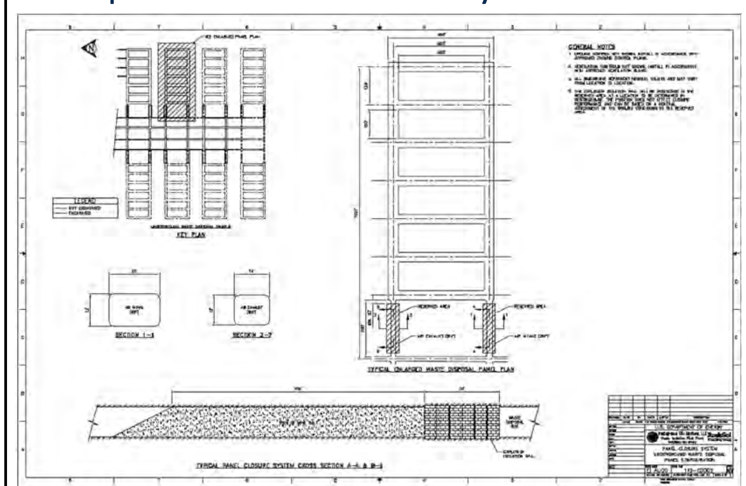




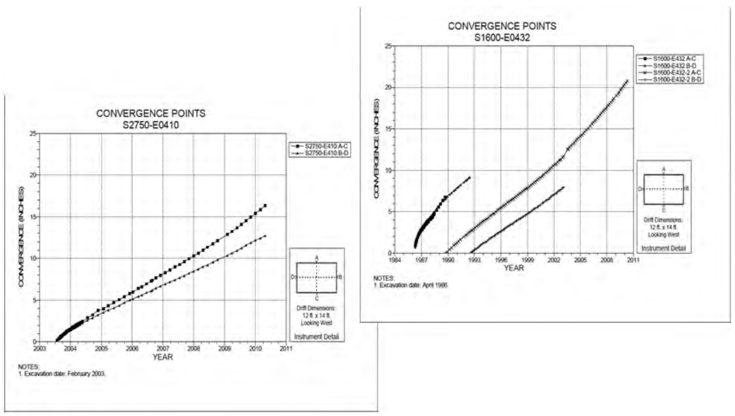
Shaft Seal System Conclusions

- The WIPP shaft seal system effectively limits fluid flow within the seal system.
- The salt column becomes an effective barrier to gas and brine migration by 100 years after closure.
- Long-term flow rates within the seal system are limited.

Proposed Panel Closure System

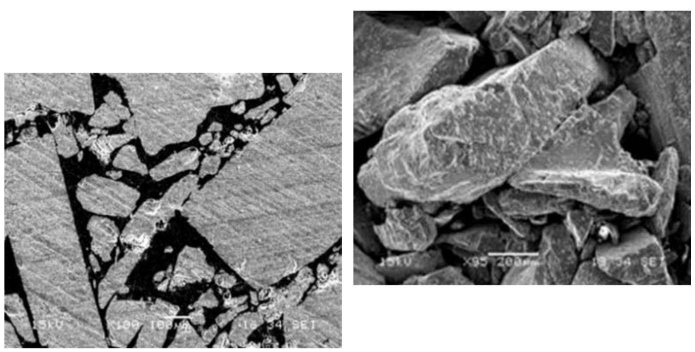


Convergence Point Array

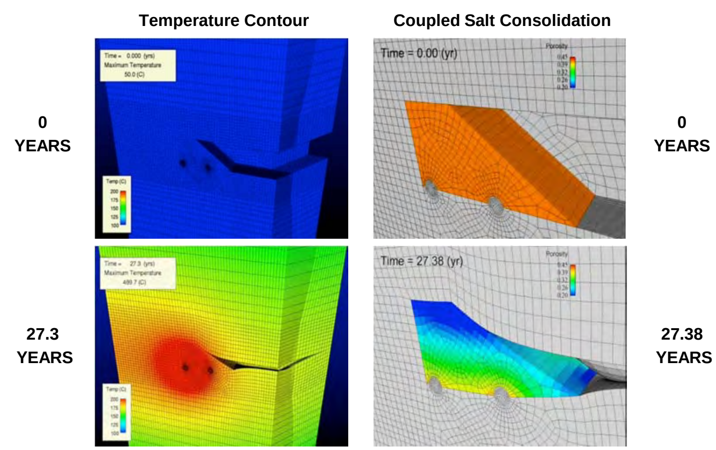


BAMBUS II Heater Surrounded by Reconsolidated Salt

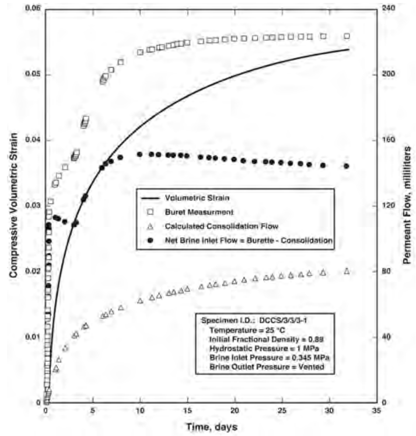
Photomicrographs BAMBUS II (20.7% porosity, K = 4.17e-13 m^2)



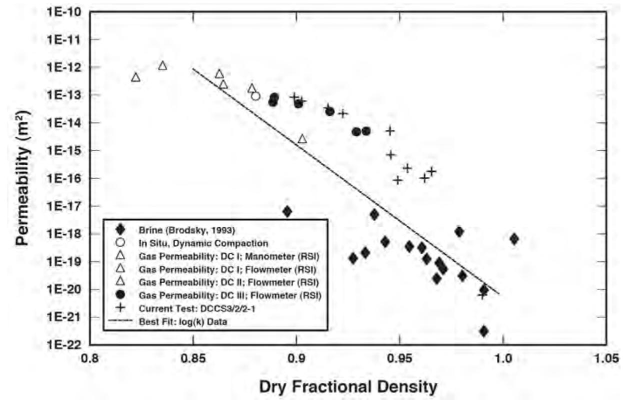
Advanced Multi-physics Modeling will Aid Salt Analyses & Performance Assessment



Volumetric Strain and Brine Flow for Tamped WIPP Salt



Permeability Density Function for Reconsolidating Salt



Observational Methods

- Optical microscopy
  - Thick thin sections
  - Etched cleavage chips
- SEM microscopy
  - Broken surfaces
  - Coated thin sections

Mechanisms of salt densification well described by Spiers and Brzesowsky

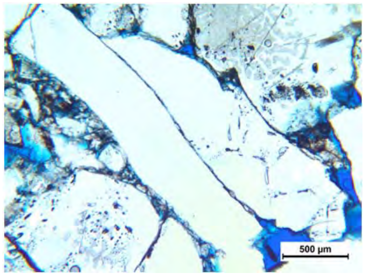
Processes at high porosity

- Instantaneous processes of grain rearrangement and microfracture

Processes at low porosity

- Plasticity coupled pressure solution

C.J. Spiers and R.H. Brzesowsky. 1993. *Densification Behaviour of Wet Granular Salt: Theory versus Experiment*. 7th Symposium on Salt. Vol. I. Elsevier Science Publishers B.V. Amsterdam.

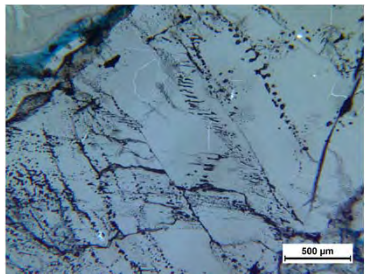


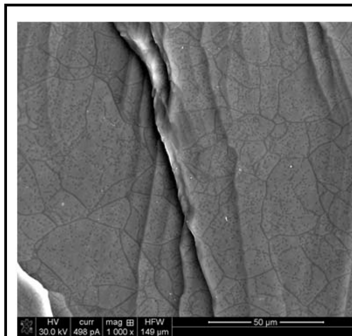
Extreme elongation experienced by individual grains and comminuted fine grains

Test conditions 250C
Hydrostatic consolidation
Volumetric strain 37%

Quantity and mobility of fluid inclusions

Test conditions 250C
Shear consolidation
Volumetric strain 37%



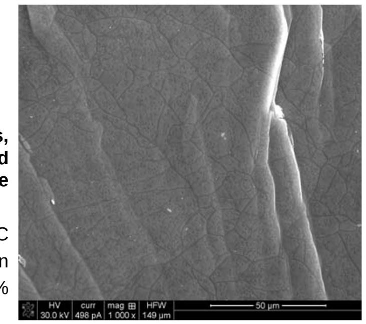


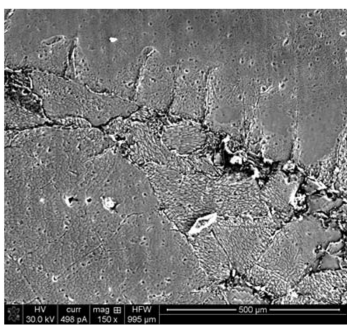
Individual grain - etched cleavage chip exhibiting climb recovery substructures

Test conditions 250C
Shear consolidation
Volumetric strain 31%

Note well developed polygons, low dislocation density, and wavy cleavage plane

Test conditions 250C
Shear consolidation
Volumetric strain 37%



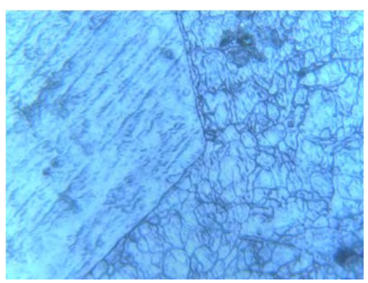


Etch thin section captures rampant crystal plasticity via polygonization

Test temperature = 250C

Etched thin section showing recrystallization in process

Test temperature = 250C



Conclusion

- Shaft seal system elements—ambient reconsolidation is well understood in terms of design, construction and performance.
- Drift seal system elements—the orientation is less favorable for initial construction, but evidence and experience provide confidence in performance.
- Dry versus wet consolidation—evidence strongly supports fluid aided consolidation processes for bedded salt, even when mine-run salt is dried

Recommendation

- Further analogue studies of backfilled chambers in operating salt mines

Salt Compaction Use for Panel Closures

Department of Energy Waste Isolation Pilot Plant

October 9, 2012

Thomas Klein
URS-RES

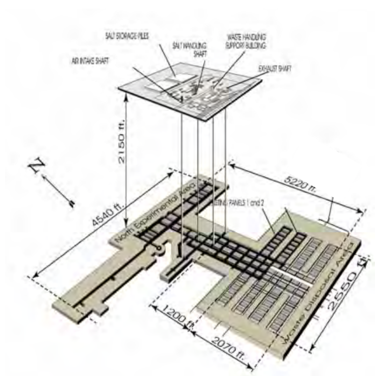
Introduction

This presentation will cover:

- Background
- Major Design Criteria
- Regulatory Requirement
- Concerns with Option D
- Decision-Making
- Re-design Criteria
- In-situ Testing
- In-situ Observations
- Conclusion

WIPP Background

- Deep Geologic Repository in Salt
- Disposal of U.S. defense related Transuranic and Transuranic Mixed waste
- Repository Design consists of:
  - o Ten panels (Eight panels currently permitted)
  - o Each panel has seven rooms
  - o Two main access drifts per panel
    - ▪ Intake
    - ▪ Exhaust
- Five Options for Panel Closures were submitted. Option D was chosen by the EPA

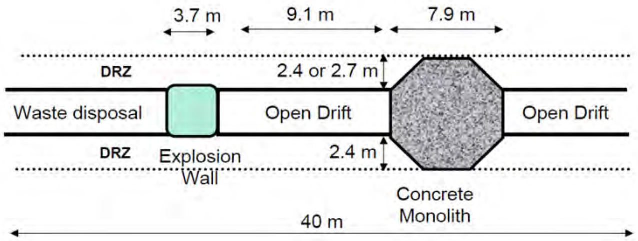


Regulatory Closure Performance Standards

- Limit migration of volatile organics compounds for 35 years.
- Maintain functionality under loads generated by salt creep.
- Maintain functionality under loads generated by internal pressures.
- Maintain functionality under loads generated by a postulated methane-based explosion.

Regulatory Requirement

- 1998- EPA's Certification decision identified Option D with Salado Mass Concrete (salt-based concrete) as the mandated panel closure design. **Long-term repository performance 10,000 yrs**.
- 1999- NMED agreed with EPA's mandated design and incorporated Option D with Salado Mass Concrete into the Hazardous Waste Facility Permit. **Short-term repository performance 30 yrs**.



4

Concerns with Option D

- 2000- DOE identified issues with construction of Option D.
- Mass concrete specification was found problematic
- Complex Option D design would interrupt waste handling operations
- Hydrogen and Methane monitoring data shows no need for explosion wall

5

Panel Closure Re-design Decision-Making Process

- The design must satisfy Closure Performance Standards in 20.4.1.500 NMAC (New Mexico regulations)
- Any new design must be simpler and easier to construct, and should:
  - Be less impactive to facility operations,
  - Increase confidence in successful installation,
  - Reduce the level of worker risk,
  - Be less expensive to install
- A change in design must not adversely impact long-term repository performance

6

Panel Closure Re-design Criteria

- The panel closure system design shall limit VOC migration from a closed panel consistent with the limits found in the Permit
- The panel closure system shall consider potential flow of VOCs through the disturbed rock zone (DRZ) in addition to flow through the closure components
- The panel closure system shall perform its intended functions under loads generated by creep closure of the tunnels
- The nominal operational life of the closure system is thirty-five (35) years
- The panel closure system shall address the most severe ground conditions expected in the waste disposal area
- The panel closure system shall be built to generally accepted national design and construction standards

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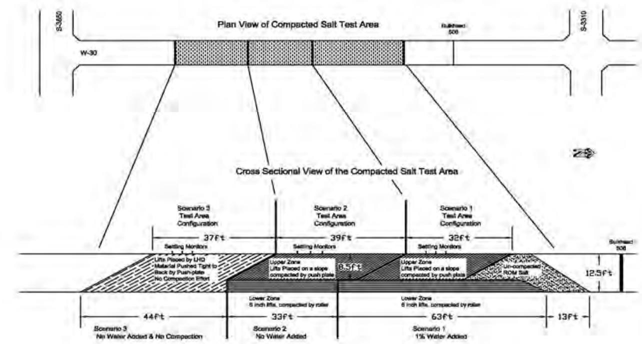
Re-design Criteria Cont.

- The design and construction shall follow conventional mining practices
- Structural analysis shall use data acquired from the WIPP underground
- Materials shall be compatible with their emplacement environment and function
- Treatment of surfaces in the closure areas shall be considered in the design
- During construction, a Quality Assurance/Quality Control (QA/QC) program shall be established to verify material properties and construction practices
- Construction of the panel closure system shall consider shaft and underground access and services for materials handling

Compacted Salt Test Area Plan and Cross Section



Construction of Compaction Tests: Lower Zone

Load-Haul-Dump Placing ROM Salt on Lower Zone Lift

Walk-behind Roller Compactor Compacting Lower Zone Lift

Construction of Compaction Tests: Upper Zone

Fletcher Compacting Upper Zone

Test Area 1 Compaction Data

Date	Lift #	Compactor Type	Avg. Compactor Speed (ft/min)	Cumulative Number of Compaction (No. of Passes)	Maximum Density %	Minimum Density %	Avg. Wet Density %	Avg. Moisture %	Avg. Dry Density %
LOWER ZONE									
6/5/2012-6/15/2012	1-7	ROLLER	132.2 8	2	77.4	71.8	75.12	1.62	74.10
6/5/2012-6/15/2012	1-7	ROLLER	141.3 1	4	76.6	72.4	75.84	1.70	74.50
6/5/2012-6/15/2012	1-7	ROLLER	148.1 2	6	78.2	73.3	76.03	1.36	74.80
UPPER ZONE									
6/26/2012-6/29/2012	3-7	PUSHPLATE W/ VIBRATION		1	68.3	58.4	64.08	1.07	63.33
7/10/2012-7/11/2012	13-32	PUSHPLATE W/O VIBRATIO		1	72.6	54.6	64.19	1.35	63.30
	3' From Back				68.3	58.4	64.1	1.2	63.4
	5' From Back				72.9	59.9	65.4	1.3	64.6
	7' From Back				68.7	54.7	62.5	1.4	61.5

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Grain Size Summary

Screen Size	Particle size	% Passing
75.0 mm	3"	91
63.0 mm	2½"	85
50.0 mm	2"	82
37.5 mm	1½"	80
31.5 mm	1¼"	78
25.0 mm	1"	76
19.0 mm	¾"	74
12.5 mm	½"	71
9.5 mm	3/8"	67
4.75 mm	#4 sieve	52
2.0 mm	#10 sieve	32
425 µm	#40 sieve	13
180 µm	#80 sieve	7
75 µm	#200 sieve	3.1

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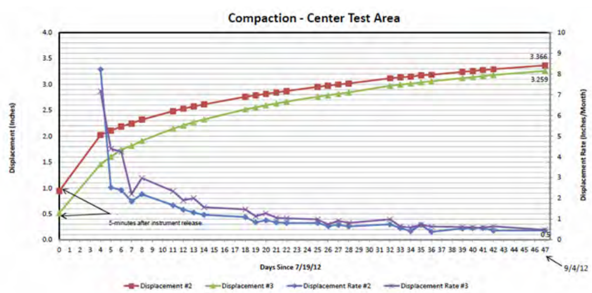
Settlement Data



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Observations

- FLAC3D modeling shows the lower initial fractional density, the larger an air gap forms from particle settling.
- In-situ testing shows the settling is actually smaller than the FLAC3D modeling results.
- Additional moisture (1-3%) during compaction does not aid in increasing the initial fractional density.

Intake Drift FLAC3D Results

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

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Conclusion

- Description of final design likely to be proposed to NMED:
  - Lower zone 65% compaction, upper zone 65% compaction,
  - no additional moisture added,
  - if air gap forms, grouting may be used to seal,
  - steel bulkhead with flexible flashing.

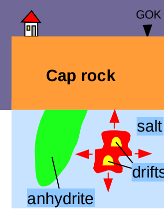
EM Environmental Management
safety ◇ performance ◇ cleanup ◇ closure
www.em.doe.gov

16

Final Disposal in Rock Salt

Mechanical-Hydraulic Conditions for an Integrity Loss of Salinar Barriers

W. Minkley & T. Popp
Institut für Gebirgsmechanik GmbH, Leipzig, Germany



Outline

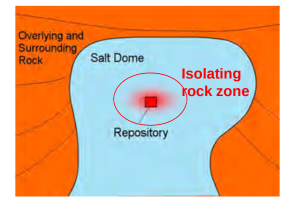
- Loss of tightness of rock salt – fundamental processes
- Geotechnical safety analysis to evaluate the long-term integrity of the geological barrier
  Case study:
  – Gorleben salt dome
- Summary

IfG

Safety requirements for storage of radioactive waste

➢ **Long-term statement on the integrity of the isolating rock zone**
… For probable developments, evidence must be provided on the basis of a long-term geoscientific prognosis verifying that the integrity of the isolating rock zone is guaranteed throughout the reference period of 1 million years. …

It has to be demonstrated, that
… the formation of secondary water pathways within the isolating rock zone which could lead to the ingress or escape of potentially contaminated aqueous solutions can be excluded. …



Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

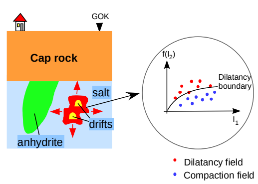
BMU, 2010

Mechanically or hydraulically induced permeability

Deviatoric stresses induce damage which results in the opening and percolation of microcracks

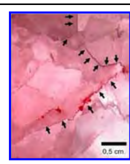
⇒ **Dilatancy criterion**

Stress induced intergranular crack
Alkan & Müller (2008)

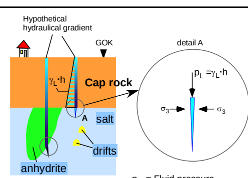


Hydraulically induced pathway opening or fracturization which results in percolation of microcracks

⇒ **Minimum stress criterion**



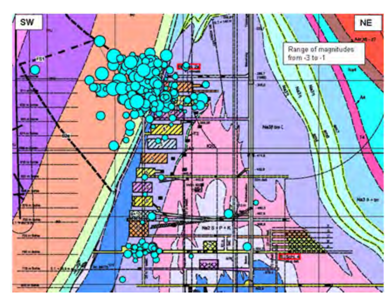
Crack opening due to gas injection
Popp et al. (2007)



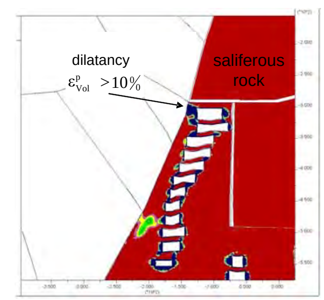
p_L = Fluid pressure
σ_3 = minimum stress

Case study (1) Asse II

Violation of the Dilatancy Criterion ⇒
Inflow of water into the former salt-mine, used as URL



Recorded micro-seismic activities

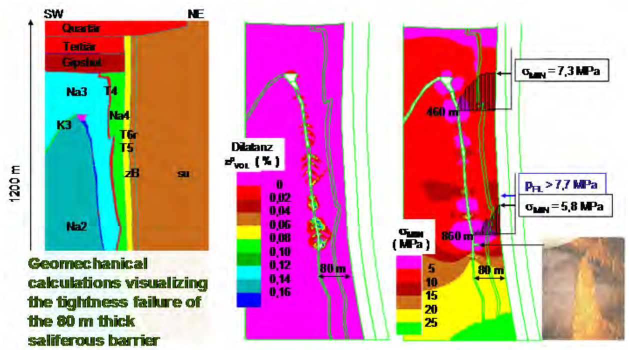


Calculated dilatant zones around the mining rooms at the southern flank of the Asse II mine

Case study (2): Salt dome Bokeloh

Violation of the Minimum Stress Criterion ⇒

Inflow of water into the active salt mine



Final Disposal in Rock Salt - Barrier Integrity

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Loss of tightness of salt rocks

Conclusion

- The mechanically or hydraulically induced permeability at the field scale bases on the same microphysical processes, i.e. the percolation of flow paths along grain boundaries after exceeding a threshold, which correspond:
  - (1) at deviatoric conditions with the **dilatancy boundary** and
  - (2) at increased fluid pressures with the **minimum stresses**

    i.e. in both cases due to a removal of intergranular cohesion.
- **In the past some examples of integrity loss occurred during conventional mining ≠ radioactive waste repository**

Sophisticated geo-mechanical analysis is needed to demonstrate the integrity of the geological barrier

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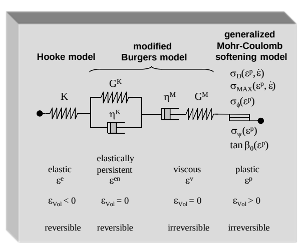
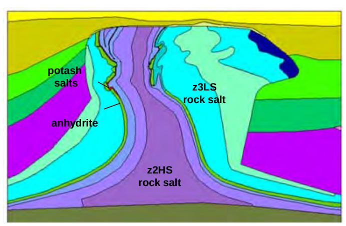
Constitutive models for salt rocks and imbedded weakness planes

1. visco-elasto-plastic softening model (creep, dilatancy, destrengthening)





2. shear model for discontinuities and bedding planes with displacement-and velocity-dependent softening

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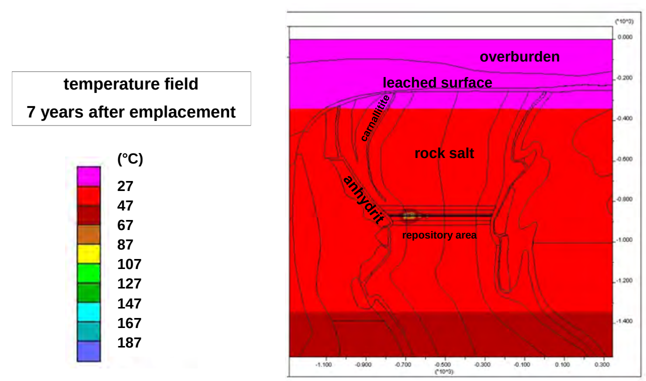
Development of the temperature field



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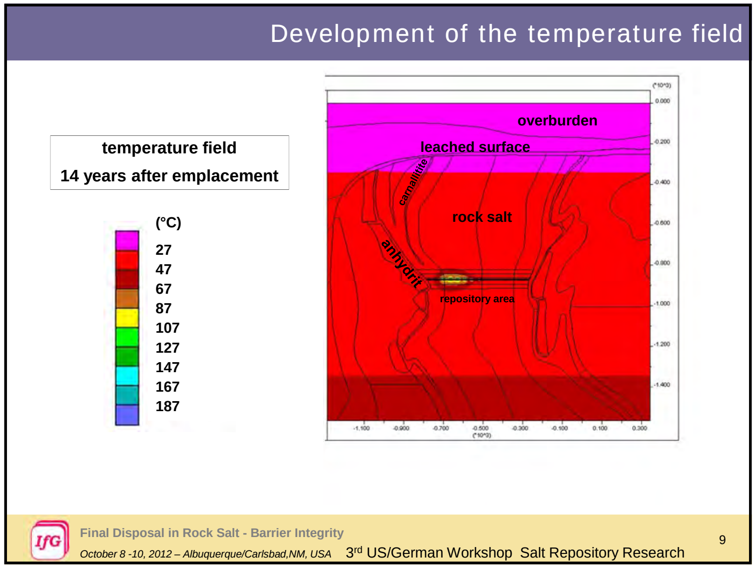
Development of the temperature field
temperature field
14 years after emplacement
(°C)
27
47
67
87
107
127
147
167
187
overburden
leached surface
carnallitite
rock salt
anhydrit
repository area
Final Disposal in Rock Salt - Barrier Integrity
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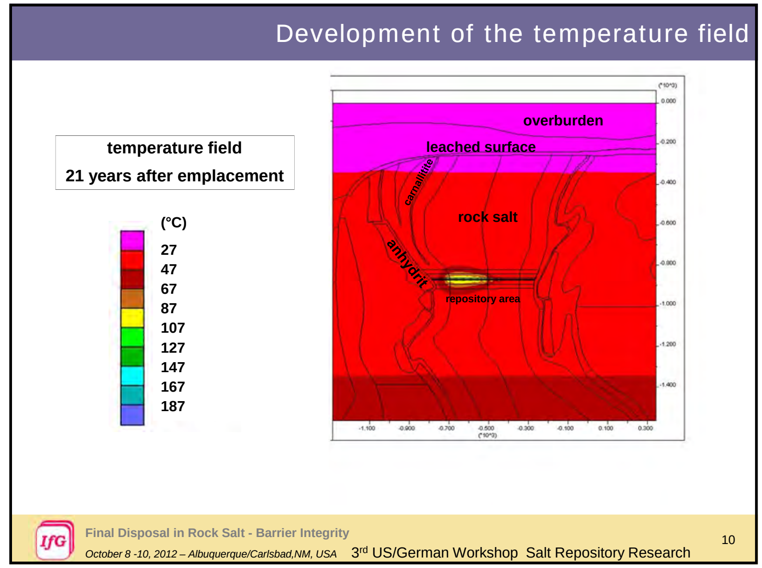
Development of the temperature field
temperature field
21 years after emplacement
(°C)
27
47
67
87
107
127
147
167
187
overburden
leached surface
carnallitite
rock salt
anhydrit
repository area
Final Disposal in Rock Salt - Barrier Integrity
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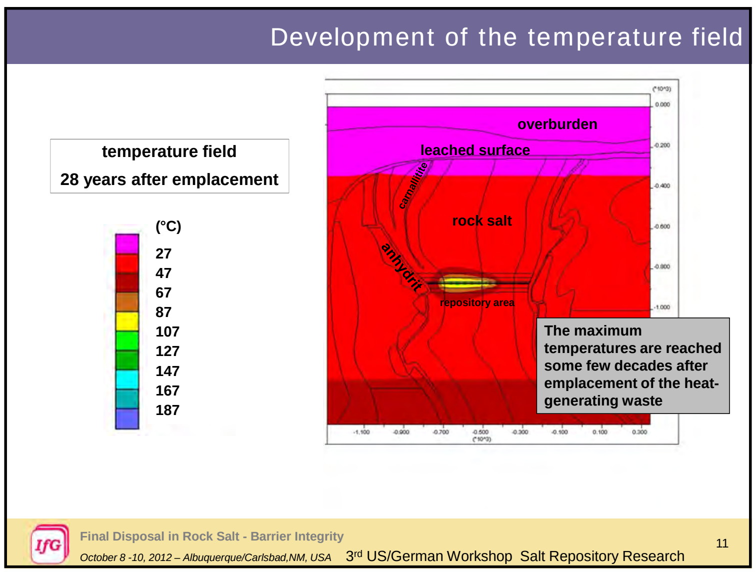
10


Development of the temperature field
temperature field
28 years after emplacement
(°C)
27
47
67
87
107
127
147
167
187
overburden
leached surface
carnallitite
rock salt
anhydrit
repository area
The maximum temperatures are reached some few decades after emplacement of the heat-generating waste
Final Disposal in Rock Salt - Barrier Integrity
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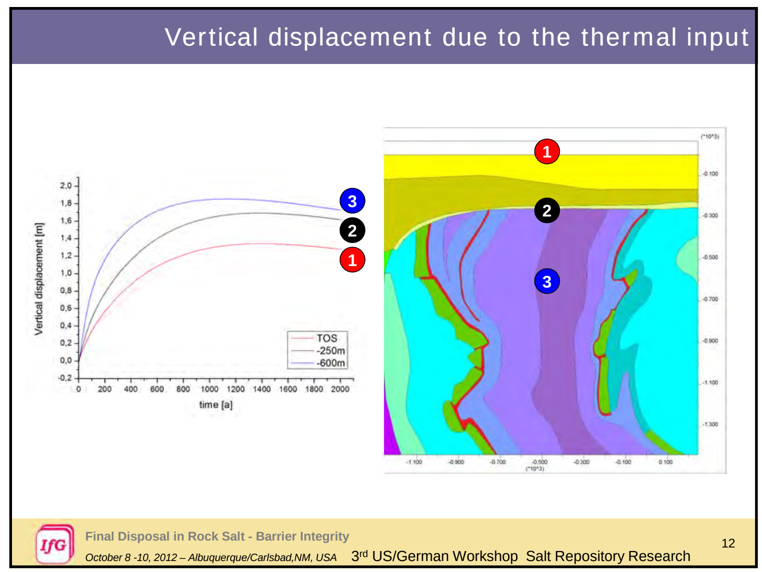
Vertical displacement due to the thermal input
Vertical displacement [m]
time [a]
TOS
-250m
-600m
1
2
3
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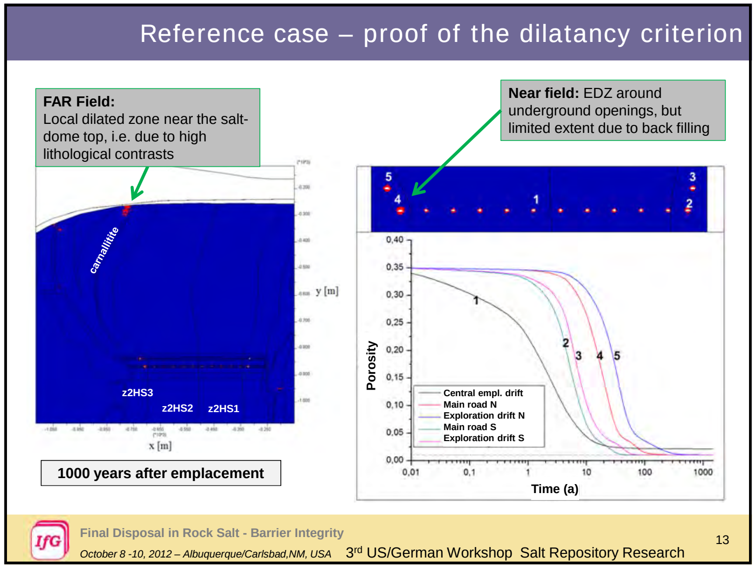
Reference case – proof of the dilatancy criterion
FAR Field:
Local dilated zone near the salt-dome top, i.e. due to high lithological contrasts
Near field: EDZ around underground openings, but limited extent due to back filling
carnallitite
z2HS3
z2HS2 z2HS1
y [m]
x [m]
1000 years after emplacement
Porosity
Time (a)
Central empl. drift
Main road N
Exploration drift N
Main road S
Exploration drift S
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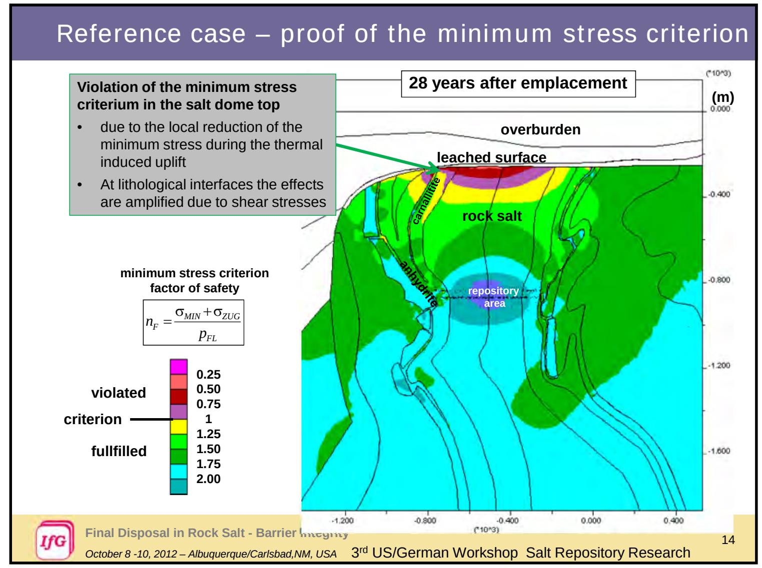
Reference case – proof of the minimum stress criterion
Violation of the minimum stress criterium in the salt dome top
due to the local reduction of the minimum stress during the thermal induced uplift
At lithological interfaces the effects are amplified due to shear stresses
28 years after emplacement
(m)
overburden
leached surface
rock salt
carnallitite
anhydrite
repository area
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
Final Disposal in Rock Salt - Barrier Integrity
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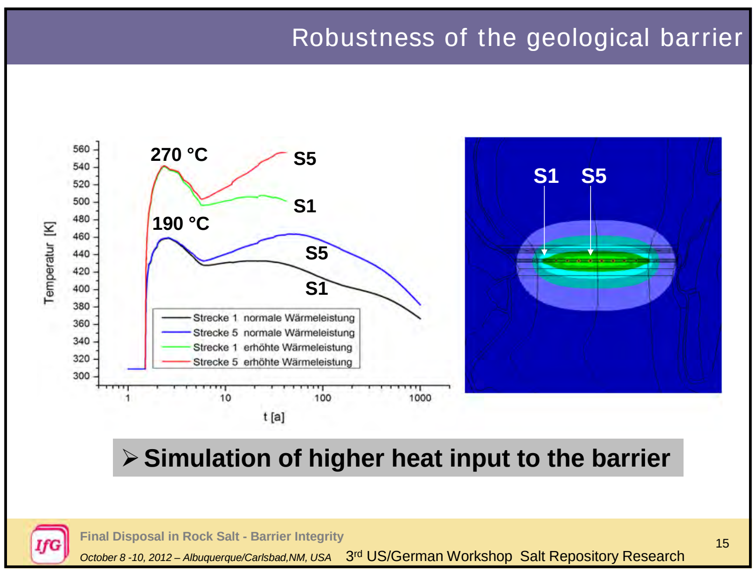
Robustness of the geological barrier
270 °C
190 °C
S5
S1
S5
S1
Temperatur [K]
t [a]
Strecke 1 normale Wärmeleistung
Strecke 5 normale Wärmeleistung
Strecke 1 erhöhte Wärmeleistung
Strecke 5 erhöhte Wärmeleistung
S1 S5
➢ Simulation of higher heat input to the barrier
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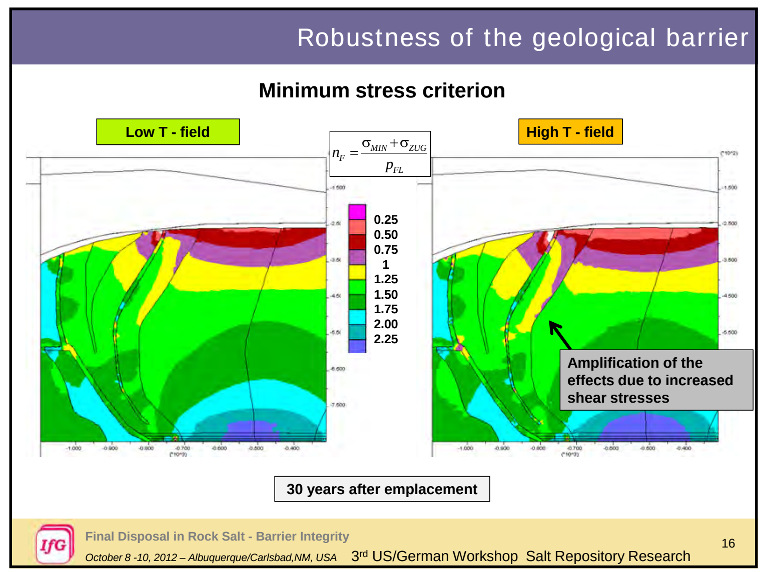
Robustness of the geological barrier
Minimum stress criterion
Low T - field
High T - field
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
Amplification of the effects due to increased shear stresses
30 years after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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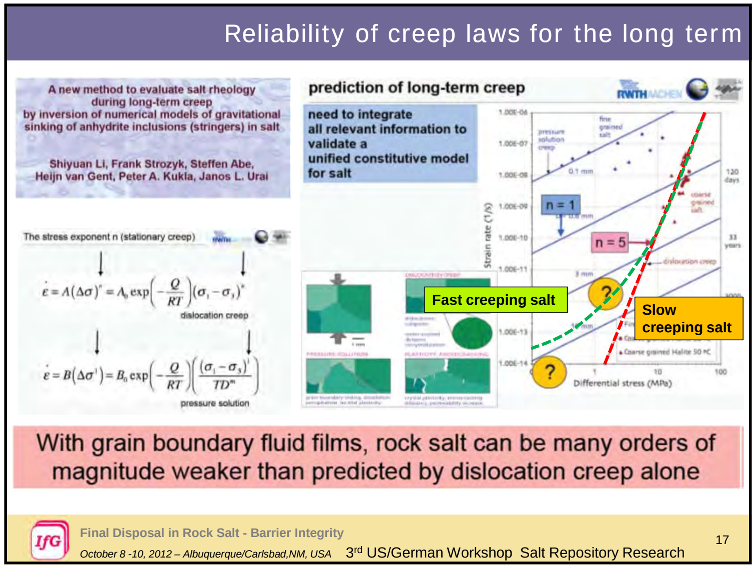
Reliability of creep laws for the long term
A new method to evaluate salt rheology during long-term creep by inversion of numerical models of gravitational sinking of anhydrite inclusions (stringers) in salt
Shiyuan Li, Frank Strozyk, Steffen Abe, Heijn van Gent, Peter A. Kukla, Janos L. Urai
prediction of long-term creep
need to integrate all relevant information to validate a unified constitutive model for salt
The stress exponent n (stationary creep)
dislocation creep
pressure solution
n = 1
n = 5
Fast creeping salt
Slow creeping salt
Strain rate (1/s)
Differential stress (MPa)
With grain boundary fluid films, rock salt can be many orders of magnitude weaker than predicted by dislocation creep alone
Final Disposal in Rock Salt - Barrier Integrity
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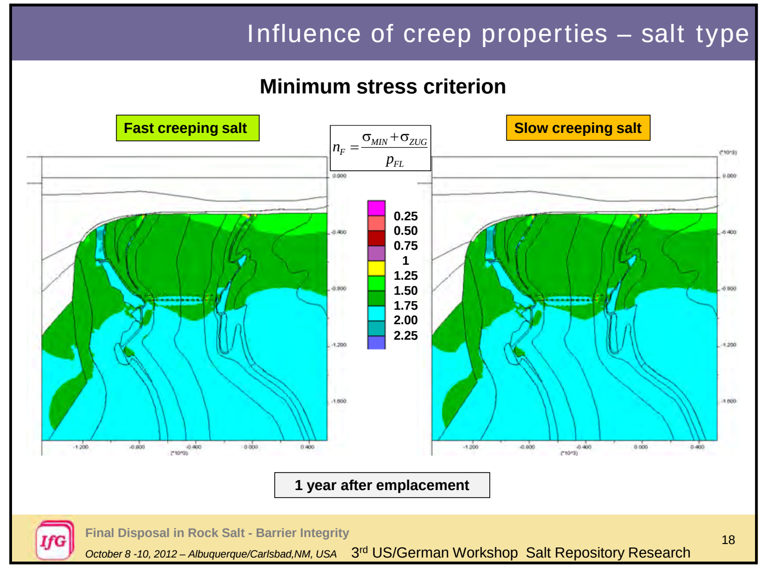
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
1 year after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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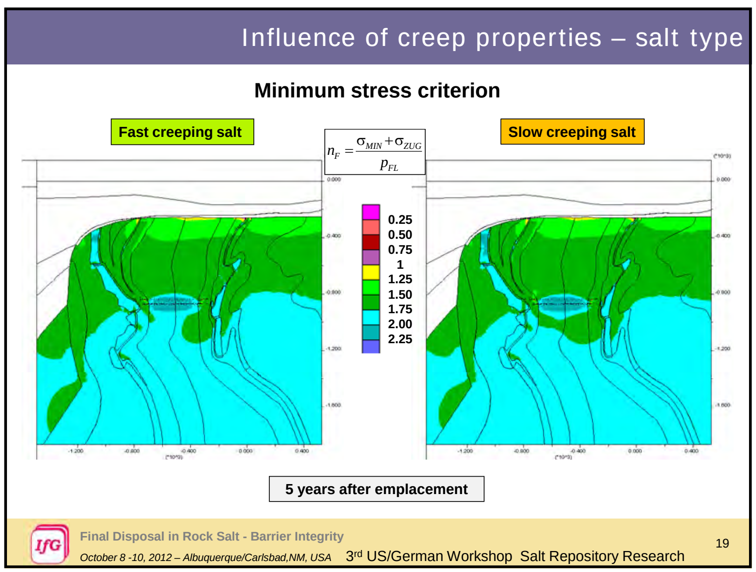
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
5 years after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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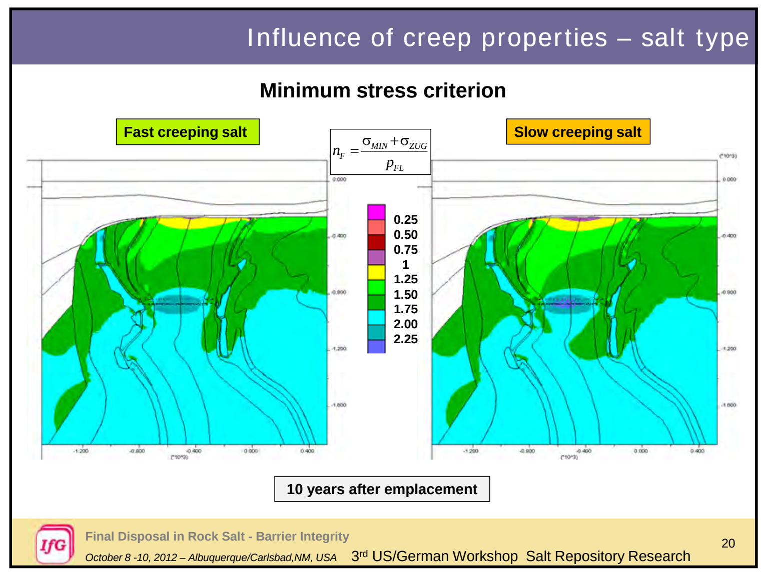
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
10 years after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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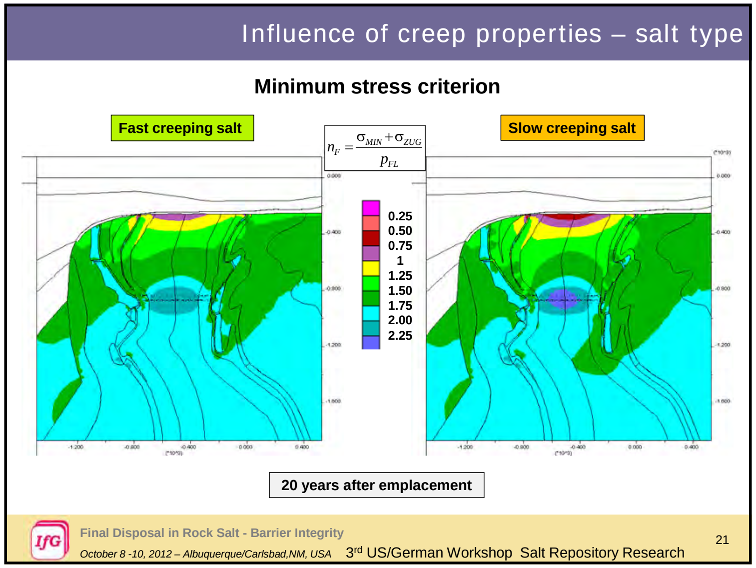
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
20 years after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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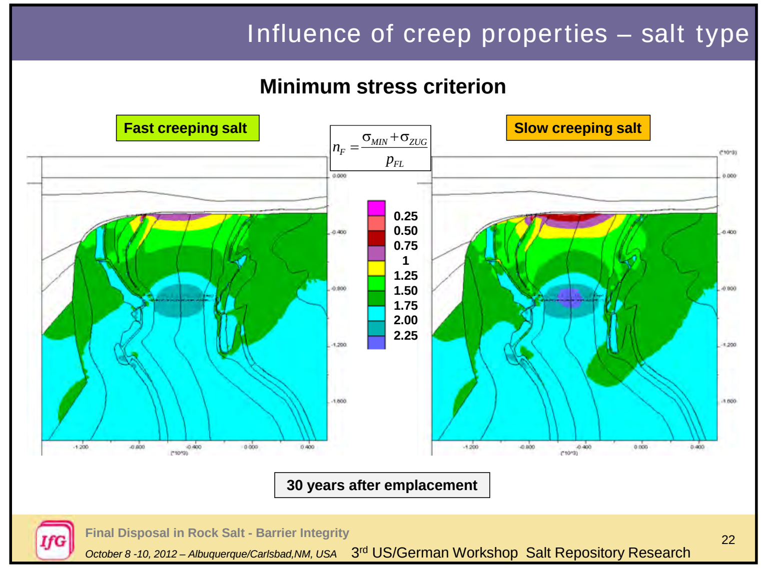
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
30 years after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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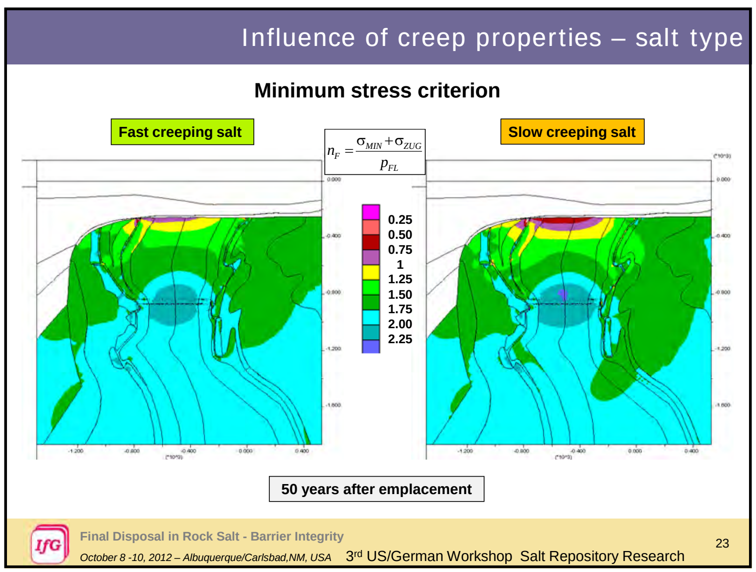
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
50 years after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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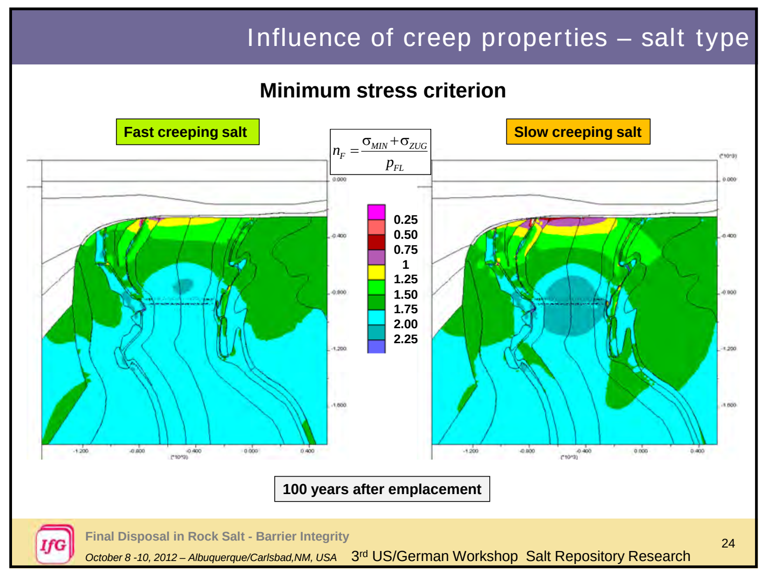
Influence of creep properties – salt type
Minimum stress criterion
Fast creeping salt
Slow creeping salt
$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$
0.25
0.50
0.75
1
1.25
1.50
1.75
2.00
2.25
100 years after emplacement
Final Disposal in Rock Salt - Barrier Integrity
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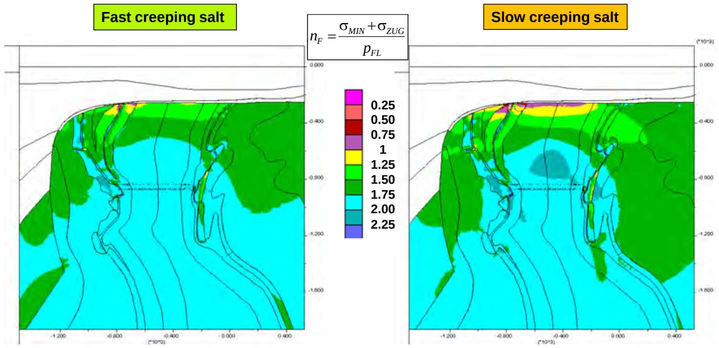
Influence of creep properties – salt type

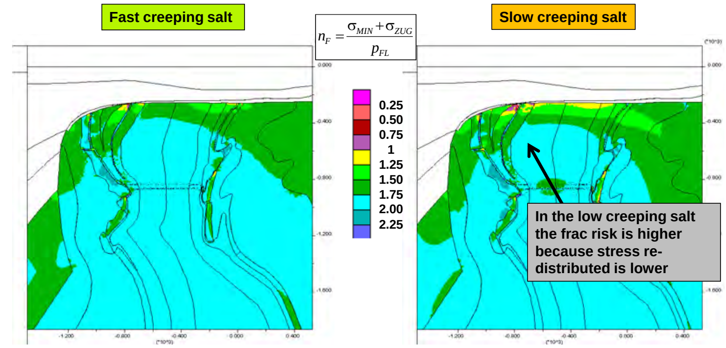
Minimum stress criterion



200 years after emplacement

Influence of creep properties – salt type

Minimum stress criterion



1000 years after emplacement

Lessons learned from the various case studies!

➢ General conclusion

- Verified geo-mechanical criteria are available for an integrity proof
- The geo-mechanical analysis is robust, i.e reliable material laws exist
- The impermeability of a saliferous barrier will already be lost if one of these two criteria: (1) minimum stress criterion or
  (2) dilatancy criterion is violated!

Note, *most critical for the integrity of saliferous barrier is the minimum stress criterion because the importance of the dilatancy criterion is pre-dominantly significant in the EDZ !*

Fluid pressure driven fluid flow along interfaces increases significantly the reach of fluid percolation along the bedding

➢ Gorleben site

The integrity of the saliferous barrier has been demonstrated for both criteria , also if unrealistic “bad” assumptions were applied!

Exceptional service in the national interest

Thermomechanical-Hydrology Modeling for HLW Disposal

James Bean
Mario Martinez
Teklu Hadgu

3rd US/German Workshop on Salt Repository Research, Design and Operations
Albuquerque, NM, USA
October 9-10, 2012
SAND 2012-8030P

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Organization of Presentation

- ❑ **SIERRA Mechanics Physics Coupling Strategy**
  - Using workstation and/or massively parallel-processor computers
- ❑ **Thermal- Mechanical (TM) Modeling**
  - Constitutive model for intact and crushed salt
  - Porosity and temperature dependent thermal conductivity model
  - Results- Focus on consolidation time of the crushed salt backfill for varying values of assumed moisture content
- ❑ **Thermal-Hydraulic (TH) Modeling**
  - Thermal and 2-phase porous flow properties
  - Model moisture movement due to decay heat in the crushed salt and EDZ regions
- ❑ **Summary and Future Work**

SIERRA T-H-M Physics Solution

Thermal-Hydraulic

ARPEGGIO Handles Data Transfers

Mechanical (deformation)

ARIA

Solves conservation of component mass (water and air) equations for 2- phase porous flow plus energy equation (*i.e.,* temperature field) on a deforming computational grid.

temperature → "pore pressure" →

← node displacements

ADAGIO

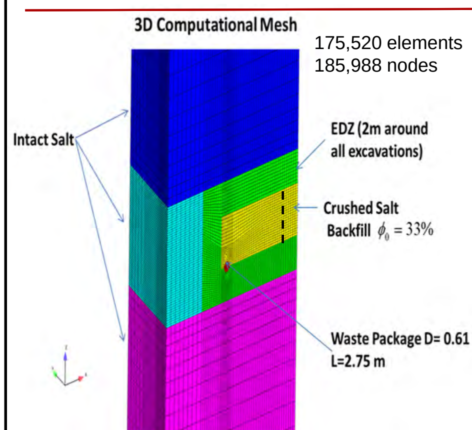
Solves Conservation of linear momentum equations for quasi-static conditions.

Constitutive model for salt implemented in LAME library

- Temperatures are used in the constitutive equations for all salt materials (intact and crushed). Pore pressures can be used to compute effective stresses from the total stresses in ADAGIO.
- Node displacements from ADAGIO are used to update the ARIA finite element mesh and crushed salt porosity. Thermal conductivity and intrinsic permeability of crushed salt backfill can be adjusted to account for change in porosity due to deformation.

3

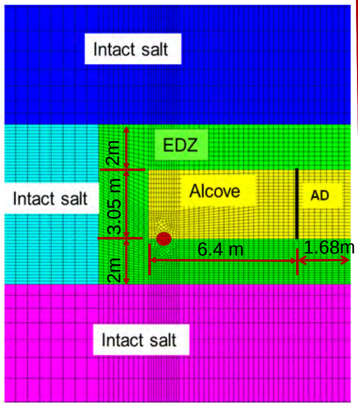
TM and TH Computational Model



- Starting point was model developed by D. Clayton in FY11
- A EDZ region added to model to account for enhanced permeability due to excavation induced damage. The constitutive models in our codes do not include damage/healing in their formulation.
- Need coupling of crushed salt TH properties with mechanical deformation (*e.g.*, porosity [Φ] changes)

4

Model Details



Waste package:
2.7 m (9 ft) long
0.61 m (2 ft) diameter
12.2 m (40 ft) from the center of the waste canister to a neighboring waste container

Alcove:
6.4 m (21 ft) long, 3.05 m (10 ft) tall and 3.35m (11 ft) wide. It was assumed that the alcove connects at right angle to the access drift

Access Drift (AD):
3.05 m (10 ft) tall, 3.35 m (11 ft) wide access drift.

Constitutive Model for Intact and Crushed Salt

- **Developed by Gary Callahan at RESPEC for modeling shaft seals at WIPP**
- **A continuum representation of micro-scale and pore scale processes**
- **Two types of creep behavior**
  - **Multimechanism Deformation Model (Munson and Dawson) represents dislocation creep behavior and is active for both intact and crushed salt. Uses Tresca equivalent stress.**
  - **Grain boundary diffusional pressure solution creep (modified Spiers and Brzesowsky) active in crushed salt when moisture is present. Active only when the density of the salt is less than that of intact salt.**

Thermal properties for crushed salt

Thermal conductivity based on Bambus II (Bechtold)

$$\lambda_{c-salt}(T) = k_{cs}(\phi)\left(\frac{300}{T}\right)^{\gamma}$$

$$k_{cs}(\phi) = \left(-270\,\phi^4 + 370\,\phi^3 - 136\,\phi^2 + 1.5\,\phi + 5\right)\cdot f$$

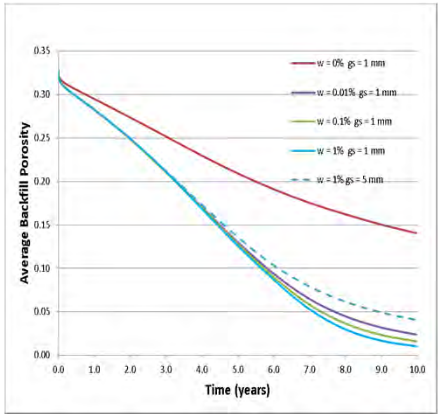
γ = material constant = 1.4
T = temperature [K]
f = scale factor = 5.4/5.0
ε^T = thermal expansion constant = 4.5×10^{-5} K^{-1}
C_s = specific heat = 931 J/Kg-K
ρ = density =2160 Kg/m^3

TM Model: Boundary and Initial Conditions

- **Mechanical BC and IC**
  - No lateral displacement on vertical external boundaries of mesh implies an array of alcoves.
  - Bottom boundary- no vertical displacement
  - Top boundary above alcove- applied pressure represents overburden
  - Initial stress varies linearly with depth and at the alcove elevation is 14.8 Mpa
- **Thermal BC and IC**
  - No heat transfer across vertical external boundaries of the mesh
  - Constant temperature maintained on top and bottom
  - Initial temperature throughout mesh is constant at 25 °C
  - Heat source is 2 kW with decaying half-life of ~26.5 years
- Moisture content in crushed salt is constant in all TM calculations

Average Backfill Porosity vs. Time

Influence of water content (w) and grain size (gs)



Model Inputs :

- **Water content varied (0, 0.01% , 0.1% and 1%)**
- **Unless noted all results are for grain size (gs) = 1 mm**

Simulation Results:

- **After about 4 years, crushed salt backfill provides less resistance to creep of surrounding rock as the water content is increased.**
- **Increasing grain size increases time to reach a target backfill consolidation**

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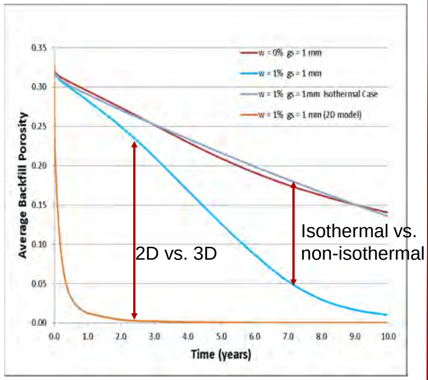
Average Backfill Porosity vs. Time

Influence of thermal effects and 2D-3D model geometry



2D Model ignores the pillars between the alcoves resulting in rapid consolidation of excavated regions.

Isothermal simulation gives closure history very similar to the non-isothermal dry crushed salt backfill case.

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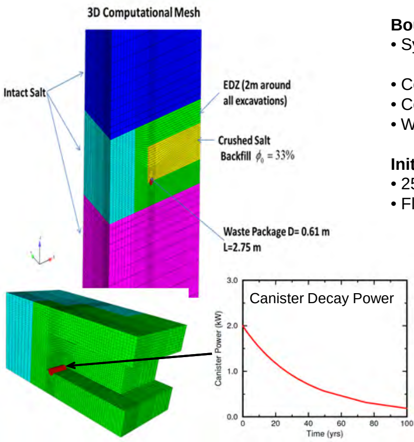
Thermo-Hydrologic Simulation: Geometry, Boundary & Initial Conditions



Boundary Conditions:

- Symmetry on lateral (vertical) boundaries
  - insulated (*i.e.*, adiabatic), no-flow
- Constant T top & bottom
- Constant P top, no-flow bottom
- Waste canister: solid, volumetrically heated

Initial Conditions:

- 25 ºC
- Fluid Saturation
  - EDZ: 50% saturation (0.7% moisture)
  - Backfill: 4% saturation (1.3% moisture)

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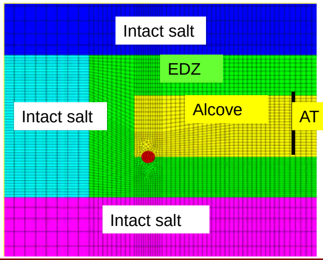
Properties

Property	Intact Salt	EDZ Salt	Crushed Salt	Waste Package
Porosity	0.01	0.014	0.35	-
Permeability (m^2)	10^{-21}	10^{-17}	10^{-13}	-
Saturation, liquid-residual; S_{lr}	0.05	0.05	0.01	
Grain density (kg/m^3)	2190	2190	2190	2200
Specific heat (J/kg K)	931	931	931	840
Thermal Conductivity (W/m K)	5	5	1	2



Relative permeability & capillary pressure

$$k_{rl} = s^3 \qquad k_{rg} = (1-s)^3$$

$$p_c = p_{c0}\left(s^{-1/\lambda} - 1\right)^{1/\beta} \qquad \lambda = 1 - 1/\beta$$

$$s = (S_l - S_{lr}) / \left((1 - S_{gr}) - S_{lr}\right)$$

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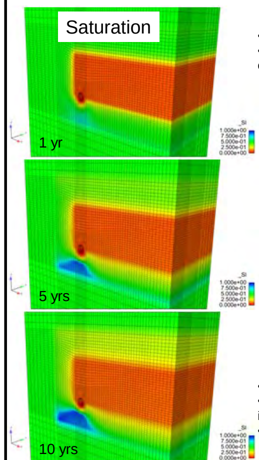
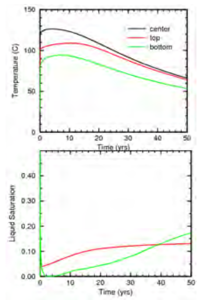
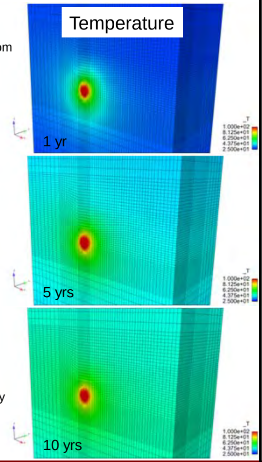
Temperature and Saturation



- canister T > 100 °C at one year
- decay heat drives EDZ moisture away from canister via pressure gradient



- Elevated temperatures at 10 years
- EDZ moisture trapped by low permeability intact salt
- EDZ dewatering



Observations on Moisture Transport (uncoupled from mechanics)

- ❑ Decay heat evaporates liquid moisture at the canister, creating a region of high vapor concentration and elevated gas pressure near the canister
- ❑ Pressure pushes vapor and liquid from canister, creating near-canister dry-out (no-liquid) regions in EDZ
- ❑ Moisture is trapped below canister by ultra-low intact salt permeability (1 nano-Darcy)

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Future Work

- ❑ Coupled flow and mechanics (THM)
  - Strain-dependent transport properties (ϕ(strain), k(ϕ), λ(ϕ), …)
  - Pore-pressure effects (resists consolidation?)
  - Moisture effects on crushed salt consolidation included in a spatially and time dependent manner
- ❑ Numerical issues with coupling large-strain reconsolidation?
  - Investigate coupling strategies
- ❑ Need to introduce damage effects (dilation) in salt constitutive models as in German models
- ❑ Funding to continue moving forward and future international collaborations?

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Backup Slides

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Crushed Salt Model Equations

total creep strain rate

$$\dot{\varepsilon}_{ij}^{c} = \dot{\varepsilon}_{ij}^{d} + \dot{\varepsilon}_{ij}^{w}$$

dislocation creep strain rate

$$\dot{\varepsilon}_{ij}^{d} = \dot{\varepsilon}_{eq}^{d}\left(\sigma_{eq}^{f}, T\right)\frac{\partial \sigma_{eq}}{\partial \sigma_{ij}}$$

pressure solution creep strain rate

$$\dot{\varepsilon}_{ij}^{w} = \dot{\varepsilon}_{eq}^{w}\left(\sigma_{eq}^{f}, T\right)\frac{\partial \sigma_{eq}}{\partial \sigma_{ij}}$$

equivalent stress measures

$$\sigma_{eq}^{f} = \sigma_{eq}^{f}\left(\sigma_{m}, \sigma_{T}, D\right)$$

$$\sigma_{eq} = \sigma_{eq}\left(\sigma_{m}, \sigma_{T}, D\right)$$

σ_m = mean stress

σ_T = maximum principal stress difference = $\sigma_1 - \sigma_3$

D = fractional density = 1 - porosity

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Kinetic Equations for Dislocation Creep

$$\dot{\varepsilon}_{eq}^{d} = F\dot{\varepsilon}_{s} = F\sum_{i=1}^{3}\dot{\varepsilon}_{s_i}$$

F accounts for primary or transient creep

Three dislocation mechanisms in the model

1st mechanism: $$\dot{\varepsilon}_{s_1} = A_1\left(\frac{\sigma_{eq}^{f}}{\mu}\right)^{n_1} e^{-\frac{Q_1}{RT}}$$

2nd mechanism: $$\dot{\varepsilon}_{s_2} = A_2\left(\frac{\sigma_{eq}^{f}}{\mu}\right)^{n_2} e^{-\frac{Q_2}{RT}}$$

These are secondary or steady state creep terms

All dislocation creep mechanisms are temperature and stress dependent

3rd mechanism: $$\dot{\varepsilon}_{s_3} = \left(B_1 e^{-Q_1/RT} + B_2 e^{-Q_2/RT}\right)\sinh\left[q\left(\frac{\sigma_{eq}^{f} - \sigma_0}{\mu}\right)\right] H\left(\sigma_{eq}^{f} - \sigma_0\right)$$

The first mechanism (dislocation climb) dominates at low equivalent stress and high temperature. The second mechanism dominates at low stress and temperature. The third mechanism (dislocation slip) is predominately active at high stress for all temperatures.

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Kinetic Equation for Pressure Solution Creep

$$\dot{\varepsilon}_{eq}^{w} = \frac{r_1 w^a}{d^p} e^{-\bar{\varepsilon}_v}\left(\frac{e^{r_3\bar{\varepsilon}_v}}{\left|e^{\bar{\varepsilon}_v} - 1\right|^{r_4}}\right)\frac{e^{-\frac{Q_s}{RT}}}{T}\Gamma\sigma_{eq}^{f}$$

r_1, r_3, r_4, Q_s, a, p	material constants
T	absolute temperature
R	universal gas constant
d	salt grain size
w	moisure fraction by weight
$\bar{\varepsilon}_v$	volumetric strain
Γ	geometry function

Note that if the crushed salt is dry (w=0), the pressure solution contribution to the total strain rate vanishes. As porosity goes to zero the value of the geometry function also goes to zero.

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Organization of Presentation

- **Sierra Mechanics Physics Coupling Strategy**
- **Thermal- Mechanical (TM) Modeling**
  - **Briefly describe the constitutive model for intact and crushed salt**
  - **Results- Focus on consolidation time of the crushed salt backfill for varying values of assumed moisture content**
- **Thermal-Hydraulic (TH) Modeling**
  - **Model moisture movement due to decay heat in the crushed salt and EDZ regions**
- **Summary and Future Work**

Aria Porous Flow Physics

Two-Phase Heat and Mass Flow

Mathematical Model

- Two-Phase Component Mass and Energy Balances:

$$\frac{\partial}{\partial t}\begin{bmatrix} \phi\left(S_l\rho_l^w + S_g\rho_g^w\right) \\ \phi\left(S_l\rho_l^a + S_g\rho_g^a\right) \\ (1-\phi)\,\rho_s e_s + \phi\left(\rho_l S_l e_l + \rho_g S_g e_g\right) \end{bmatrix} + \nabla \bullet \begin{bmatrix} \mathbf{F}_l^w + \mathbf{F}_g^w \\ \mathbf{F}_l^a + \mathbf{F}_g^a \\ \mathbf{q}_e \end{bmatrix} + \begin{bmatrix} Q_w \\ Q_a \\ Q_e \end{bmatrix} \begin{matrix} \text{water} \\ \text{air} \\ \text{energy} \end{matrix}$$

- **Net Mass Flux:** $\mathbf{F}_\beta^\alpha = Y_\beta^\alpha \rho_\beta \mathbf{v}_\beta + \mathbf{J}_\beta^\alpha$

$\alpha = \text{component}$

$\beta = \text{phase}$

- **Darcy Velocity:** $\mathbf{v}_\beta = -\frac{k_{r\beta}}{\mu_\beta}\mathbf{k} \bullet \left(\nabla P_\beta - \rho_\beta \mathbf{g}\right)$
- **Binary Diffusion (gas phase):**

$$\mathbf{J}_g^\alpha = -\rho_g D_g^\alpha \nabla Y_g^\alpha$$

Aria Porous Flow Physics

Two-Phase Heat and Mass Flow

Mathematical Model (cont.)

- Total Energy Flux (heat conduction, convection, binary diffusion):

$$\mathbf{q}_e = -\lambda_T \nabla T + \sum_\beta \rho_\beta \mathbf{v}_\beta h_\beta + \sum_\alpha h_g^\alpha \mathbf{J}_g^\alpha$$

- **Saturation Constraint:** $S_l + S_g = 1$
- **Mixing Rules:** $\sum_{\beta=l,g} Y_\beta^\alpha = 1, \quad \alpha = w\,(\text{water}),\ a\,(\text{air})$
- **Capillary Pressure:** $P_g - P_l = P_c(S_l)$
- **Relative Permeability:** $k_{r,\beta} = f(S_l, T, \ldots)$

Microstructure simulation based on discrete element models

Christian Müller

DBE TECHNOLOGY GmbH, Eschenstraße 55, 31224 Peine, Germany

US-German Meeting

Albuquerque

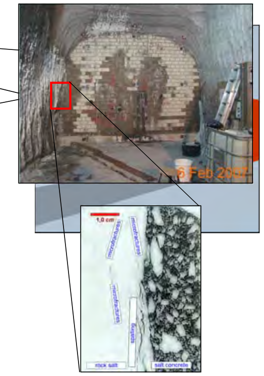
10.10.2012

The work presented is/was funded by the German Federal Ministry of Economics and Technology (Bundesministerium für Wirtschaft und Technologie, BMWi Nos 02E10649 and 02E11082)

Introduction

- The closure of a nuclear waste repository necessitates the sealing of all man-made openings in order to ensure the isolation capability

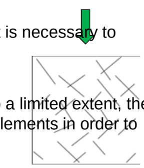
multibarrier system
- host rock
- sealing body
- excavation damaged zone (EDZ)

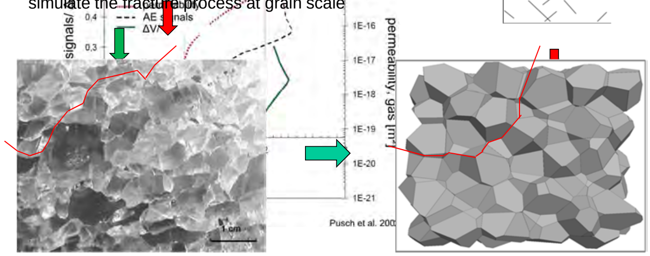


- The EDZ endangers the sealing function of geotechnical barriers
- The objective of this investigation is the development of a modeling strategy that can be used to investigate the permeability increase due to mechanical deterioration of rock salt

General modelling strategy

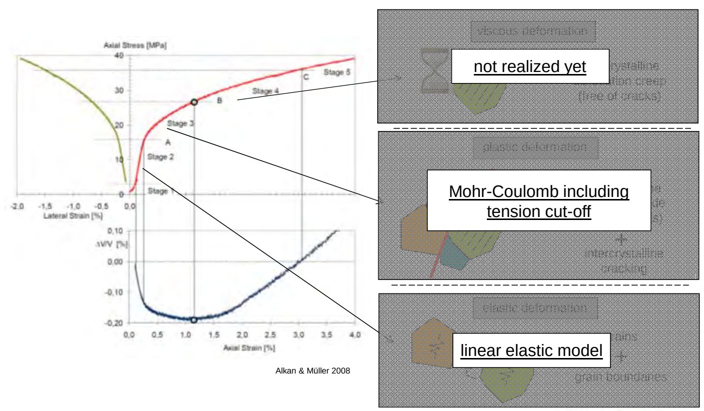
- permeability increases due to the connections between fractures
- to investigate the development and interaction of fractures, it is necessary to study the behavior at grain scale
- since continuum mechanical approaches are only suitable to a limited extent, the discrete element code 3DEC was applied using polyhedral elements in order to simulate the fracture process at grain scale

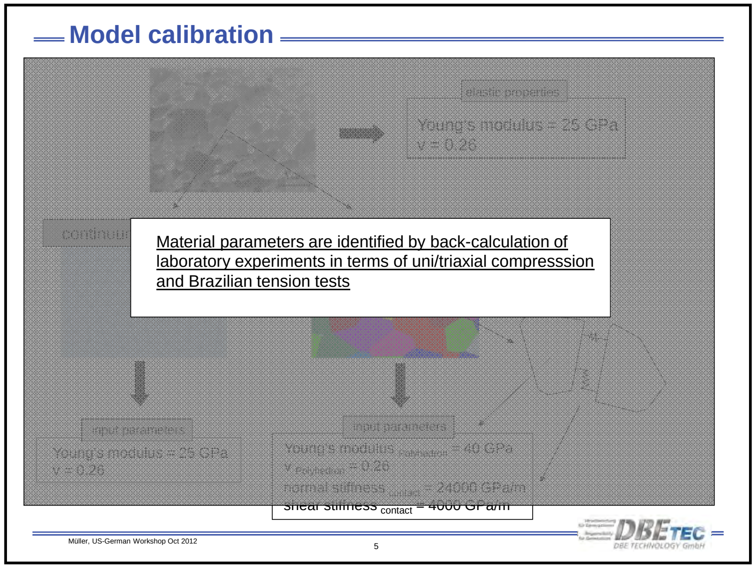




deterioration of rock salt

- the deformation of rock salt is characterised by a visco-elastoplastic behavior




Model calibration
elastic properties
Young's modulus = 25 GPa
v = 0.26
continuum
Material parameters are identified by back-calculation of laboratory experiments in terms of uni/triaxial compresssion and Brazilian tension tests
input parameters
Young's modulus = 25 GPa
v = 0.26
input parameters
Young's modulus Polyhedron = 40 GPa
v Polyhedron = 0.26
normal stiffness contact = 24000 GPa/m
shear stiffness contact = 4000 GPa/m
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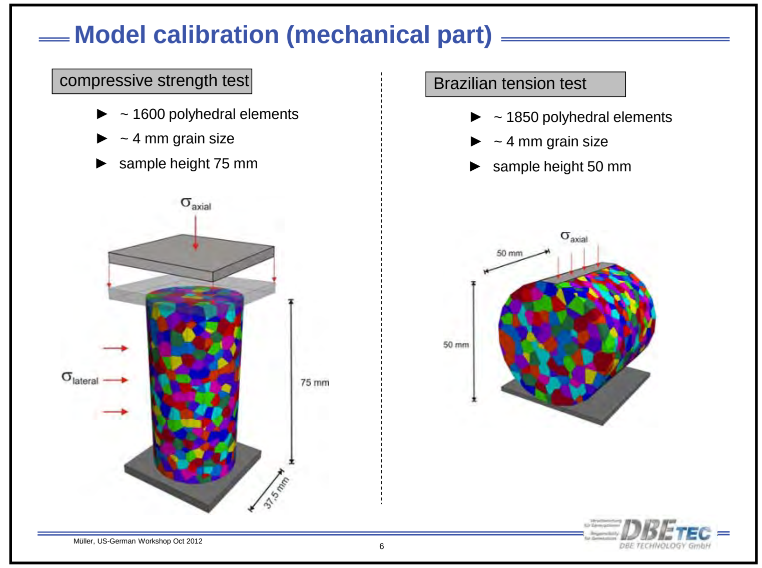
Model calibration (mechanical part)
compressive strength test
~ 1600 polyhedral elements
~ 4 mm grain size
sample height 75 mm
σaxial
σlateral
75 mm
37,5 mm
Brazilian tension test
~ 1850 polyhedral elements
~ 4 mm grain size
sample height 50 mm
σaxial
50 mm
50 mm
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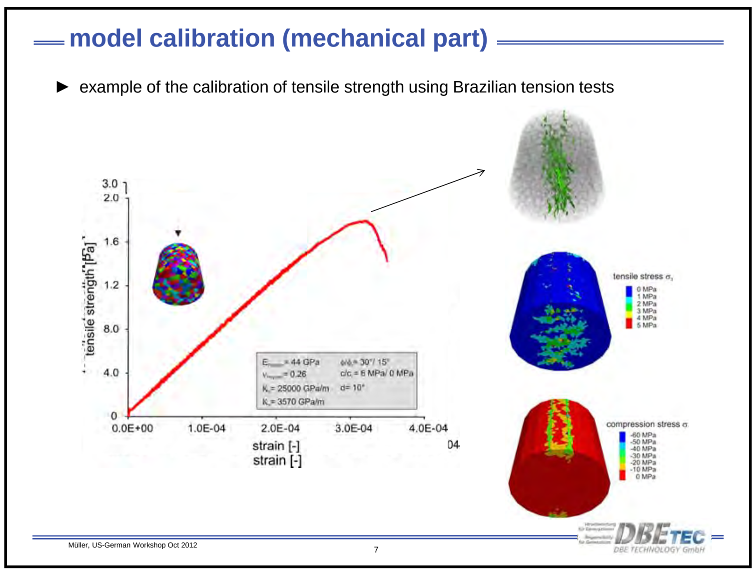
model calibration (mechanical part)
example of the calibration of tensile strength using Brazilian tension tests
tensile strength [Pa]
3.0
2.0
1.6
1.2
8.0
4.0
0
0.0E+00
1.0E-04
2.0E-04
3.0E-04
4.0E-04
strain [-]
tensile stress
compression stress
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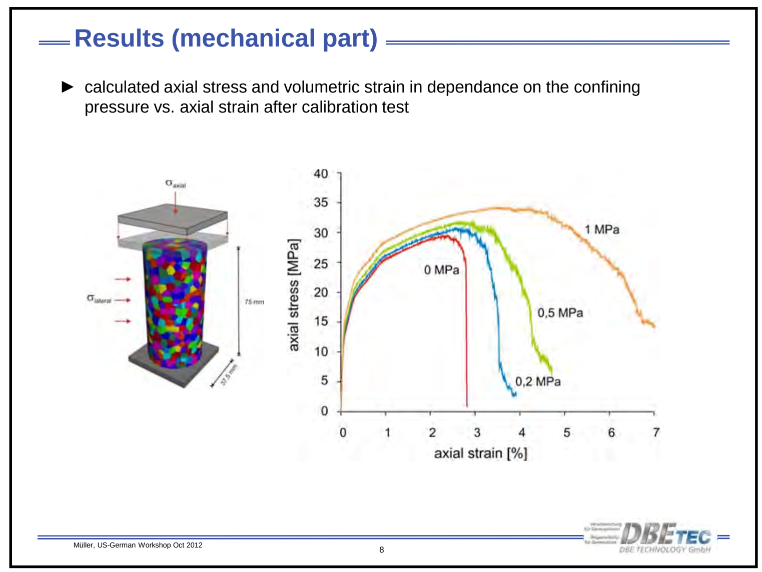
Results (mechanical part)
calculated axial stress and volumetric strain in dependance on the confining pressure vs. axial strain after calibration test
σaxial
σlateral
75 mm
37,5 mm
axial stress [MPa]
axial strain [%]
0 MPa
0,2 MPa
0,5 MPa
1 MPa
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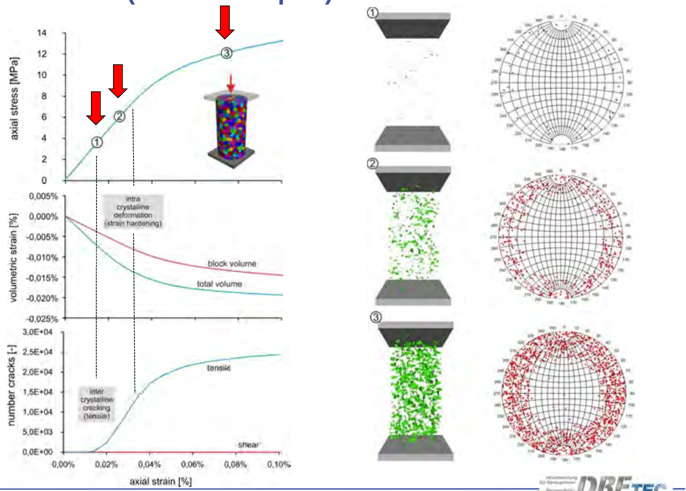
Results (mechanical part)



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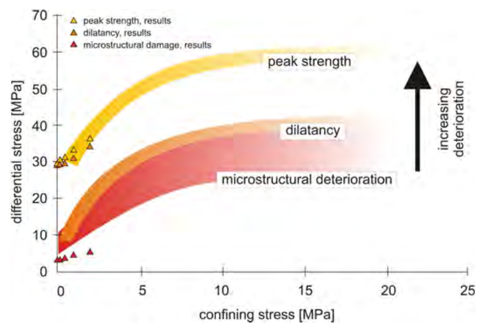
Results (mechanical part)



- the dilatancy boundary is quite late, shortly before the peak strength is reached, a result that is contrary to laboratory results

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Conclusion I

- first results from an initial calibration process show that the modeling approach is suitable to simulate intercrystalline microcracking in a realistic manner (-> tensile cracking)
- interaction between intra- and intercrystalline deformation does not fully correspond to laboratory experiments and needs further research
- more advanced creep models have to be implemented in order to simulate time-dependent deformation

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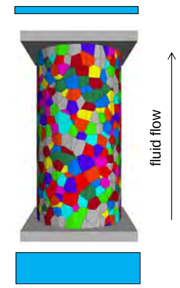
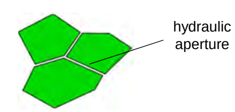
Model calibration (hydraulic part)



- macroscopic permeability is calculated by means of the cubic law using the hydraulic conductivity along the grain boundaries
- the cubic law is the hydraulic resitence against fracture aperture. Discharge largely depends on fracture aperture.



- the numerically determinded hydraulic conductivities have to be adapted to the results of laboratory tests by varying the hydraulic aperture

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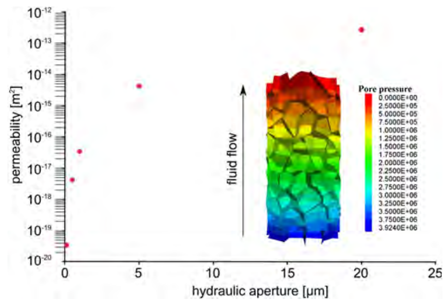
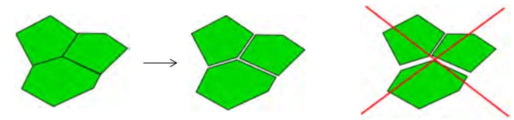
Results (hydraulic part)



- hydraulic aperture of 0.1 µm leads to permeability in the order of 10^{-19} – 10^{-20} m². Mechanical apertures derived from thin sections of undisturbed rocks salt indicate 1-5 µm.
- hydraulic apertures of 1-5 µm lead to permeability in the order of 10^{-15} – 10^{-17} m². In literature, mechanical apertures of up to 100 µm are documented but mechanical apertures below 10 µm are most common.

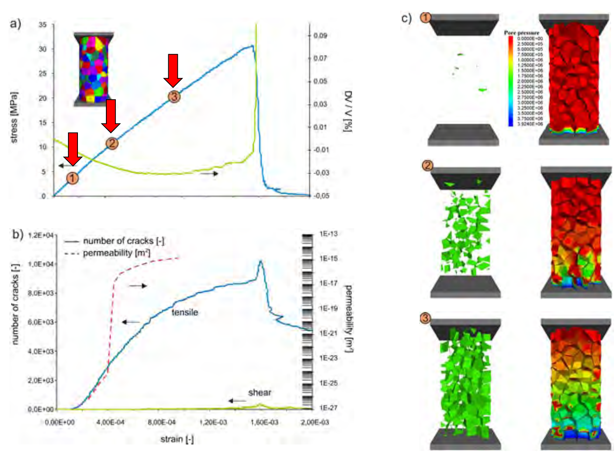
hydro-mechanical tests

- predictions about the percolation behavior cannot be made with simple hydraulic simulations
- in order to investigate the interrelationship between permeability and fracture development with increasing stress, fluid flow in unbroken contacts was inhibited, and a constant hydraulic aperture of 5 µm was assumed for every broken grain boundary



- this way, the hydraulic conductivity is solely controlled by the fracture connectivity since the fluid flow is limited by a constant hydraulic aperture after contact failure

results (hydo-mechanical part)



conclusion II

- first results from an initial calibration process show that the modeling approach is suitable to simulate intercrystalline microcracking in a realistic manner (-> tensile cracking)
- interaction between intra- and intercrystalline deformation does not fully correspond to laboratory experiments and needs further research
- more advanced creep models have to be implemented in order to simulate time-dependent deformation
- first results show a permeability increase above a certain fracture density threshold, which verifies that the polyhedral elements and 3DEC can be used for studying the percolation behavior at grain scale

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Thank you
for your attention

The work presented is/was funded by the German Federal Ministry of Economics and Technology (Bundesministerium für Wirtschaft und Technologie, BMWi Nos 02E10649 and 02E11082)

3rd US-German Workshop on

Salt Repository Research, Design and Operations

hosted by Sandia National Laboratories

Albuquerque, New Mexico, USA, October 9 - 11, 2012

Benchmark Modeling Status Report of the Current Joint Project III

Dr. Andreas Hampel

Sponsored by Federal Ministry of Economics and Technology (BMWI)

Joint Project III on the Comparison of Constitutive Models for Rock Salt

Managed by PTKA Projektträger Karlsruhe

Joint Project III on the Comparison of Constitutive Models for Rock Salt

BMWI Grant No.	Project Partners	
02E10810	Hampel Consulting, Mainz	A. Hampel
02E10820	Technische Universität Clausthal (TUC)	K. Herchen, R. Wolters, K.-H. Lux
02E10830	Institut für Gebirgsmechanik (IfG), Leipzig	R.-M. Günther, K. Salzer, W. Minkley
02E10840	Karlsruher Institut für Technologie (KIT)	A. Pudewills
02E10850	Leibniz Universität Hannover (LUH-IUB)	S. Yildirim, B. Leuger, D. Zapf, K. Staudtmeister, R. Rokahr
02E10860	Technische Universität Braunschweig (TUBS)	A. Gährken, C. Missal, J. Stahlmann
associated	Sandia National Laboratories (SNL)	J.G. Argüello, F. Hansen

Three Joint Projects on the Comparison of Constitutive Models for Rock Salt

Project	Period	Title	Main Objectives: Document, check and compare
I	04/2004 – 11/2006	The Modeling of the Mechanical Behavior of Rock Salt: Comparison of Current Constitutive Models and Modeling Procedures	• capabilities of the models to describe reliably the basic relevant deformation phenomena in rock salt
II	08/2007 – 07/2010	Comparison of Current Constitutive Models and Modeling Procedures with 3-D Calculations of the Mechan. Long-term Behavior of an Underground Structure in Rock Salt	suitability of the models to perform • 3-D simulations, • predictions of the future behavior, • calculation of permeability
III extens. (intent)	10/2010 – (01/2014) 09/2016	Comparison of Current Constitutive Models and Modeling Procedures with Calculations of the Thermo-mechanical Behavior and Healing of Rock Salt	• modeling of the temperature influence on the deformation behavior • modeling of sealing/healing of damaged rock salt with the models • simulations of Rooms B & D at WIPP (WIPP benchmark on T influence)

Partner	Constitutive Model	Numerical Code
Hampel	CCDM	FLAC3D (finite difference code)
IfG Leipzig	Günther/Salzer	FLAC3D (finite difference code)
IfG Leipzig	Minkley	FLAC3D (finite difference code)
KIT	KIT model	ADINA (finite element code)
TUC	Lux/Wolters	FLAC3D (finite difference code)
LUH-IUB	Lubby - MDCF	FLAC3D (finite difference code)
TUBS	Döring	FLAC3D (finite difference code) ANSYS (finite element code)
Sandia	MD	SIERRA Mechanics Code Suite (various coupled codes)

Work packages: see …

- Present the current status of considered constitutive models → Ralf-Michael Günther
- Plan and perform specific laboratory tests: T influence, healing → Uwe Düsterloh
- Determine salt type-specific model parameter values based on results of laboratory tests → this presentation
- Select and define in-situ structures for benchmark simulations → Lupe Argüello
- Perform simulations of selected in-situ structures
- Compare the simulation results with each other and with experimental results → this presentation
- Document models, parameter determinations, procedures, simulation results, comparisons, conclusions

General Procedure for Parameter Determination

1. At first, all salt type-specific parameter values of a constitutive model are determined with back-calculations of laboratory tests.

   => In lab tests, the various deformation phenomena are investigated under precisely defined conditions and partially independently of each other.

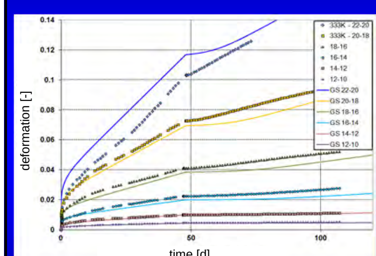
2. Then, a fine-tuning of parameter values is performed with an adjustment of the constitutive model to experimental data from in-situ measurements.

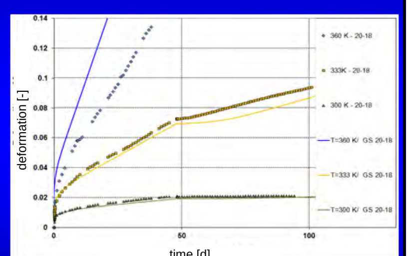
   => Take specific location into account and reduce effects of simplifications.

I. Modeling of the in-situ thermo-mechanical behavior of rock salt

Determine salt type-specific parameter values (1)

Back-calculations of creep tests (different σ_{eff}, different T) with one unique salt type-dependet set of parameter values





T = 60 °C
σ_{min} = 20 MPa
σ_{eff} = 22-20, 20-18, 18-16, 16-14, 14-12, 12-10 MPa

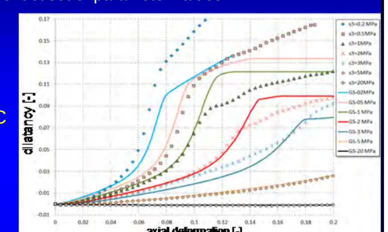
(examples: IfG-G/S) Asse-Speisesalz

T = 27, 60, 87 °C
σ_{min} = 20 MPa
σ_{eff} = 20-18 MPa

Determine salt type-specific parameter values (2)

Back-calculations of strength tests (different σ_{min}, different T) with the same unique salt type-dependet set of parameter values

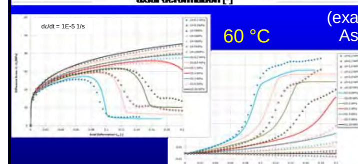
27 °C

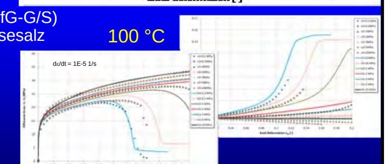


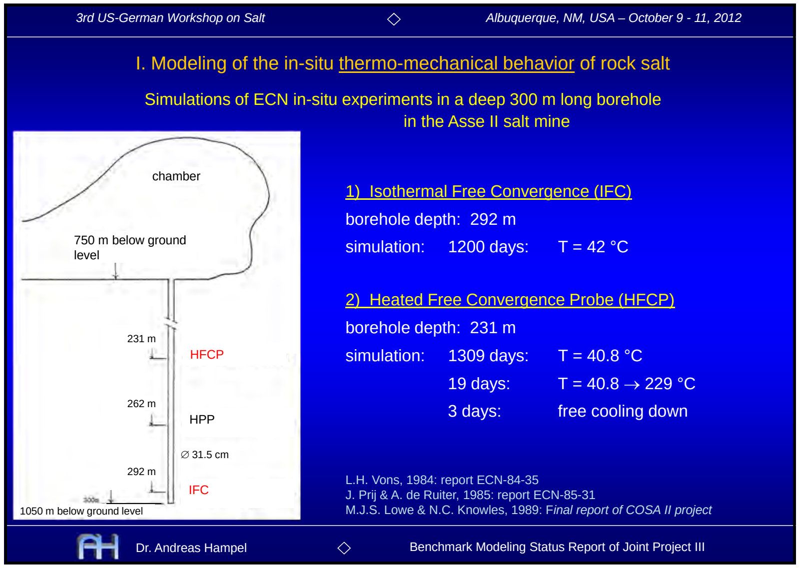
60 °C

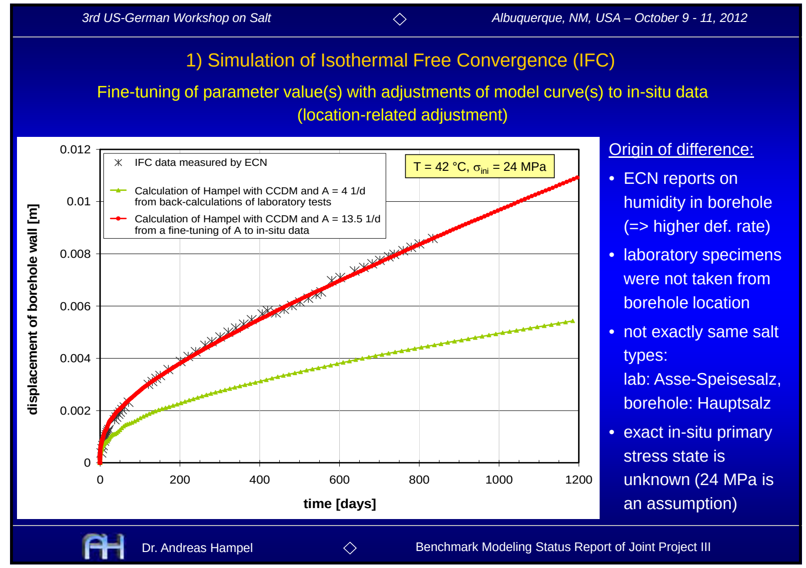
(examples: IfG-G/S) Asse-Speisesalz

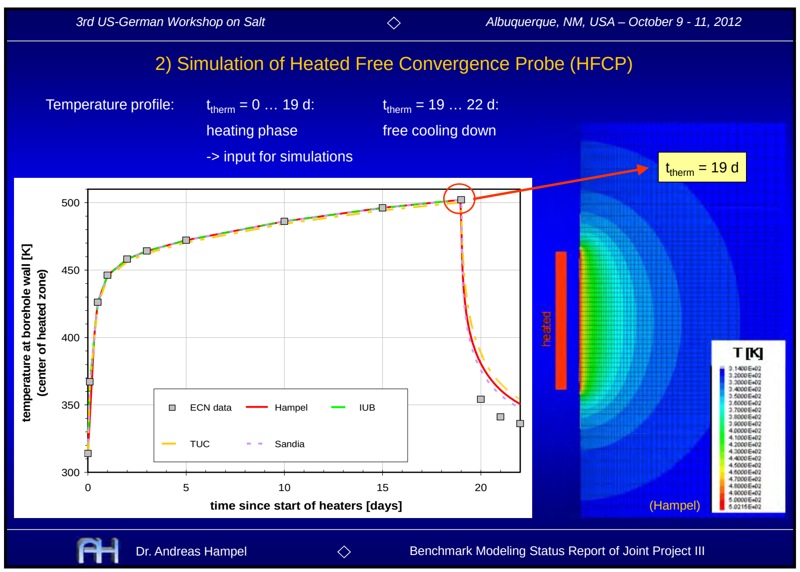
100 °C

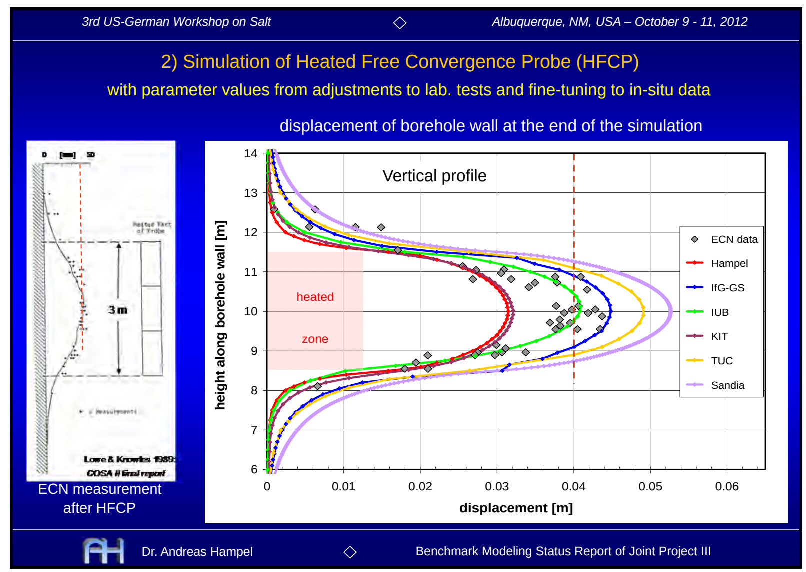


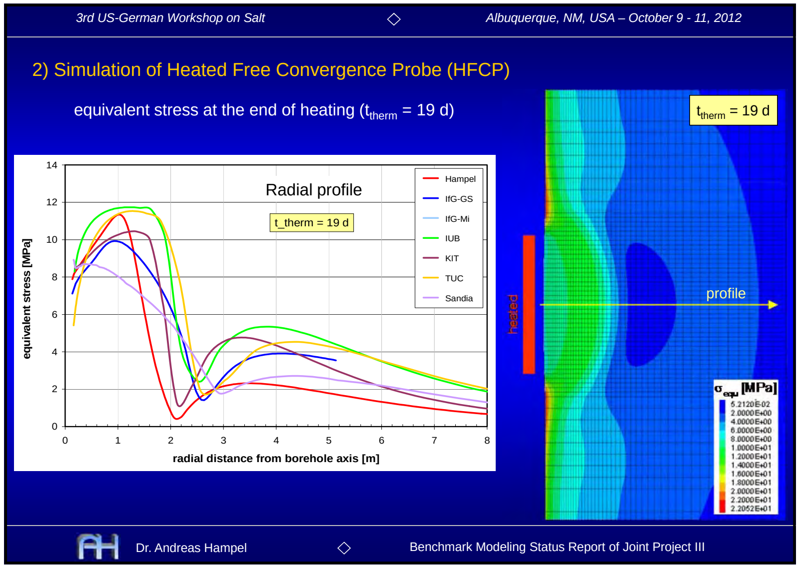


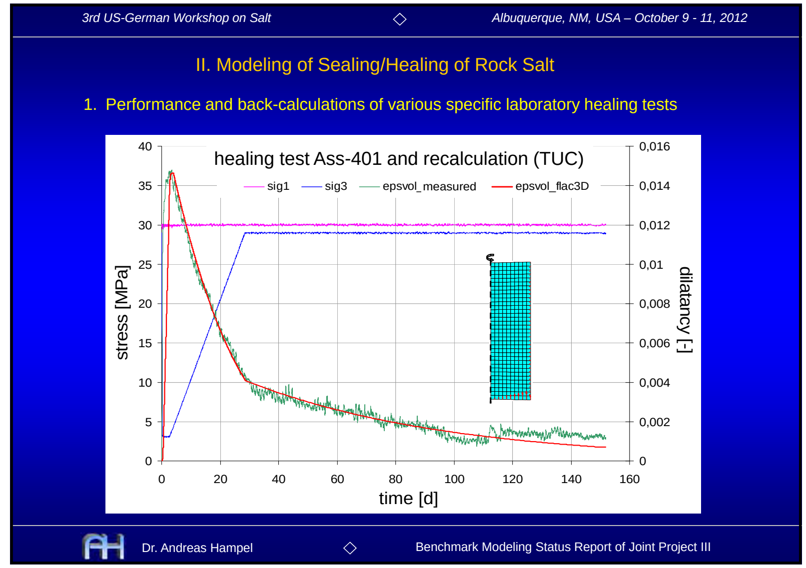

3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
I. Modeling of the in-situ thermo-mechanical behavior of rock salt
Simulations of ECN in-situ experiments in a deep 300 m long borehole in the Asse II salt mine
chamber
750 m below ground level
231 m
HFCP
262 m
HPP
∅ 31.5 cm
292 m
IFC
1050 m below ground level
1) Isothermal Free Convergence (IFC)
borehole depth: 292 m
simulation: 1200 days: T = 42 °C
2) Heated Free Convergence Probe (HFCP)
borehole depth: 231 m
simulation: 1309 days: T = 40.8 °C
19 days: T = 40.8 → 229 °C
3 days: free cooling down
L.H. Vons, 1984: report ECN-84-35
J. Prij & A. de Ruiter, 1985: report ECN-85-31
M.J.S. Lowe & N.C. Knowles, 1989: Final report of COSA II project
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III

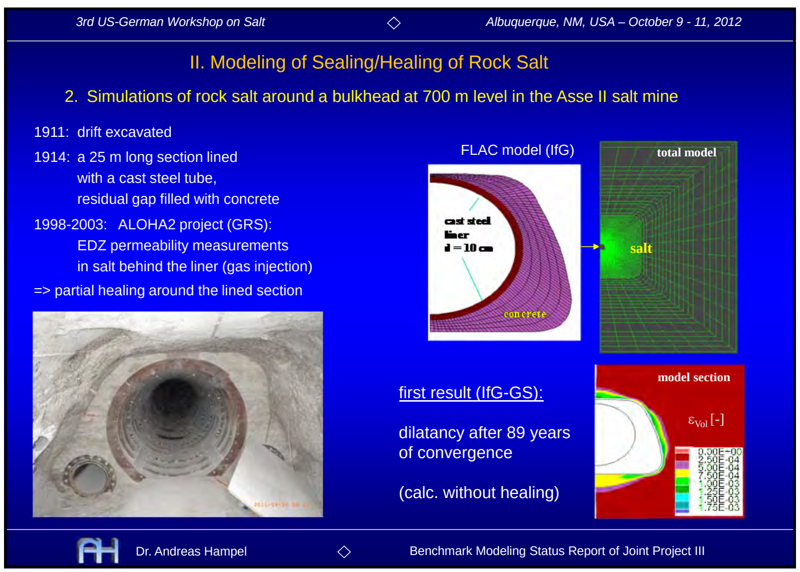

3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
1) Simulation of Isothermal Free Convergence (IFC)
Fine-tuning of parameter value(s) with adjustments of model curve(s) to in-situ data (location-related adjustment)
IFC data measured by ECN
Calculation of Hampel with CCDM and A = 4 1/d from back-calculations of laboratory tests
Calculation of Hampel with CCDM and A = 13.5 1/d from a fine-tuning of A to in-situ data
T = 42 °C, σini = 24 MPa
displacement of borehole wall [m]
time [days]
Origin of difference:
• ECN reports on humidity in borehole (=> higher def. rate)
• laboratory specimens were not taken from borehole location
• not exactly same salt types: lab: Asse-Speisesalz, borehole: Hauptsalz
• exact in-situ primary stress state is unknown (24 MPa is an assumption)
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III

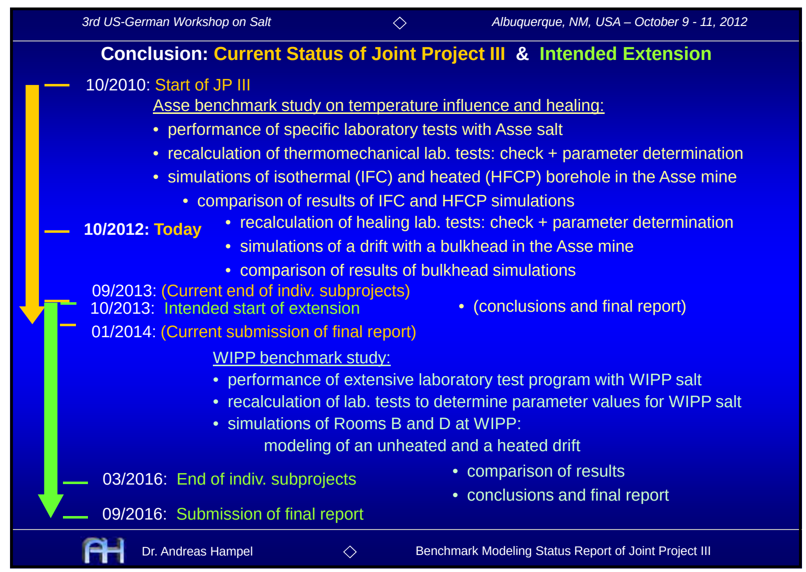

3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
2) Simulation of Heated Free Convergence Probe (HFCP)
Temperature profile: ttherm = 0 … 19 d: heating phase -> input for simulations
ttherm = 19 … 22 d: free cooling down
ttherm = 19 d
temperature at borehole wall [K] (center of heated zone)
time since start of heaters [days]
ECN data
Hampel
IUB
TUC
Sandia
heated
T [K]
(Hampel)
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III


3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
2) Simulation of Heated Free Convergence Probe (HFCP)
with parameter values from adjustments to lab. tests and fine-tuning to in-situ data
displacement of borehole wall at the end of the simulation
3 m
ECN measurement after HFCP
Vertical profile
heated
zone
height along borehole wall [m]
displacement [m]
ECN data
Hampel
IfG-GS
IUB
KIT
TUC
Sandia
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III


3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
2) Simulation of Heated Free Convergence Probe (HFCP)
equivalent stress at the end of heating (t_{therm} = 19 d)
Radial profile
t_therm = 19 d
Hampel
IfG-GS
IfG-Mi
IUB
KIT
TUC
Sandia
equivalent stress [MPa]
radial distance from borehole axis [m]
t_{therm} = 19 d
heated
profile
σ_{equ} [MPa]
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III


3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
II. Modeling of Sealing/Healing of Rock Salt
1. Performance and back-calculations of various specific laboratory healing tests
healing test Ass-401 and recalculation (TUC)
sig1
sig3
epsvol_measured
epsvol_flac3D
stress [MPa]
dilatancy [-]
time [d]
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III


3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
II. Modeling of Sealing/Healing of Rock Salt
2. Simulations of rock salt around a bulkhead at 700 m level in the Asse II salt mine
1911: drift excavated
1914: a 25 m long section lined
with a cast steel tube,
residual gap filled with concrete
1998-2003: ALOHA2 project (GRS):
EDZ permeability measurements
in salt behind the liner (gas injection)
=> partial healing around the lined section
FLAC model (IfG)
total model
cast steel liner d = 10 cm
salt
concrete
model section
first result (IfG-GS):
dilatancy after 89 years of convergence
(calc. without healing)
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III


3rd US-German Workshop on Salt
Albuquerque, NM, USA – October 9 - 11, 2012
Conclusion: Current Status of Joint Project III & Intended Extension
10/2010: Start of JP III
Asse benchmark study on temperature influence and healing:
• performance of specific laboratory tests with Asse salt
• recalculation of thermomechanical lab. tests: check + parameter determination
• simulations of isothermal (IFC) and heated (HFCP) borehole in the Asse mine
• comparison of results of IFC and HFCP simulations
10/2012: Today
• recalculation of healing lab. tests: check + parameter determination
• simulations of a drift with a bulkhead in the Asse mine
• comparison of results of bulkhead simulations
09/2013: (Current end of indiv. subprojects)
10/2013: Intended start of extension
• (conclusions and final report)
01/2014: (Current submission of final report)
WIPP benchmark study:
• performance of extensive laboratory test program with WIPP salt
• recalculation of lab. tests to determine parameter values for WIPP salt
• simulations of Rooms B and D at WIPP:
modeling of an unheated and a heated drift
03/2016: End of indiv. subprojects
• comparison of results
• conclusions and final report
09/2016: Submission of final report
Dr. Andreas Hampel
Benchmark Modeling Status Report of Joint Project III

Joint Project III

Comparison of Constitutive Models

Ralf-Michael Günther

Institut für Gebirgsmechanik Leipzig

3^{th} US-German Workshop in Albuquerque

Laboratory Tests - Examination of the **Mechanical Behavior** of Rock Salt

In Situ Tests – Observation of the **Geo-Mechanical Behavior** of Bearing Elements and the Salt- and Overburden Rock Masses

Examination, observation, understanding and discussion of the present and previous behavior

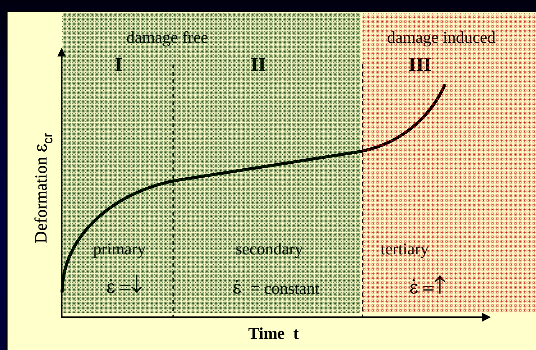
Numerical Calculations - Long Term **Prediction of Complex Geo Mechanical Structures**

Constitutive Models

which comprise the current knowledge of the Mechanical Behavior and the Geo-Mechanical Behavior

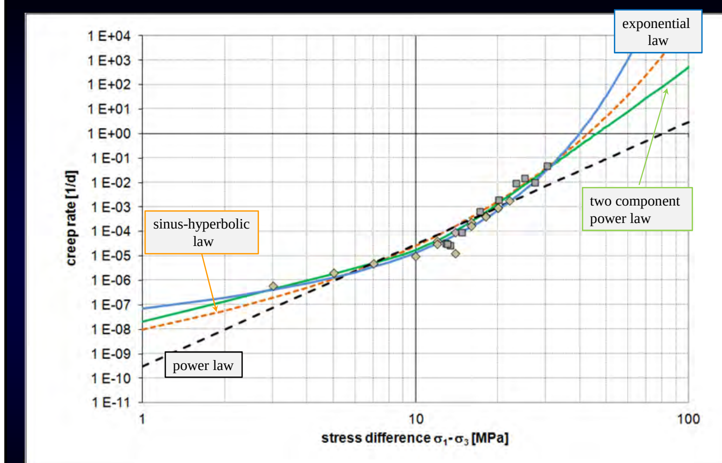
Suitable Models Wanted

Characteristical Creep Phases



The three creep phases are closely related and they change into each other as a result of intra-crystalline deformation processes.

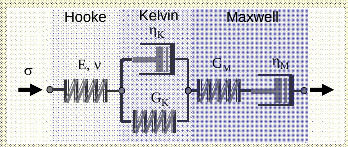
Models to Fit Creep Test Results (creep tests: Asse-Speisesalz – VBIII)



Principle Model Concepts for Primary and Secondary Creeping

Rheological Models

$$\dot{\varepsilon}_{cr} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{cr}^{prim} + \dot{\varepsilon}_{cr}^{second}$$



primary (p. cr.) and secondary (s. cr.) creep:
Kelvin-model is superposed to the Maxwell model

The following models work in such or in a similar way:

- **the Lux-Wolters model by TU Clausthal,**
  p. cr.=>strain hardening
  s. cr=> coupled exponential/ power law
- **the modified Döring model by TU Braunschweig,**
  p. cr.=>strain hardening/ s. cr=> exponential law
- **the modified Hein-model by the KIT,**
  p. cr.=>time hardening/ s. cr=> power law
- **the Minkley model by IfG Leipzig and**
  p. cr.=>time hardening/ s. cr=> sinus-hyperbolical law
- **the Lubby-MDCF model by IUB Hannover.**
  p. cr.=>time hardening/ s. cr=> exponential law

Structure Based Models

$$\dot{\varepsilon}_{cr} \rightarrow \left\{\dot{\varepsilon}_{el};\ \dot{\varepsilon}_{cr}^{prim};\ \dot{\varepsilon}_{cr}^{second}\right\}$$

$$\eta = f(S)$$

continuous transition form primary to secondary creep depending on one or more structural parameters

in analogy to the dislocation density:
- viscosity non constant for primary creep
- viscosity becomes constant for secondary creep

The following models work in such or in a similar way:

- **the CDM – model by Hampel**
  p. cr. strain hardening/ s. cr=> sinus-hyperbolical law
- **the MD – model by Sandia**
  p. cr.=>strain hardening/
  s. cr=> 2 component power law
  plus a sinus-hyperbolical law at higher stresses
- **the strain hardening Günther/ Salzer model by IFG**
  p cr. =>strain hardening
  s. cr=>2 component power law
  plus an optional high temperature creep term (power law)

Principle Model Concepts for Primary and Secondary Creeping

Structure Adapted Models

The CDM Model by Hampel

$$\dot{\varepsilon}_{cr} = \frac{b}{M}\frac{1}{r^2} v_0 \exp\left(-\frac{Q}{RT}\right)\sinh\left(\frac{b\ \Delta a(r,d_p)\ \sigma^*(w_i, r, a, \Delta\sigma, T)}{M\, k_B\, T}\right)$$

w_i, r, a = microstructural properties => S

$$\dot{S} = \frac{S_{ss} - S}{k_S} \cdot \dot{\varepsilon}_{cr}$$

$\dot{S} > 0 \Rightarrow$ primary creep
$\dot{S} = 0 \Rightarrow$ secondary creep

The Strain Hardening Günther/ Salzer Model by IFG

$$\dot{\varepsilon}_{cr} = \frac{A_p}{\varepsilon_{cr,V}^{\ \mu}} \cdot \sigma_{eff}^{\ n_p} \longleftrightarrow \dot{\varepsilon}_{cr,V} = \dot{\varepsilon}_{cr} - \dot{\varepsilon}_{cr,E} - \dot{\varepsilon}_{cr,S}$$

effective hardening deformation

$\dot{\varepsilon}_{cr,V} > 0 \Rightarrow$ primary creep
$\dot{\varepsilon}_{cr,V} = 0 \Rightarrow$ secondary creep
$\dot{\varepsilon}_{cr,V} < 0 \Rightarrow$ tertiary creep

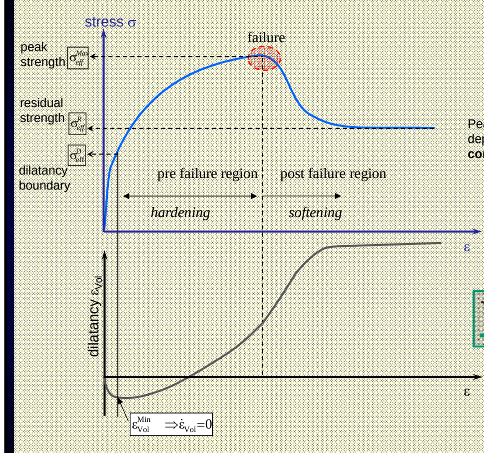
The MD Model by Sandia

$$\dot{\varepsilon}_{cr} = F \cdot \dot{\varepsilon}_{ss}$$

F- transient function
→ a distinction is made for hardening and recovery

$F > 1 \Rightarrow$ primary creep
$F = 1 \Rightarrow$ secondary creep

Behavior of a Rock Salt Sample at a Triaxial Strength Test



Dilatancy boundary, residual strength depend on the confining pressure

$$\sigma_{eff}^{D} = f(\sigma_3)$$
$$\sigma_{eff}^{R} = f(\sigma_3)$$

Peak strength and dilatancy development depend on the **confining pressure and the deformation rate**

$$\sigma_{eff}^{Max} = f(\sigma_3, \dot{\varepsilon})$$
$$\dot{\varepsilon}_{Vol} = f(\sigma_3, \dot{\varepsilon})$$

Temperature effect and damage healing?!
→ **subjects of the present joint project**

Dilatancy Boundaries

Aspects for Fixing the Dilatancy

Different dilatancy boundaries for extension and compression for Lux/Wolters (TUC) and the Lubby-MDCF(IUB) models.

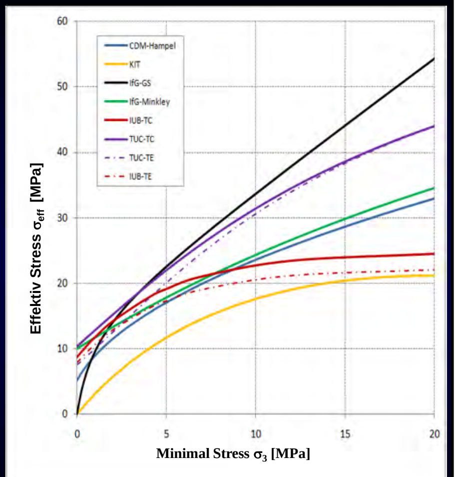
Lux/Wolters model considers also the ultrasonic wave velocity measurement.

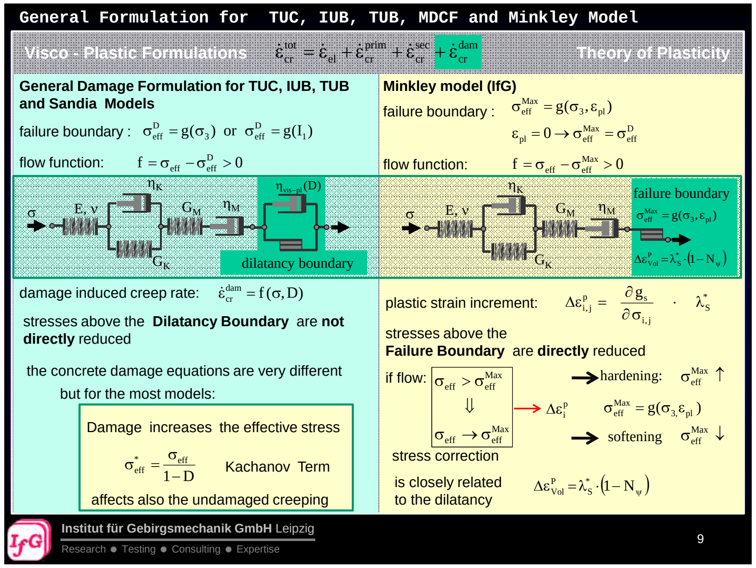
IUB dilatancy boundary is also closely related to the peak strength boundary (about 30% of peak strength).

Günther/Salzer model (IfG) considers dilatancy minimum and the residual strength

CDM-model (Hampel) and the Minkley-model (IfG) set the the dilatancy boundaries at dilatancy minimum

KIT-model uses the Hunsche/Cirstescu formulation from BGR as a non site-dependent universal dilatancy boundary.




General Formulation for TUC, IUB, TUB, MDCF and Minkley Model
Visco - Plastic Formulations
$\dot{\varepsilon}_{cr}^{tot} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{cr}^{prim} + \dot{\varepsilon}_{cr}^{sec} + \dot{\varepsilon}_{cr}^{dam}$
Theory of Plasticity
General Damage Formulation for TUC, IUB, TUB and Sandia Models
failure boundary: $\sigma_{eff}^{D} = g(\sigma_3)$ or $\sigma_{eff}^{D} = g(I_1)$
flow function: $f = \sigma_{eff} - \sigma_{eff}^{D} > 0$
dilatancy boundary
damage induced creep rate: $\dot{\varepsilon}_{cr}^{dam} = f(\sigma, D)$
stresses above the Dilatancy Boundary are not directly reduced
the concrete damage equations are very different but for the most models:
Damage increases the effective stress
$\sigma_{eff}^{*} = \frac{\sigma_{eff}}{1-D}$ Kachanov Term
affects also the undamaged creeping
Minkley model (IfG)
failure boundary: $\sigma_{eff}^{Max} = g(\sigma_3, \varepsilon_{pl})$
$\varepsilon_{pl} = 0 \rightarrow \sigma_{eff}^{Max} = \sigma_{eff}^{D}$
flow function: $f = \sigma_{eff} - \sigma_{eff}^{Max} > 0$
failure boundary
$\sigma_{eff}^{Max} = g(\sigma_3, \varepsilon_{pl})$
$\Delta\varepsilon_{Vol}^{p} = \lambda_S^{*} \cdot (1 - N_\psi)$
plastic strain increment: $\Delta\varepsilon_{i,j}^{p} = \frac{\partial g_s}{\partial \sigma_{i,j}} \cdot \lambda_S^{*}$
stresses above the Failure Boundary are directly reduced
if flow: $\sigma_{eff} > \sigma_{eff}^{Max}$ → hardening: $\sigma_{eff}^{Max} \uparrow$
$\Delta\varepsilon_i^p$ $\sigma_{eff}^{Max} = g(\sigma_3, \varepsilon_{pl})$
$\sigma_{eff} \rightarrow \sigma_{eff}^{Max}$ → softening $\sigma_{eff}^{Max} \downarrow$
stress correction
is closely related to the dilatancy $\Delta\varepsilon_{Vol}^{p} = \lambda_S^{*} \cdot (1 - N_\psi)$
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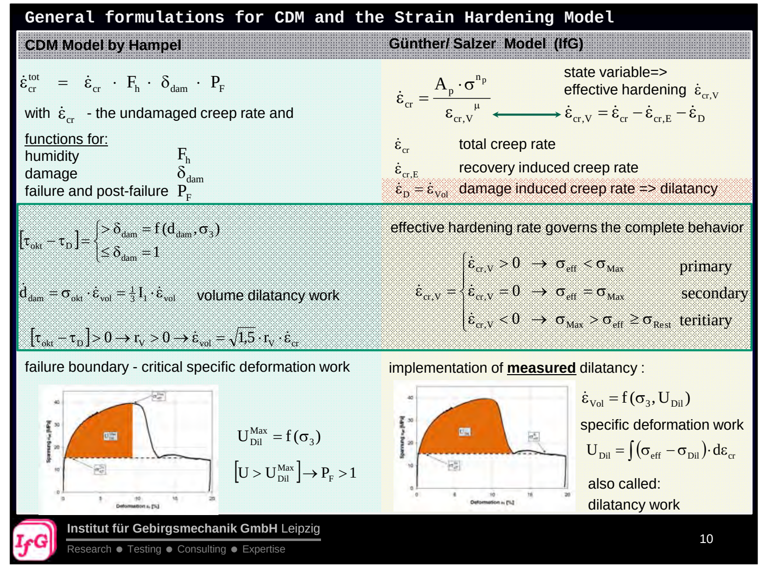
General formulations for CDM and the Strain Hardening Model
CDM Model by Hampel
$\dot{\varepsilon}_{cr}^{tot} = \dot{\varepsilon}_{cr} \cdot F_h \cdot \delta_{dam} \cdot P_F$
with $\dot{\varepsilon}_{cr}$ - the undamaged creep rate and
functions for:
humidity F_h
damage δ_{dam}
failure and post-failure P_F
$[\tau_{okt} - \tau_D] = \begin{cases} > \delta_{dam} = f(d_{dam}, \sigma_3) \\ \le \delta_{dam} = 1 \end{cases}$
$\dot{d}_{dam} = \sigma_{okt} \cdot \dot{\varepsilon}_{vol} = \frac{1}{3} I_1 \cdot \dot{\varepsilon}_{vol}$ volume dilatancy work
$[\tau_{okt} - \tau_D] > 0 \rightarrow r_V > 0 \rightarrow \dot{\varepsilon}_{vol} = \sqrt{1,5} \cdot r_V \cdot \dot{\varepsilon}_{cr}$
failure boundary - critical specific deformation work
$U_{Dil}^{Max} = f(\sigma_3)$
$[U > U_{Dil}^{Max}] \rightarrow P_F > 1$
Günther/ Salzer Model (IfG)
$\dot{\varepsilon}_{cr} = \frac{A_p \cdot \sigma^{n_p}}{\varepsilon_{cr,V}^{\mu}}$
state variable=> effective hardening $\varepsilon_{cr,V}$
$\dot{\varepsilon}_{cr,V} = \dot{\varepsilon}_{cr} - \dot{\varepsilon}_{cr,E} - \dot{\varepsilon}_D$
$\dot{\varepsilon}_{cr}$ total creep rate
$\dot{\varepsilon}_{cr,E}$ recovery induced creep rate
$\dot{\varepsilon}_D = \dot{\varepsilon}_{Vol}$ damage induced creep rate => dilatancy
effective hardening rate governs the complete behavior
$\dot{\varepsilon}_{cr,V} > 0 \rightarrow \sigma_{eff} < \sigma_{Max}$ primary
$\dot{\varepsilon}_{cr,V} = 0 \rightarrow \sigma_{eff} = \sigma_{Max}$ secondary
$\dot{\varepsilon}_{cr,V} < 0 \rightarrow \sigma_{Max} > \sigma_{eff} \ge \sigma_{Rest}$ teritiary
implementation of measured dilatancy :
$\dot{\varepsilon}_{Vol} = f(\sigma_3, U_{Dil})$
specific deformation work
$U_{Dil} = \int (\sigma_{eff} - \sigma_{Dil}) \cdot d\varepsilon_{cr}$
also called: dilatancy work
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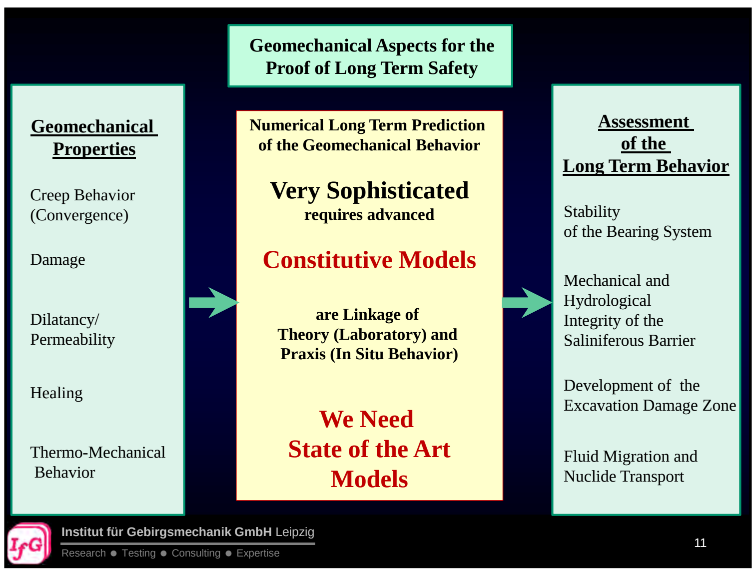
Geomechanical Aspects for the Proof of Long Term Safety
Geomechanical Properties
Creep Behavior (Convergence)
Damage
Dilatancy/ Permeability
Healing
Thermo-Mechanical Behavior
Numerical Long Term Prediction of the Geomechanical Behavior
Very Sophisticated
requires advanced
Constitutive Models
are Linkage of Theory (Laboratory) and Praxis (In Situ Behavior)
We Need State of the Art Models
Assessment of the Long Term Behavior
Stability of the Bearing System
Mechanical and Hydrological Integrity of the Saliniferous Barrier
Development of the Excavation Damage Zone
Fluid Migration and Nuclide Transport
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Approved methods for the salt type-specific parameter determination and laboratory test program matrix for WIPP salt

1. Corporate demands of different constutive models on strength and creep tests to determine mechanical material parameters
2. Lab procedures and methods to determine failure and dilation strength
3. Lab procedures and methods to determine damage free and damage induced creep behavior
4. Lab procedure and methods to determine healing induced creep behavior

3rd US/German Workshop on Salt Repository Research, Design and Operations
Albuquerque – 9th October 2012
PD Dr.-Ing. habil. U. Düsterloh – Clausthal University of Technology - Chair for Waste Disposal Technologies and Geomechanics

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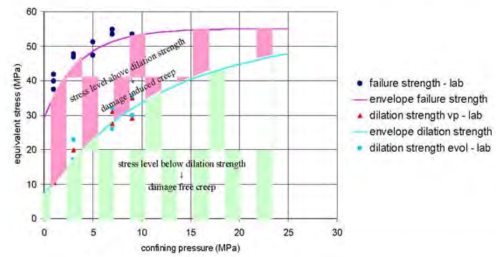
Corporate demands of different constitutive models on lab tests to determine material parameters

general remarks to the load bearing behavior of rock salt

Task of lab testing is given by the demand to guarantee in each case the ability to evaluate the specific model parameters



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Corporate demands of different constitutive models on lab tests to determine material parameters – proposed lab tests on WIPP salt

strength of rock salt in general depends on $\sigma_3, \dot{\varepsilon}_1, T, \theta, S$

σ_3 MPa	strain rate 1/s	T °C	Quantity -
0,2	1,00E-05	27	3
0,5	1,00E-05	27	3
1	1,00E-05	27	3
2	1,00E-05	27	3
3	1,00E-05	27	3
5	1,00E-05	27	3
20	1,00E-05	27	3

Σ = 21

σ_3 MPa	strain rate 1/s	T °C	Quantity -
0,2	1,00E-05	60	3
0,5	1,00E-05	60	3
1	1,00E-05	60	3
2	1,00E-05	60	3
3	1,00E-05	60	3
5	1,00E-05	60	3
20	1,00E-05	60	3

Σ = 21

σ_3 MPa	strain rate 1/s	T °C	Quantity -
0,2	1,00E-05	100	3
0,5	1,00E-05	100	3
1	1,00E-05	100	3
2	1,00E-05	100	3
3	1,00E-05	100	3
5	1,00E-05	100	3
20	1,00E-05	100	3

Σ = 21

σ_3 MPa	strain rate 1/s	T °C	Quantity -
0,2	1,00E-06	27	3
0,5	1,00E-06	27	3
1	1,00E-06	27	3
2	1,00E-06	27	3
3	1,00E-06	27	3
5	1,00E-06	27	3
20	1,00E-06	27	3

Σ = 21

σ_3 MPa	strain rate 1/s	T °C	Quantity -
0,2	1,00E-04	27	1
1	1,00E-04	27	1
2	1,00E-04	27	1
5	1,00E-04	27	1
20	1,00E-04	27	1

Σ = 5

σ_3 MPa	strain rate 1/s	T °C	Quantity -
?	?	?	?
?	?	?	?
?	?	?	?
?	?	?	?
?	?	?	?
?	?	?	?
?	?	?	?

Σ = 20

scatter band lab bench mark

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Corporate demands of different constitutive models on lab tests to determine material parameters

general remarks to creep behavior

albeit the various constitutive models the total creep rate is calculated in each case by single creep parts

$$\dot{\varepsilon}^{total} = f(\dot{\varepsilon}^{e}, \dot{\varepsilon}^{tr}, \dot{\varepsilon}^{s}, \dot{\varepsilon}^{d}, \dot{\varepsilon}^{h})$$

creep of rock salt in general depends on σ_{eq}, T, t, S

a significant change of creep behavior is observed by exceeding dilation strength

$$\dot{\varepsilon}^{d} \neq 0 \text{ if } \sigma_{eq} > \beta_{dil}$$

a previous damaged rock salt can by healed by reducing the stress level below dilation strength

$$\dot{\varepsilon}^{h} \neq 0 \text{ if } D > 0, \sigma_{eq} \leq \beta_{dil}$$

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Corporate demands of different constitutive models on lab tests to determine material parameters – proposed lab tests on WIPP salt

general remarks to creep behavior

creep of rock salt depends on σ_{eq}, T, t, D, S

scatter band lab bench mark

σ_3 MPa	σ_{eq} MPa	T °C	load level -	duration d	loading / unloading	above/below dilation strength	quantity -
20	>10	27	2	60/60	L/U	b/b	5
20	>10	60	2	60/60	L/U	b/b	5
20	>10	100	2	60/60	L/U	b/b	5
20	<10	60	1	120	L	b	4
20		27/60/100	3	60/60/60	L/L/L	b	3
5	>35	27	1		L	a	1
different	different	27	4	60/60/30/30	L/L/L/L	b/b/a/a	4
?	?	?	?	?	?	?	10

Σ = 37

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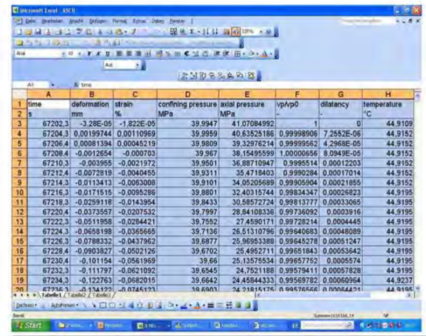
Corporate demands of different constitutive models on lab tests to determine material parameters



handover of tabular lab data to guarantee parameter determination regarding specific constitutive models

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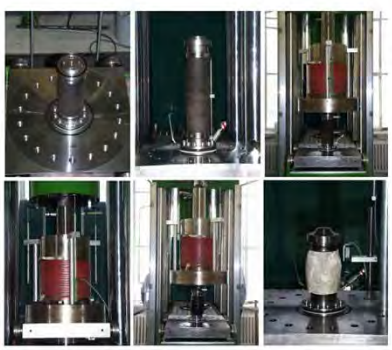
Lab procedure and methods to determine failure and dilation strength



in general similar to that used since decades of years to determine failure strength

+
recompaction and tempering phase

+
measuring of volume change

+
measuring ultrasonic wave velocity

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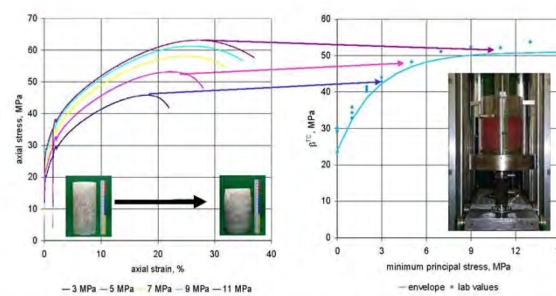
Lab procedure and methods to determine failure and dilation strength

appointment of failure strength – depending on minimum principal stress



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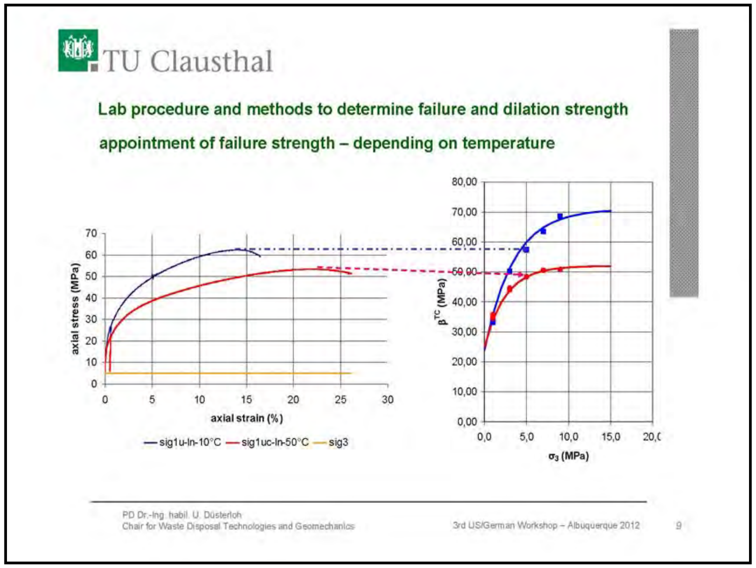
TU Clausthal
Lab procedure and methods to determine failure and dilation strength
appointment of failure strength – depending on temperature
axial stress (MPa)
axial strain (%)
sig1u-ln-10°C
sig1uc-ln-50°C
sig3
β^{TC} (MPa)
σ_3 (MPa)
PD Dr.-Ing. habil. U. Düsterloh
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3rd US/German Workshop – Albuquerque 2012
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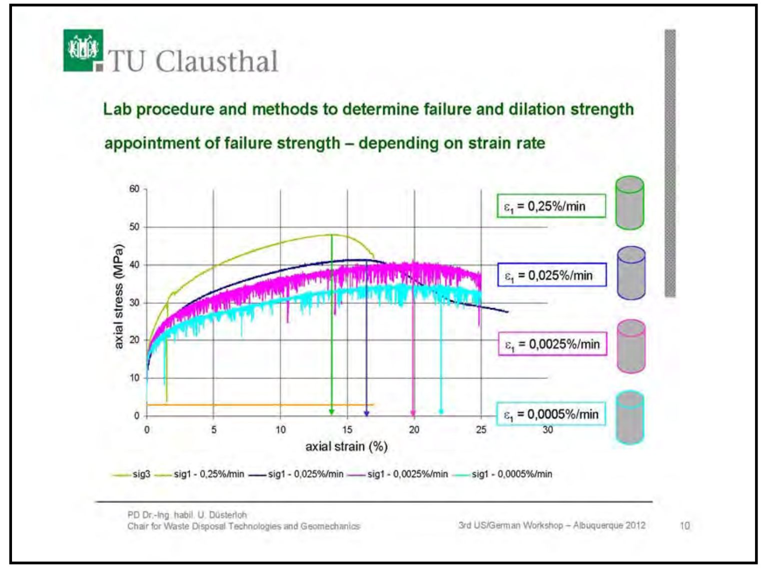
TU Clausthal
Lab procedure and methods to determine failure and dilation strength
appointment of failure strength – depending on strain rate
axial stress (MPa)
axial strain (%)
ε_1 = 0,25%/min
ε_1 = 0,025%/min
ε_1 = 0,0025%/min
ε_1 = 0,0005%/min
sig3
sig1 - 0,25%/min
sig1 - 0,025%/min
sig1 - 0,0025%/min
sig1 - 0,0005%/min
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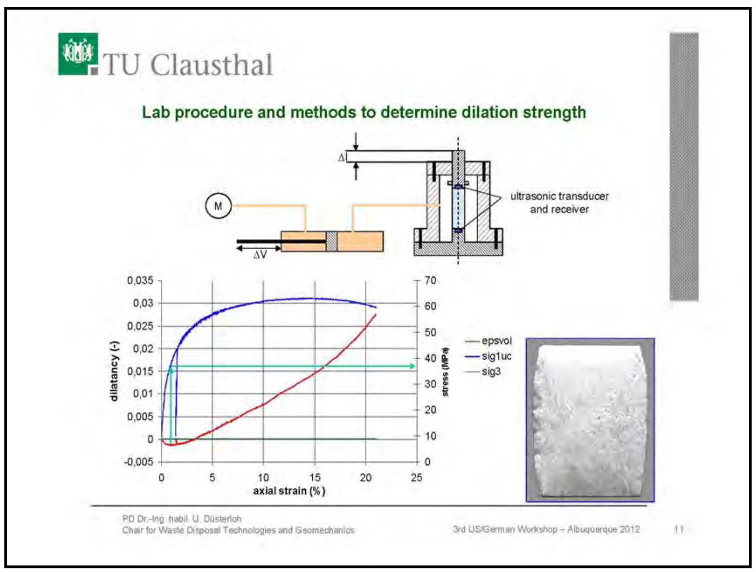
TU Clausthal
Lab procedure and methods to determine dilation strength
M
ΔV
Δl
ultrasonic transducer and receiver
dilatancy (-)
stress (MPa)
axial strain (%)
epsvol
sig1uc
sig3
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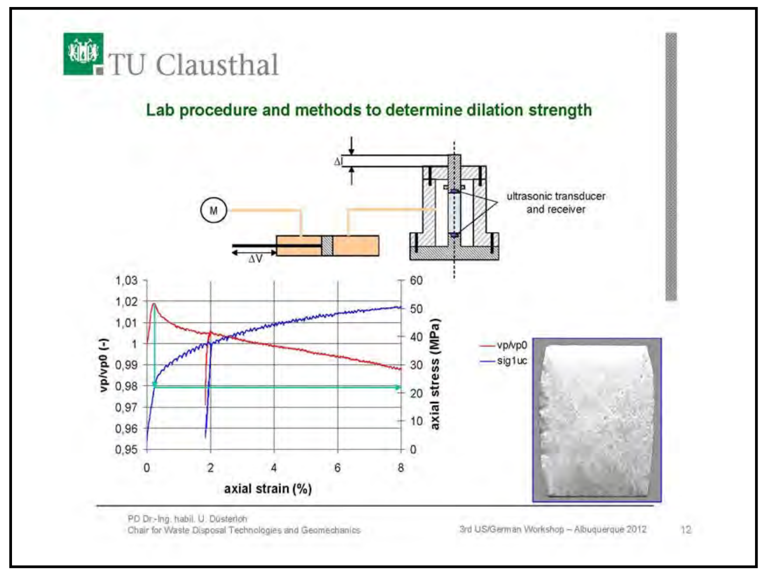
TU Clausthal
Lab procedure and methods to determine dilation strength
M
ΔV
Δl
ultrasonic transducer and receiver
vp/vp0 (-)
axial stress (MPa)
axial strain (%)
vp/vp0
sig1uc
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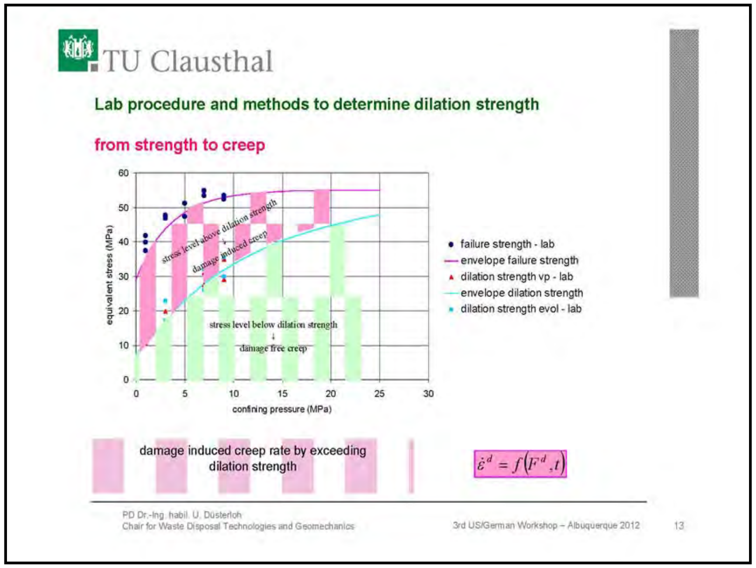
TU Clausthal
Lab procedure and methods to determine dilation strength
from strength to creep
equivalent stress (MPa)
confining pressure (MPa)
stress level above dilation strength
damage induced creep
stress level below dilation strength
damage free creep
failure strength - lab
envelope failure strength
dilation strength vp - lab
envelope dilation strength
dilation strength evol - lab
damage induced creep rate by exceeding dilation strength
$\dot{\varepsilon}^d = f(F^d, t)$
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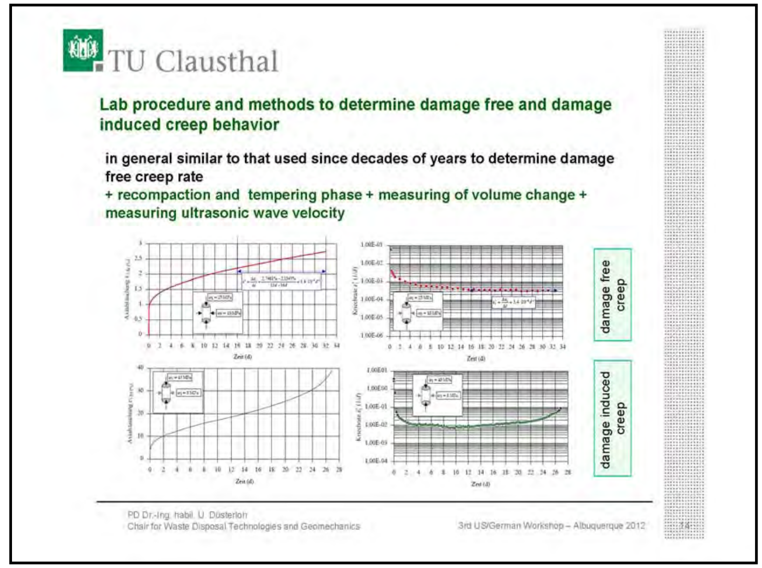
TU Clausthal
Lab procedure and methods to determine damage free and damage induced creep behavior
in general similar to that used since decades of years to determine damage free creep rate
+ recompaction and tempering phase + measuring of volume change + measuring ultrasonic wave velocity
damage free creep
damage induced creep
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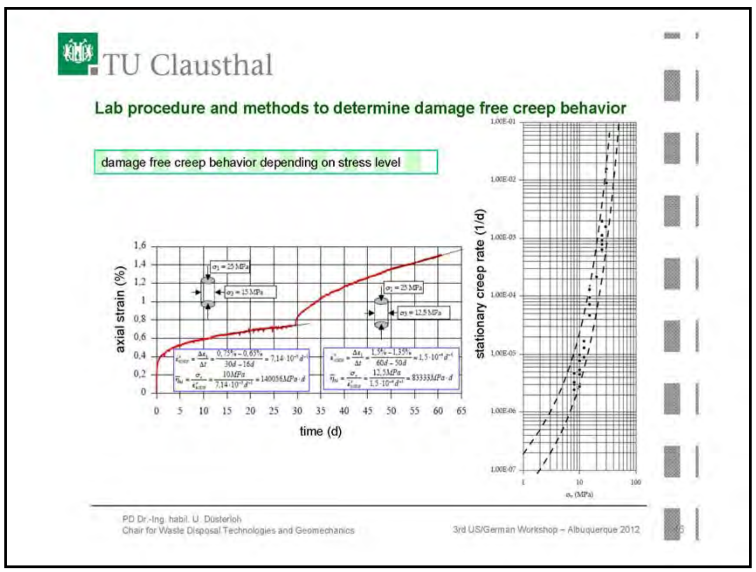
TU Clausthal
Lab procedure and methods to determine damage free creep behavior
damage free creep behavior depending on stress level
axial strain (%)
time (d)
stationary creep rate (1/d)
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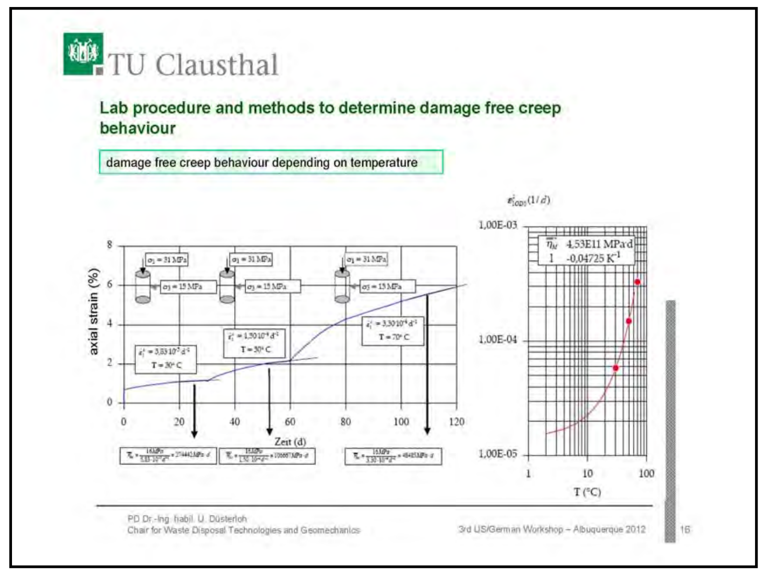
TU Clausthal
Lab procedure and methods to determine damage free creep behaviour
damage free creep behaviour depending on temperature
axial strain (%)
Zeit (d)
T (°C)
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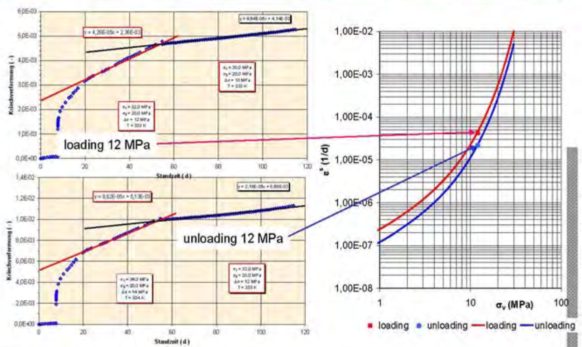
Lab procedure and methods to determine damage free creep behavior

Loading-Unloading creep tests to determine damage free creep behavior depending on testing time



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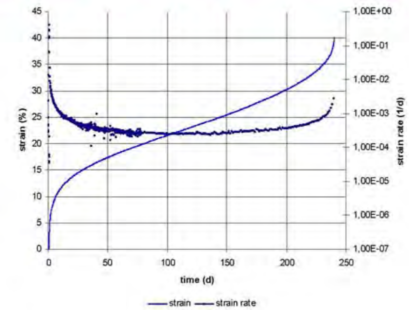
Lab procedure and methods to determine damage induced creep behavior

damage induced creep behavior → loading above dilation strength



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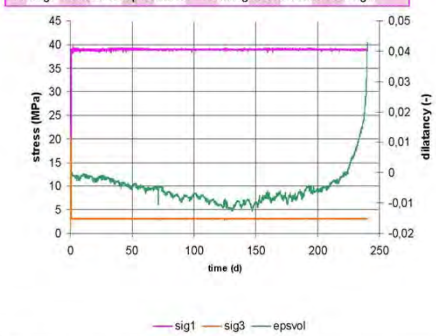
Lab procedure and methods to determine damage induced creep behavior

damage induced creep behavior → loading above dilation strength



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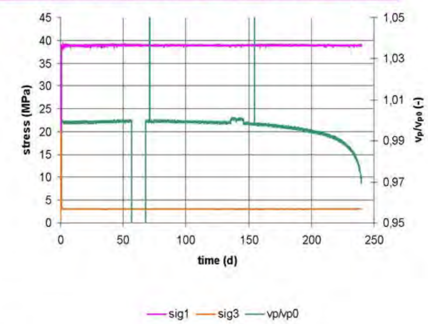
Lab procedure and methods to determine damage induced creep behavior

damage induced creep behavior → loading above dilation strength



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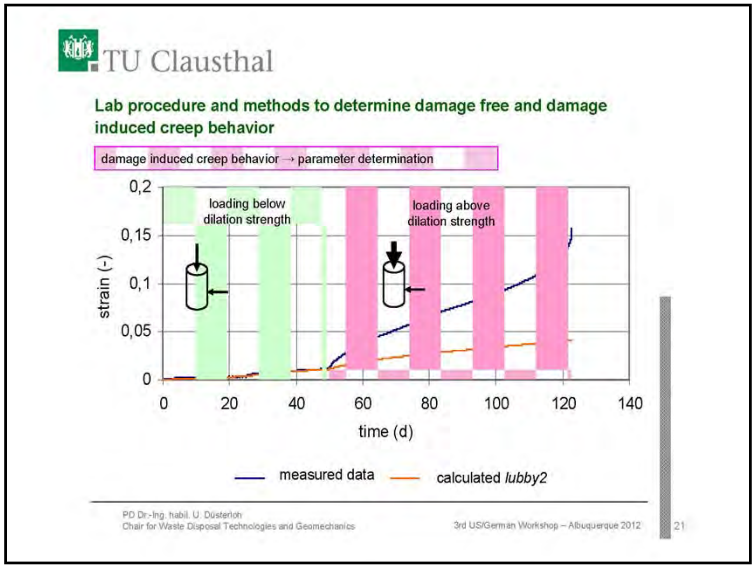
TU Clausthal
Lab procedure and methods to determine damage free and damage induced creep behavior
damage induced creep behavior → parameter determination
loading below dilation strength
loading above dilation strength
strain (-)
time (d)
measured data
calculated lubby2
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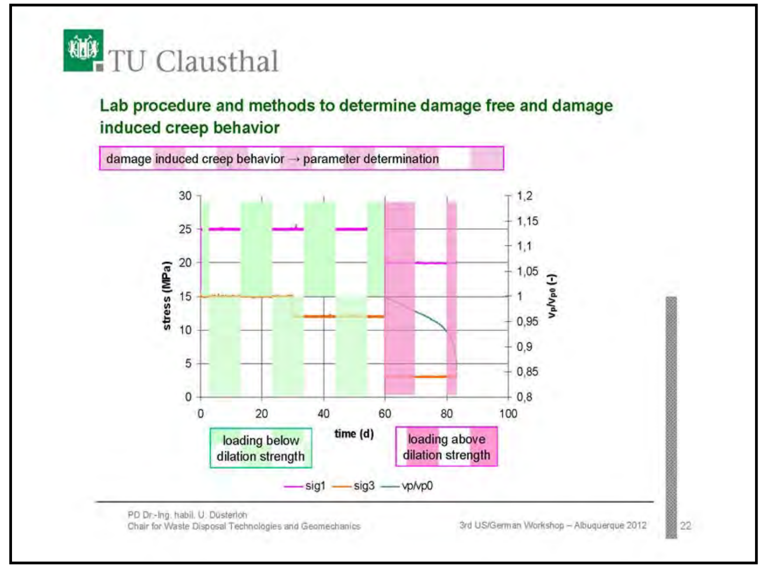
TU Clausthal
Lab procedure and methods to determine damage free and damage induced creep behavior
damage induced creep behavior → parameter determination
stress (MPa)
time (d)
loading below dilation strength
loading above dilation strength
sig1
sig3
vp/vp0
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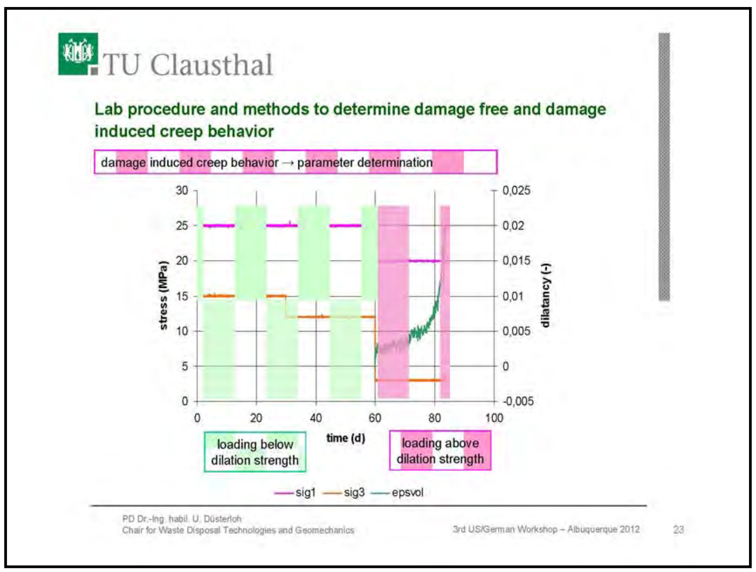
TU Clausthal
Lab procedure and methods to determine damage free and damage induced creep behavior
damage induced creep behavior → parameter determination
stress (MPa)
dilatancy (-)
time (d)
loading below dilation strength
loading above dilation strength
sig1
sig3
epsvol
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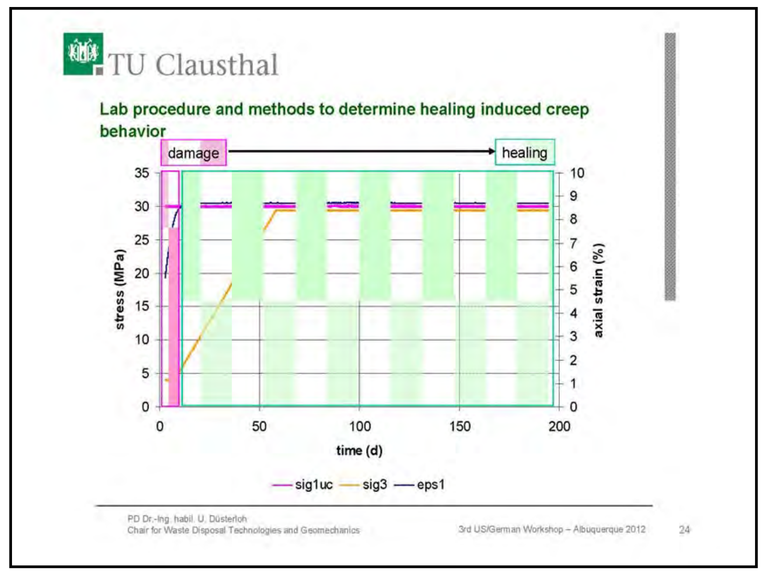
TU Clausthal
Lab procedure and methods to determine healing induced creep behavior
damage
healing
stress (MPa)
axial strain (%)
time (d)
sig1uc
sig3
eps1
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Chair for Waste Disposal Technologies and Geomechanics
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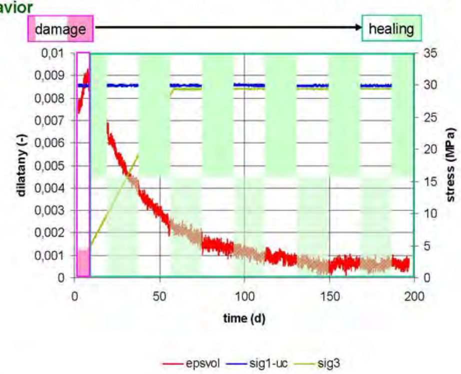
TU Clausthal

Lab procedure and methods to determine healing induced creep behavior



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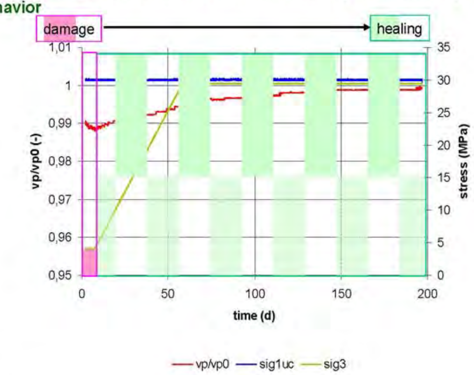
Lab procedure and methods to determine healing induced creep behavior



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Approved methods for the salt type- specific parameter determination and laboratory test program matrix for WIPP salt

conclusion and remarks

- to image the damage induced load bearing behavior of rock salt a yield surface is needed to seperate loadings above and below a damage inducing stress level
- to indicate damage processes an online measuring of volume change and ultrasonic wave velocity is suitable
- to analyze damage induced processes special attention is demanded to the measuring accuracy, that is to say volume measuring must be able to define values of few ml in times of weeks to months
- due to the influence of alternating environment temperatures to the
- volume measuring the lab temperature should be regulated as much as possible

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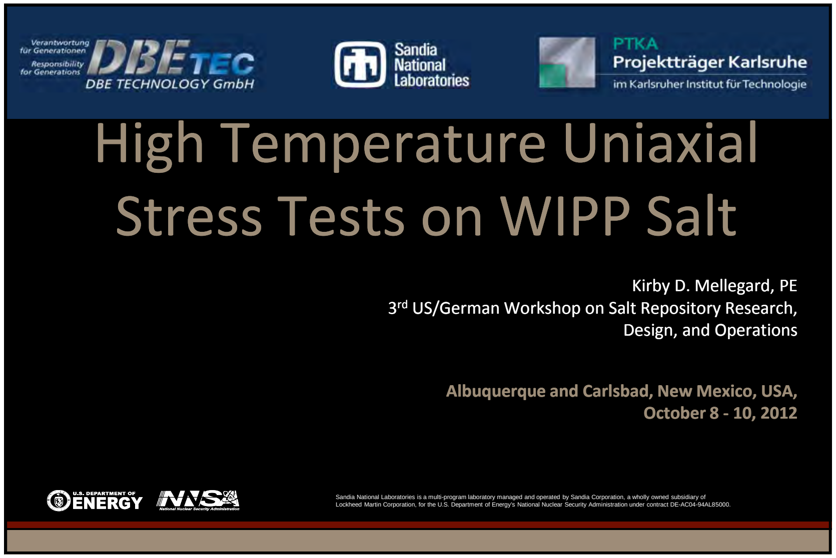
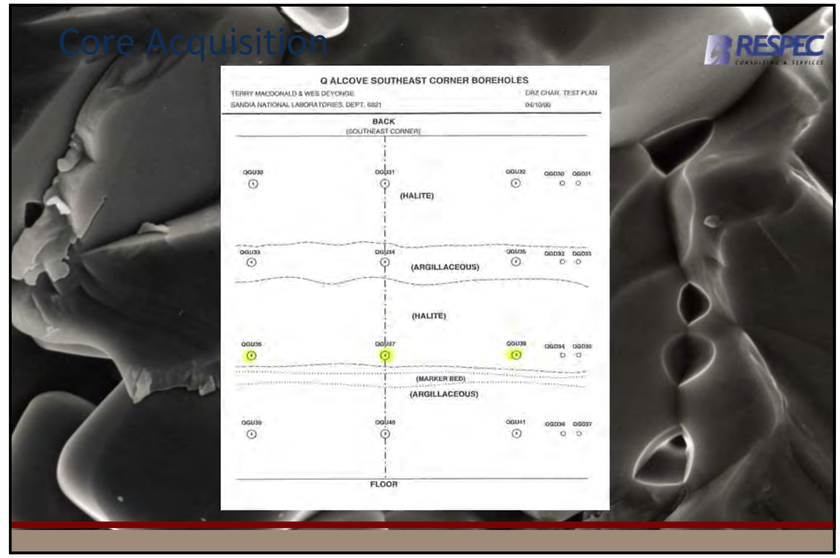

DBE TEC
DBE TECHNOLOGY GmbH
Sandia National Laboratories
PTKA
Projektträger Karlsruhe
im Karlsruher Institut für Technologie
High Temperature Uniaxial Stress Tests on WIPP Salt
Kirby D. Mellegard, PE
3rd US/German Workshop on Salt Repository Research, Design, and Operations
Albuquerque and Carlsbad, New Mexico, USA, October 8 - 10, 2012


Core Acquisition
Q ALCOVE SOUTHEAST CORNER BOREHOLES
BACK
(HALITE)
(ARGILLACEOUS)
(HALITE)
(MARKER BED)
(ARGILLACEOUS)
FLOOR

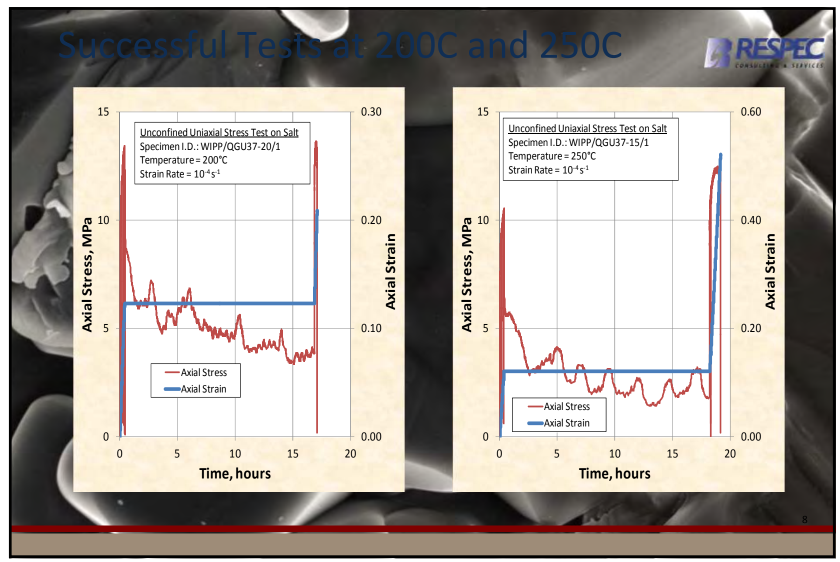

Lathe for Specimen Preparation

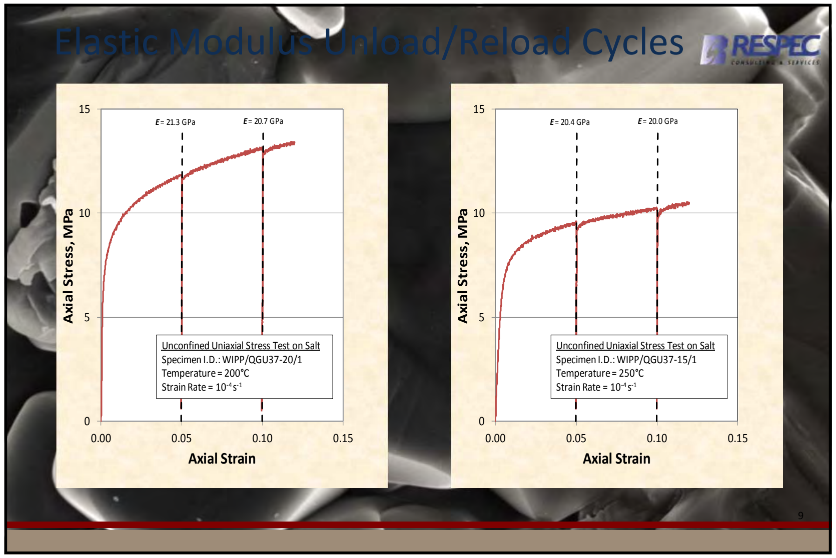

Brine Inclusions

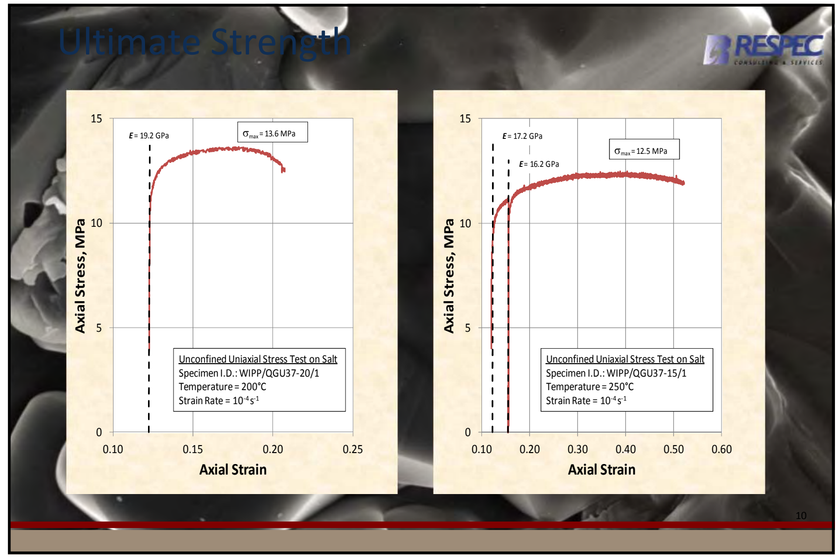

Test System
RESPEC


Typical Pretest Specimens
RESPEC
WIPP/QGU37-20/2
WIPP/QGU37-45/1


Violent Decrepitation at T ≈ 280C
RESPEC


Successful Tests at 200C and 250C
RESPEC
Unconfined Uniaxial Stress Test on Salt
Specimen I.D.: WIPP/QGU37-20/1
Temperature = 200°C
Strain Rate = $10^{-4}s^{-1}$
Axial Stress
Axial Strain
Axial Stress, MPa
Axial Strain
Time, hours
Unconfined Uniaxial Stress Test on Salt
Specimen I.D.: WIPP/QGU37-15/1
Temperature = 250°C
Strain Rate = $10^{-4}s^{-1}$
Axial Stress
Axial Strain
Axial Stress, MPa
Axial Strain
Time, hours





Summary of Test Results

Specimen I.D. (Temperature)	Strain Level (%)	Stress (MPa)	Young's Modulus (GPa)	Comment
WIPP/QGU37-20/1 (200°C)	5	11.8	21.3	First unload/reload
	10	13.1	20.7	Second unload/reload
	12	13.4	—	Start of stress relaxation
	12	~4	19.2	End of stress relaxation
	~18	13.6	—	Ultimate strength
	21	12.6	—	Test termination
WIPP/QGU37-15/1 (250°C)	5	9.6	20.4	First unload/reload
	10	10.2	20.0	Second unload/reload
	12	10.5	—	Start of stress relaxation
	12	~2	17.2	End of stress relaxation
	15.5	11.1	16.2	Unload/reload for LVDT reset
	~40	12.5	—	Ultimate strength
	52	11.9	—	Test termination

11


Conclusions
RESPEC
WIPP salt exhibits violent decrepitation at about 280C. This behavior is consistent with previous studies reported by Project Salt Vault. This behavior is predominantly associated with bedded salts. Domal salts have been successfully heated to 400C.
The test protocol was successful and should be used in future uniaxial testing with temperature limited to 275C.
Expanded database will be used to evaluate numerical simulations made using existing models that extrapolate to previously uninvestigated temperatures above 200C.

Exceptional service in the national interest

Sandia National Laboratories

Outlook on the Benchmark Proposal for WIPP Rooms B & D

J. Guadalupe Argüello
Frank D. Hansen

3rd US/German Workshop on
Salt Repository Research, Design and Operations
Albuquerque, NM, USA
October 9-10, 2012
SAND 2012-8068P

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

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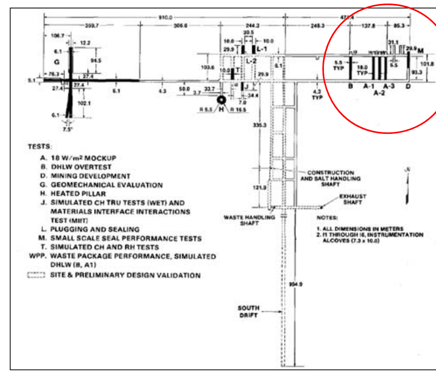
WIPP TSI Experimental Rooms

Several Thermal-Structural Interactions (TSI) Experimental Rooms Fielded at the Waste Isolation Pilot Plant (WIPP) in the early 80's



- **Under the US/German Joint Project on "Comparison of Current Constitutive Models . . ." there has been a proposal under consideration to include some additional *in-situ* experiments in the benchmarking exercise**
- **Experimental WIPP Rooms D & B are of special interest & well-suited for benchmarking**

2

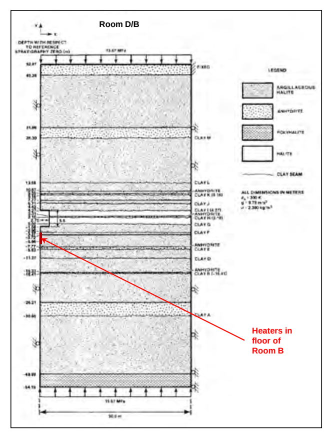
WIPP Rooms D & B Proposed for Benchmarking

Room D – "Mining Development" room is an isothermal room at ambient temperature 300 °K (~27 °C) – Ref. SAND88-1460

Room B – "Overtest for Simulated Defense High-Level Waste" room is a heated room (heaters in the floor) – Ref. SAND89-2671

3

Why WIPP Rooms D & B for Benchmarking?

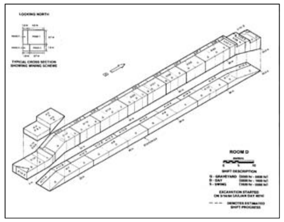


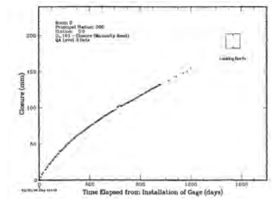
Except for the heat load in Room B, both rooms are essentially identical

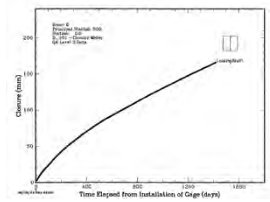
- Both rooms are located in the same general area of WIPP
- Both rooms are relatively "isolated" from other workings
- Both rooms are 5.5 X 5.5 m in cross-section (~100 m long)
- Both rooms are at the same horizon and thus in the same vertical stratigraphic location
- Both rooms were extensively instrumented and data were taken for approximately 3.5 years (1300-1400 days) after excavation
- The comprehensive dataset for both rooms was archived and is available

4

WIPP Room D Details







Room D Data Report (SAND88-1460) Contains the Various Details

- Excavation sequence
- Instrumentation
- Manual measurements
- Closure meter measurements
- Extensometer measurements

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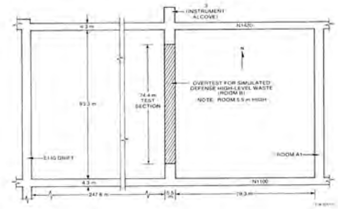
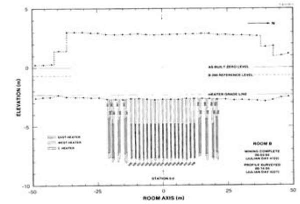
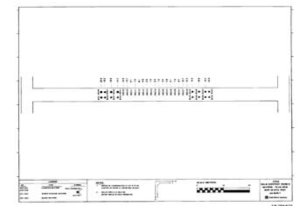
WIPP Room B Details







Likewise, Room B Data Report (SAND89-2671) Contains Various Details Similar to Room D, Plus Information on Heaters

- Locations of main heaters
- Arrangement of "guard" heaters
- Heater configuration and emplacement
- Thermal instrumentation
- Thermal measurements

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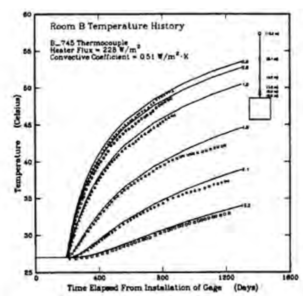
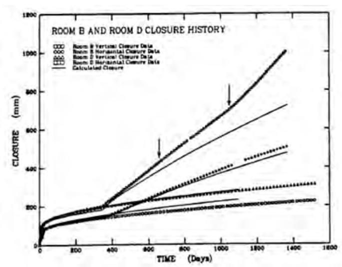
V&V Activities on WIPP Rooms D & B with Legacy Simulation Codes



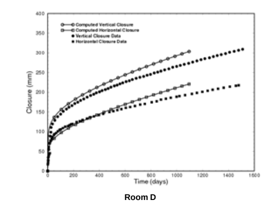


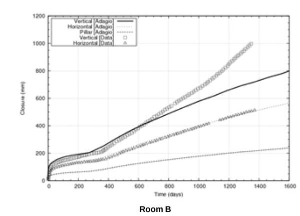
- WIPP Rooms D & B have been analyzed in the past with 1980-1990's Sandia-developed technology (*e.g.*, MD model, SPECTROM-32, SANTOS, JAC3D, etc.)
- Ref: Munson, D. E., "Constitutive Model of Creep in Rock Salt Applied to Underground Room Closure," Int. J. Rock Mech. Min. Sci., Vol. 34, No. 2, pp. 233-247, 1997

7

Results of Past Benchmarking & Motivation for Benchmarking Proposal

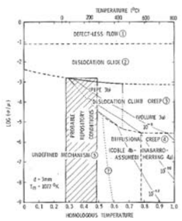
- Recently, a preliminary computational re-analysis of WIPP Rooms D & B was completed by SNL (SAND2012-7525)with the current SOA Sierra Mechanics toolset (initial efforts were also reported in SaltMech7)
- Results from the legacy tools can essentially be replicated
- General agreement with Room D closure data can also be replicated
- Both general agreement with the closure data at early times in Room B and its divergence from the data at later times can be replicated
- Divergence from data believed due to damage and roof separation that occur at later times in Room B





8

Motivation for Joint Project Benchmark Proposal for WIPP Rooms D & B



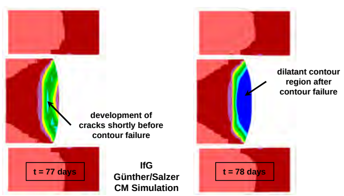
$$\dot{\varepsilon}_{ij}^{c} = F\,\dot{\varepsilon}_s \frac{\partial \bar{\sigma}}{\partial \sigma_{ij}}$$

$$\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i}$$

$$F = \begin{cases} e^{\Delta[1-\zeta/\varepsilon_t^*]^2}, & \zeta < \varepsilon_t^* \\ 1 & \zeta = \varepsilon_t^* \\ e^{-\delta[1-\zeta/\varepsilon_t^*]^2} & \zeta > \varepsilon_t^* \end{cases}$$

$$\dot{\zeta} = (F-1)\dot{\varepsilon}_s$$

MD Creep Model



- These SNL efforts used the legacy MD Creep Constitutive Model
- Has capability to capture quite well Thermal-Mechanical (TM) behavior of rock salt up to the point when damage begins
- Although advanced for its time, development of the MD Creep Model stopped the mid-1990's
- Several additional advanced features to model damage, healing, etc. were never completely developed into model (MDCF Model)
- Model may have some deficiencies relative to current SOA constitutive models for capturing damage, healing, etc.
- Believe that capturing the damage and separation evident in the Room B closure data may be within reach using current SOA models,

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Status of Benchmarking Proposal for WIPP Rooms D & B

- At the June 2012 meeting of the Joint Project in Leipzig the laboratory test matrix for the determination of constitutive model parameters for WIPP salt for the various German models was discussed
- A concept for a broader and deeper investigation of WIPP salt than originally envisioned was elaborated for the following reasons
  - Advanced constitutive models require various types of well-controlled up-to-date lab tests performed with a wide range of boundary conditions
  - Special demands on the measurements result from the different ways to model damage and dilatancy
  - In the past, much information for German modeling of the thermo-mechanical behavior of rock salt was gained from the extensive laboratory test database for "Asse-Speisesalz" - probably the best-investigated salt type in Germany
  - This database was collected over decades by several institutions; in the joint projects Germany have used this database and performed some additional special tests

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Status of Benchmarking Proposal for WIPP Rooms D & B (Cont'd)

- WIPP is a somewhat different situation
- Careful assessment of available WIPP data led to the proposition that the Joint Project investigate WIPP salt in greater detail
- This will allow for a deeper and more detailed comparison of WIPP and German salt (esp. Speisesalz) in general and will yield a more comprehensive basis for the modeling
- IfG and TUC will perform creep tests, strength tests, and special tests (*e.g.*, relaxation, poss. healing, cyclic, ...) at three different temperatures and with several confining stresses
- The lab test program would be funded by the German side (OK of BMWi provided)
- The results would be made fully available to Sandia for any future purposes within and beyond our WIPP benchmark

11

Status of Benchmarking Proposal for WIPP Rooms D & B (Cont'd)

- Could Sandia supply IfG/TUC with new rock salt material (specimens or cores/blocks) from WIPP?
- Is it possible for Sandia to perform new drillings (cores, blocks) in the new in-situ testing area at WIPP (in which case, the test program would yield an extensive characterization of the salt in the new area, which might be useful for comparisons with any future in-situ testing)?
- Could the new material be delivered to IfG and TUC at the beginning of 2013 (Lab creep tests last approximately 180 days, therefore they have to start early enough before the modeling)?
- Will Sandia be able to prepare the specimens, or will Sandia ship the raw cores/blocks to IfG or TUC?
- We intend to address the most practical ways to achieve these goals at this 3rd US/German Workshop

12

Status of Benchmarking Proposal for WIPP Rooms D & B (Cont'd)

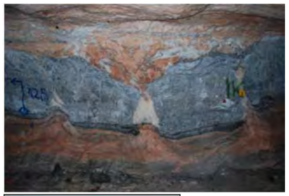
- The full test matrix, funded by BMWi, would encompass approximately 140 tests including repetitive tests
- Including back-up specimens, up to 170 specimens would be required (diameters: 40 to 90 mm, heights: 80 to 180 mm)
- Sandia certain that WIPP core can be acquired to facilitate all the testing suggested
- Sandia has inventory on hand (nominally 100 mm diameter) that could be used
- Available core was acquired under WIPP Quality Assurance program from horizontal boreholes at the WIPP horizon

13

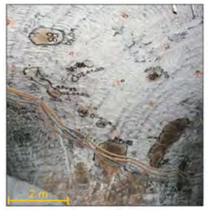
Thank you for your kind attention!!

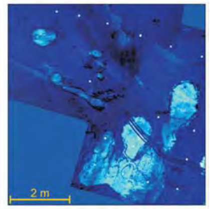
Questions?

14









Results of the Salt Club Workshop: Natural Analogues for Safety Cases of Repositories in Rock Salt

J. Wolf, U. Noseck, W. Steininger

3rd US/German Workshop on Salt Repository Research, Design and Operations - October 8-10, 2012, Albuquerque/Carlsbad, USA

Salt Club Workshop: Natural Analogues for Safety Cases of Repositories in Rock Salt

- 4. and 5. September 2012 in Braunschweig
- including visit of ERAM (6. September)
- hosted by PTKA-WTE, GRS
- 37 participants from 8 countries (Salt Club members + CH, CZ, F and UK)
  - research institutes
  - universities
  - regulators
  - federal institutes
  - engineering companies
  - salt mining and oil/gas storage industry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Salt Club Workshop: Natural Analogues for Safety Cases of Repositories in Rock Salt

- part I: presentations
  - organised in 4 sessions:
    - I. overview session
    - II. integrity of rock salt
    - III. long-term properties of technical barriers
    - IV. chemical and microbial processes
- part II: workshop
  - working groups
  - wrap-up discussion


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Part I: Presentations

- National programs of USA, NL, PL, D
- general aspects of NA (NAWG, NEA-FSC)
- integrity of rock salt (8 presentations)
  - mechanical behaviour of salt rock, especially anhydrite vs. rock salt
  - fluids in salt
  - static and dynamic impacts
- long-term properties of technical barriers (2 presentations)
  - experiences from salt mining and hazardous waste disposal
- chemical and microbial processes
  - solubility and sorption of naturally occurring radionuclides
  - hydrocarbons
  - microbial activity

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Part II: Working Groups / Wrap-up Discussion

- working in 4 groups
  - What are the most important points you have learned?
  - What are the key unresolved issues?
  - What are your highest priority recommendations for future NA studies for salt?
  - Do you have any other thoughts you would like to recommend to the Salt Club?
- plenum
  - discussion of results
  - outlook

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Results (I): General Aspects of NA

- NA are an essential part of the Safety Case portfolio (Finland, Sweden)
- When is a study an analogue?
  Are there objective criteria?
  Laboratory studies → NA
  BE CAREFUL USING NA (overinterpretation)
  →
  there is now more realism about what NA studies can achieve
  NA are for building confidence, not for proving models
- How to apply NA in a Safety Case?
  NEA/RWM/FSC(2008)3: analogue, analogy, anecdote
  Safety Case should lead NA, not vice versa
  How to document / communicate NA?

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Results (II): Aspects of NA specific to Salt

- NA are focused on the integrity of salt (main barrier for containment)
- more NA on (geo)technical barriers required
  → compaction of crushed salt
- further topics of high interest for NA
  - microbial activity in salt
  - deformation of anhydrite
  - fluid inclusions
  - gas storage
- open discussion of radwaste community with other scientific fields and industry
- How to apply NA in a Safety Case in salt?
  research project ISIBEL-II

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ISIBEL project: Status of Safety Assessment of Final Repositories for HLW in Salt

ISIBEL-I (2006-2010):
- Safety concept and assessment strategy for HLW/SF repository (borehole disposal)
- In compliance with the German Safety Requirements
- Reference Site: Salt Dome Gorleben
- Financed by Federal Ministry of Economics and Technology (BMWi)
- BGR, DBE Technology, GRS
- Identification of open questions / issues to be addressed

→ ISIBEL-II (2010-2013):
- (…)
- Applicability of Natural Analogues for a Safety Case in salt

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Analogues for the Integrity of the Geological Barrier

Aspect	Application	S	A	C
Existence of salt domes in Northern Germany	Long-term stability of salt domes	++	+	☼☼
Stability of neotectonic conditions	Occurrence of earthquakes and magmatic events	++	--	☼☼
		++	+	☼☼
		++	+	☼
		+	ø	☼☼
		++	++	☼
		++	++	☼
Chemical and isotope composition of gas inclusions in salt formations	Migration of gases in a salt dome	++	++	☼
Investigation of openings from salt mining	Behaviour of rock salt in the depth	ø	+	☼☼
Basalt intrusions in Fulda-Werra Series of	Sealing of fissures (Self sealing)	--	++	☼☼
		--	++	☼
		-	+	☼

++ Natural Analogue identified and well documented
+ Natural Analogue identified but documentation insufficient
ø Natural Analogue identified but no documentation
- Natural Analogue is not identified
-- Natural Analogue is (probably) not identifiable

☼ rather appropriate for communication with experts (analogues)
☼☼ rather appropriate for communication with public (analogies)

Step 1 → Step 2

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Analogues for the Integrity of Geotechnical Barriers

Aspect	Application	A	C
Bulkhead drift in the Asse mine	Reduction of the permeability of an EDZ around drift sealings	+	☼
Basalt intrusions in salt formations (e.g. Fulda-Werra series of Zechstein)	Long-term behaviour of basaltic gravel as part of the shaft in rock salt	++	☼☼
Chemical and mineralogical composition of natural clays	Impact of high temperatures on clay minerals	++	☼
Properties of natural salt clays in salt deposits of the Zechstein	Long-term behaviour of clays/bentonite as sealing material in rock salt	+	☼
Corrosion of historical concrete buildings	Long-term behaviour of cementitious materials in rock salt	++	☼
Bentonites in saline environment	Long-term stability of bentonite as sealing element in rock salt	+	☼
Chemical and mineralogical composition of natural bitumen	Long-term behaviour of bitumen as material in sealing elements	+	☼
Degradation of organic material	Limits for microbial gas formation from organic material in geological time frames	+	☼
Compacted backfill material from old drifts and shafts in salt mines	Compaction of Crushed Salt over long time scales	ø	☼

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Analogues for Release Scenarios

Aspect	Application	A	C
Stability of natural Basaltic glass	Corrosion of borosilicate glass	+	☼
Uraninite deposits	Corrosion of spent fuel	+	☼☼
Basaltic glass in saline environment	Formation of secondary phases during glass corrosion and retardation of radionuclides	+	☼
Co-precipitation and sorption of radionuclides	Retardation of radionuclides on corrosion products from metal corrosion	+	☼
Lanthanide distributions in low soluble mineral fractions of marine evaporites	Mobility of lanthanides (as chemical homologue for actinides) in salt formations	+	☼
Precipitation of natural elements during formation and recrystallisation of salt deposits	Retardation of radionuclides in the salt dome by co-precipitation with salts	-	☼
Behaviour of radionuclides in highly saline systems, e.g. sole of geothermic deep drillings, California	Radionuclide retardation under high saline conditions	+	☼
In-situ K_d values in sedimentary formations (Morsleben, Gorleben)	Confirmation of K_d values for the overburden from batch experiments	+	☼
Uranium migration at Ruprechtov site	Behaviour of uranium and thorium in tertiary sediments of the overburden	+	☼

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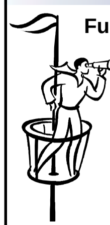
Further activities



- Proceedings to be published as NEA-R report
- Initiation of joint international projects
  - Salt Club
  - US/German Cooperation!
- Prioritization → Assessment scheme
- Investigate topics with
  - lacking knowledge
  - divergent opinions
  - new results
- (Identification of further analogues)
- Workshops focused on single aspects

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Functional Requirements to demonstrate Safety

Assessment period 1 Mio. years

Geological barrier

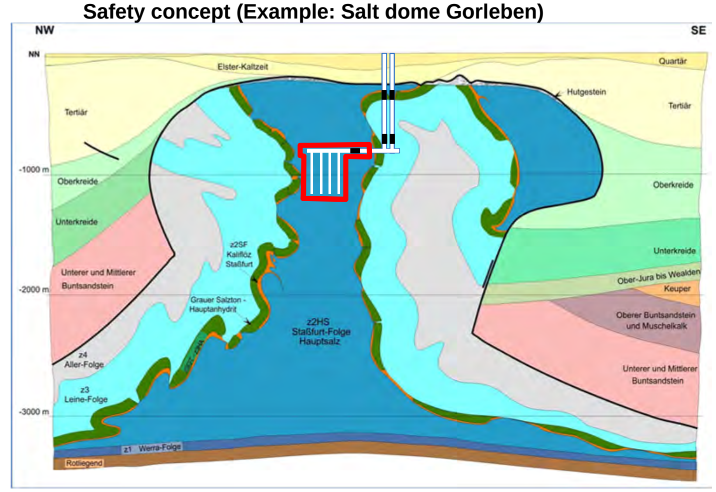
designed lifetime

Geotechnical barrier

Crushed salt

compaction

Safety concept (Example: Salt dome Gorleben)



Compaction behaviour of crushed salt

- Samples with significant reduction of porosity
- Geotechnical requirements: representative material, knowledge about initial state and history
- Suitable objects to be identified

Example: Compacted rock salt from abandoned salt mine „Riedel" (about 20 years old)

Conceptual Aspects of SNF/HLW-Repositories

Wilhelm Bollingerfehr
DBE TECHNOLOGY GmbH, Peine, Germany

3rd US/German Workshop on Salt Repository Research, Design and Operation

Albuquerque/Carlsbad
October 8-10, 2012

Outline of Presentation

- Introductory remarks
- Parameters with impact on repository design
- Examples of repository concepts
- From concept to implementation
- Optimization of repository concepts
- Alternatives to final disposal?
- Summary and conclusions

Parameters with Impact on Repository Design

- **Type and amount of waste (waste package**)
  - e.g.: Sweden: SNF only, large copper canister
  - e.g.: France: HLW from reprocessing, small waste package
- **Geological situation (selected or available host rock)**
  - Clay in France and Swizerland
  - Granite in Sweden and Finland
  - Salt in Germany and USA

Parameters with Impact on Repository Design

- **Design temperature at contact waste-package and hostrock or buffer**
  - max. 100°C (clay/bentonite)
  - max. 200°C (salt)
- **Saftey concept**
  - mainly relying on active safety (geotechnical barriers)
  - mainly relying on passive safety (geological barriers)
- **Retrievability/Reversibilty requirement**
  - show feasibility in principle or
  - demonstration in 1:1 scale (design criteria)

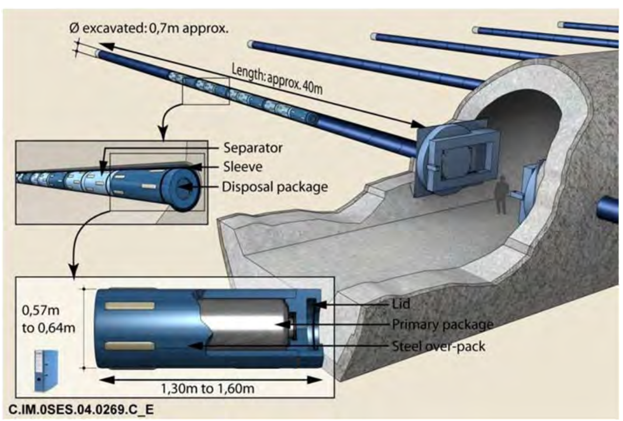
Legislation

- **National laws and regulations**
  - e.g. in Germany:
    - Nuclear Energy Act
    - Radiation Protection Ordinance
    - Mining Act
    - Safety requirements (BMU, 2010)
      - Retrievability during operational life time
- **International laws and recommendations**
  - EU-Directive (Summer 2011)
  - IAEA: safety guidelines

Examples of Repository Concepts

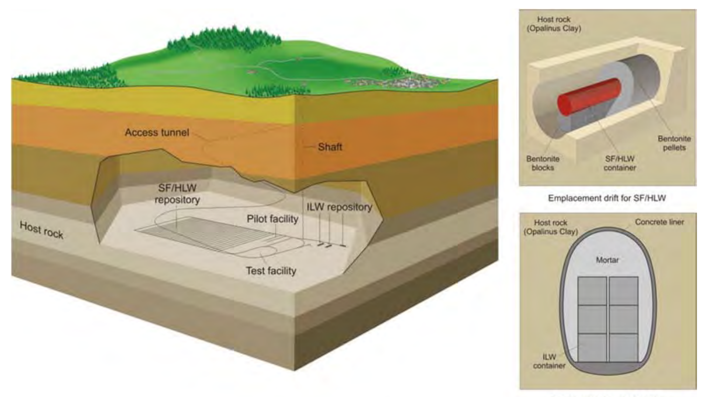
- **SNF/HLW-repositories were designed for different types of host rocks:**
  - French reference repository concept (callovo-oxfordian clay)
  - Swiss reference repository concept (opalinus clay)
  - Swedish reference repository concept (crystalline rock)
  - German reference repository concept (rock salt)

French Reference Repository Concept



host rock: callovo-oxfordian clay source: Andra

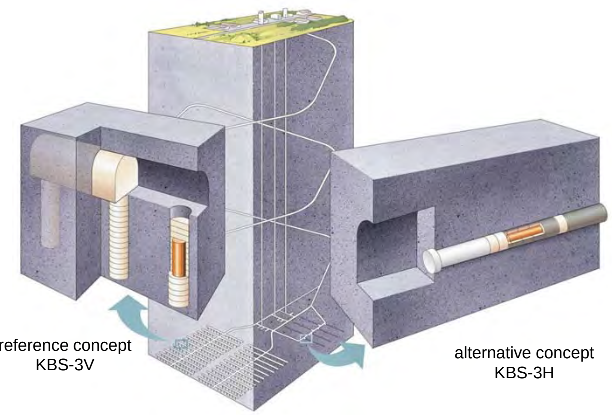
Swiss Reference Repository Concept



host rock: opalinus clay

source: Nagra

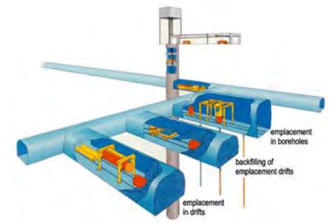
Swedish Reference Repository Concept



host rock: crystalline rock

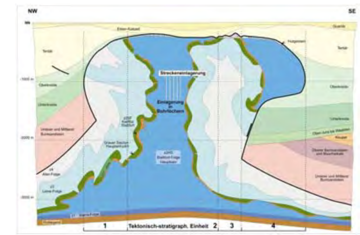
source: SKB

German Reference Repository Concept



Reference Repository Concept for SNF and HLW in Rock Salt:

- **Deep geological disposal (depth: 870 m)**
- **Emplacement of HLW in boreholesand spent fuel casks in drifts**
- **Backfill material: crushed salt**



Conceptual illustration of the German repository reference concept. (Repository shown within a simplified geologic cross-section of the Gorleben salt dome)

From Concept to Implementation

- **Stepwise approach in repository design**
  (valid for single components as well as for entire system):
  - conceptual design
  - technical Design
  - as-built design (drawings)
  - industrial **demonstrators** and test campaign prior to implementation
- **Demonstration of operational safety and reliability**
  - components are unique and site specific
  - demonstration on surface or/and in-situ (scale 1:1)
    - e.g.: POLLUX-Transport & Emplacement Technology

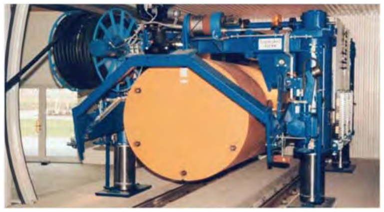
Demonstrator: Shaft Hoisting

Full Scale Demonstration of Shaft Hoisting System

Endurance tests: (> 2000 loading and reloading processes)

Longitudinal section through shaft hoisting system

Demonstrator: POLLUX Transport and Emplacement



Technical data:

- Width: 3.2 m
- Height: 3.3 m
- Length: 6.8 m
- Mass: 15.2 t
- Driving power: 2 x 22 kW
- Capacity: 65 t (diagonal)
- Radio controlled
- Inherently safe
- No hydraulic oil (fire protection)

Emplacement machine

Endurance tests:
(> 1000 transport and emplacement processes)

In-situ Heating Test with POLLUX Dummy

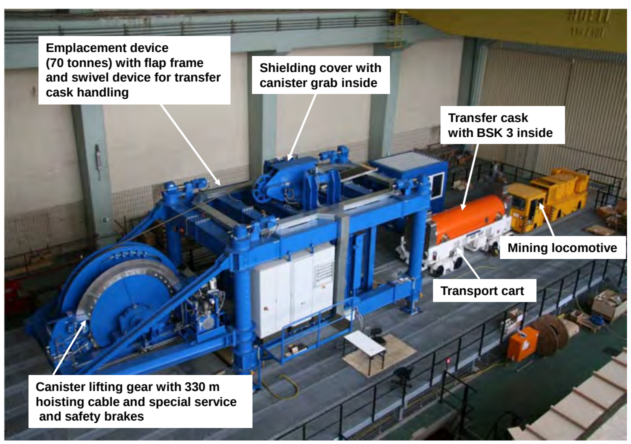
Installation of "Heater" (POLLUX Dummy) and Instrumentation in the year 1990

Dismantling of "Heater" (POLLUX Dummy) in the years 2000/2001

Results after 10 years of heating:

- temperature limit of 200 °C in rock salt not exceeded
- compaction of dry backfill increased (crushed salt)

Demonstrator: BSK 3-Emplacement Device

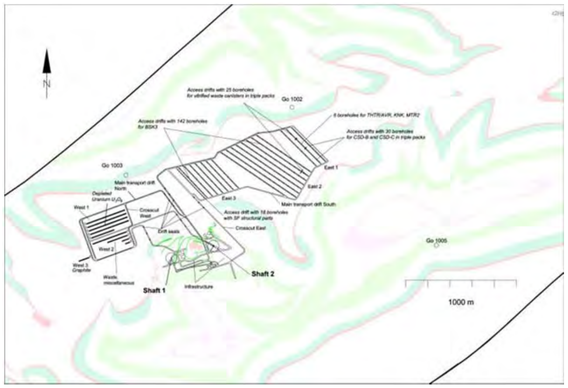


Optimization of Repository concepts

- **Motivation for design optimization:**
  - improvement of operational safety
  - Improvement of long-term safety,
  - minimizing footprint,
  - minimizing costs
  - etc.…

Minimizing of footprint

- **German reference concept: disposal of waste canisters into deep vertical borehole instead of horizontal drifts**



Alternatives to Final Disposal?

Long-Term Storage:

long term storage means safe storage of certified waste packages over decades in surface interim storage facilities

- e.g. The Netherlands: about 100 years interim storage

Partitioning and Transmutation:

separation of nuclides from Spent Nuclear Fuel and transmutation into nuclides with shorter half-life times; reducing amount of waste

- R&D activities in particular in France

EU-Directive:

In Europe: long-term storage as well as P&T not accepted as final step in WM-Program;

- thus, final disposal is indispensable

Summary and Conclusions

- **Repository concepts for the long-term safe disposal of SNF/HLW are available for different host rock formations**
- **The approach how to come from repository concept to implementation depends on national legislation and WMO engineering strategy**
- **Demonstration tests on surface or/and in-situ provide decision basis to evaluate:**
  - constructability
  - operational safety
  - Reliability
- **Long-term storage and P&T are no alternative to final disposal (at least in Europe)**

DBE TECHNOLOGY GmbH

Thank you for your attention.

Exceptional service in the national interest

Sandia National Laboratories

Photos placed in horizontal position with even amount of white space between photos and header

Disposal Concepts for Large Spent Fuel Waste Packages in Salt

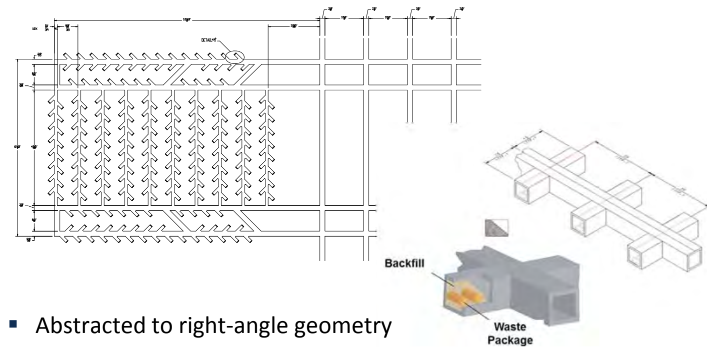
Dan Clayton & Ernest Hardin

10 October 2012

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. SAND NO. 2011-XXXXP

T-M Model Setup

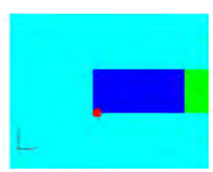
- Generic salt repository layout (Carter et al. 2011)

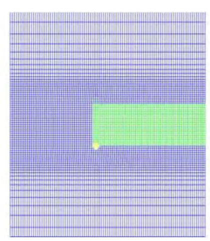


- Abstracted to right-angle geometry

T-M and T-only Approach

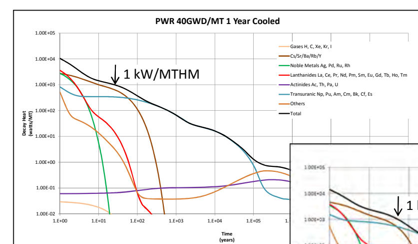
- Coupled thermal-mechanical model
- Sierra codes (Sandia)
- Salt properties and constitutive models → (Clayton et al. 2012)
  - Multi-mechanism creep model (Munson et al. 1989)
  - Crushed salt creep (Callahan 1999)
  - Thermal conductivity (Bechthold et al. 2004)
- Approach:
  - Test T-M dependence for initial problem
  - Use T-only model for sensitivity analyses

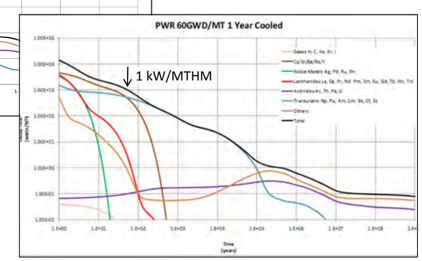




Waste Package	Diameter (m)	Length (m)
4 PWR assemblies	0.82	5.00
12 PWR assemblies	1.29	5.13
21 PWR assemblies	1.60	5.13
32 PWR assemblies	2.0	5.13

LWR UOX SNF Thermal Power ORIGEN II Based, 40 and 60 GW-d/MTU Burnup



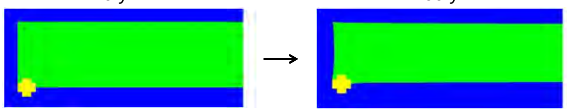


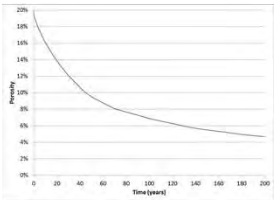
Carter et al. (2012a)

Emplacement Alcove Consolidation and Closure

Closure + thermal expansion → Porosity reduction

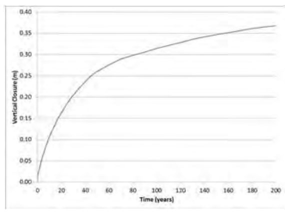
0 yr → 200 yr





<< Averaged backfill porosity vs. time (4-PWR case)

Closure at alcove-drift exit vs. time (4-PWR case) >>

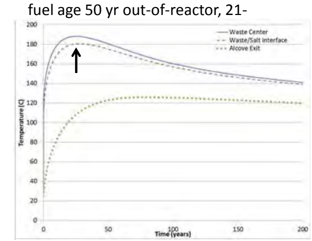


Clayton et al. (2012)

Disposal of Large Waste Packages in Salt

- Burnup: 40 & 60 GWd/MTU
- Fuel age: 10 & 50 yr OoR
- WP Sizes: 4-, 12-, 21- & 32-PWR (up to 14 MTHM)

Example: Burnup 40 GW-d/MT, fuel age 50 yr out-of-reactor, 21-



- T-M Effect (Hardin et al. 2012):

WP Size	Dimensions	Burnup (GWd/MTU)	Fuel Mass (MT)	Fuel Age (yr)	Power at Emplacement (kW)	Runs Compared	Peak Salt Temperature (C)
4-PWR	0.82 m D x 5.00 m L	40	1.88	10	3.7	T, 200 yr	100
4-PWR	0.82 m D x 5.00 m L	40	1.88	10	3.7	TM, 200 yr	100
21-PWR	1.60 m D x 5.13 m L	40	9.87	50	9	T, 200 yr	190
21-PWR	1.60 m D x 5.13 m L	40	9.87	50	9	TM, 200 yr	185

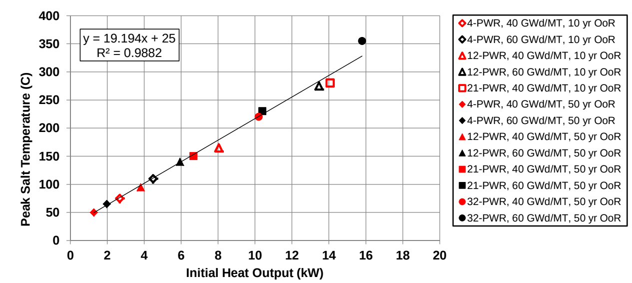
Disposal of Large Waste Packages in Salt

- Sensitivity test results:

WP Size	Dimensions	Burnup (GWd/MTU)	Fuel Mass (MT)	Fuel Age (yr)	Power at Emplacement (kW)	Peak Salt Temperature (C)
4-PWR	0.82 m D x 5.00 m L	40	1.88	10	2.7	75
4-PWR	0.82 m D x 5.00 m L	60	1.88	10	4.5	110
12-PWR	1.29 m D x 5.13 m L	40	5.64	10	8.0	165
12-PWR	1.29 m D x 5.13 m L	60	5.64	10	13.5	275
21-PWR	1.60 m D x 5.13 m L	40	9.87	10	14.1	280
4-PWR	0.82 m D x 5.00 m L	40	1.88	50	1.3	50
4-PWR	0.82 m D x 5.00 m L	60	1.88	50	2.0	65
12-PWR	1.29 m D x 5.13 m L	40	5.64	50	3.8	95
12-PWR	1.29 m D x 5.13 m L	60	5.64	50	5.9	140
21-PWR	1.60 m D x 5.13 m L	40	9.87	50	6.7	150
21-PWR	1.60 m D x 5.13 m L	60	9.87	50	10.4	230
32-PWR	2.00 m D x 5.13 m L	40	15.04	50	10.2	220
32-PWR	2.00 m D x 5.13 m L	60	15.04	50	15.8	355

Disposal of Large Waste Packages in Salt

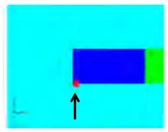
- Peak salt temperature vs. initial package thermal power
- Correlation (burnup, age, and dimensions are 2nd order)



- *∴ Use package thermal power as an emplacement criterion in system logistics studies (better than ±10% temp. accuracy)*

Summary

- Disposal of existing U.S. SNF inventory (~40 GW-d/MT):
  - 21-PWR packages at 50 yr age (oldest-fuel-first?)
  - 32-PWR packages at <<100 yr age
- Disposal of future inventory (60 GW-d/MT bounding cases):
  - 21-PWR packages at <<100 yr age
  - 32-PWR packages at >>50 yr age
- Further questions for thermal loading studies:
  - Aging required for larger packages/higher burnup?
  - Importance of initial backfill porosity (e.g., 20% vs. 35%)?
  - Importance of semi-cylindrical cavity to heat transfer?
  - Areal loading density?
  - TM coupled processes from higher density?



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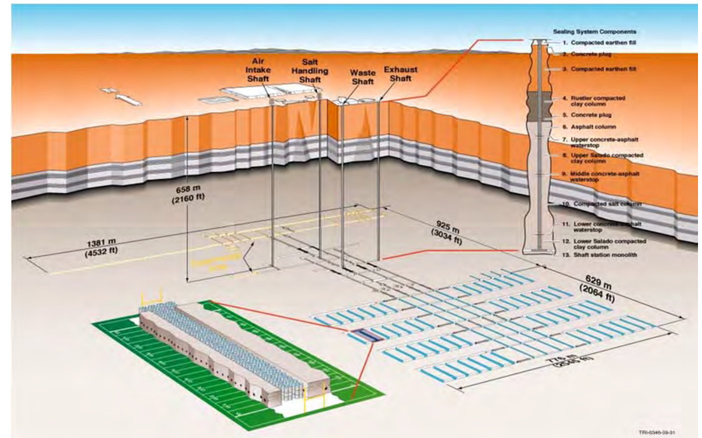
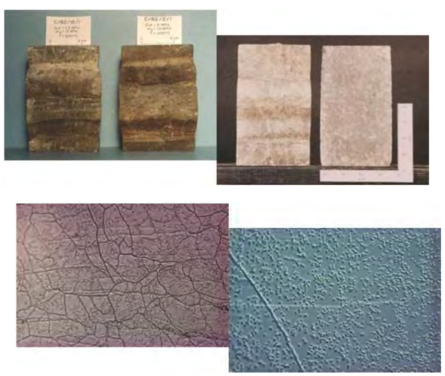
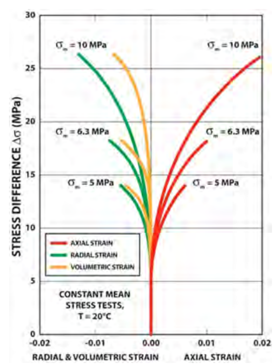
WIPP Underground Layout



Salt Behavior is Well Understood





3

Full-Scale Tests in Salt

YEAR	PROJECT	LOCATION	DESCRIPTION
1965-1969	Lyons mine, Project Salt Vault	Lyons, Kansas	Irradiated fuel & electric heaters
1968	Asse salt and potash mine	Germany	Electric heaters
1979-1982	Avery Island	Louisiana	Brine migration
1983-1985	Asse (U.S./German Cooperative)	Germany	Brine migration under heat & radiation
1984-1994	WIPP	Carlsbad, NM	1.Defense HLW Mockup 2.Defense HLW Over-test 3.Heated axisymmetric

4

Large-Scale Underground Experiments

Room H

DHLW

BAMBUS II

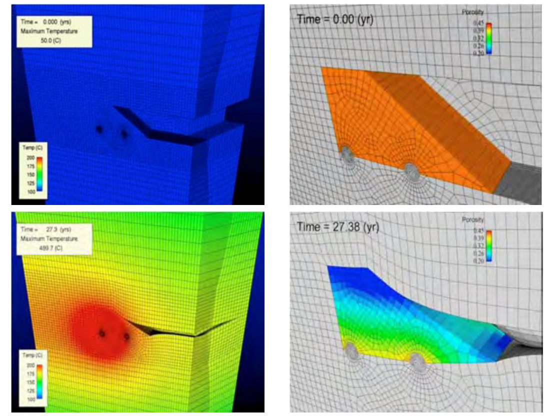
5

Advanced Multi-physics Modeling will Aid Salt Analyses & Performance Assessment

Temperature Contour | Coupled Salt Consolidation

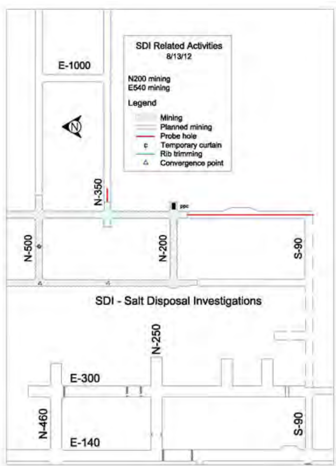
0 YEARS | 0 YEARS

27.3 YEARS | 27.38 YEARS



6

Progress on the SDI Access Drifts



7

URL Potential Activities at WIPP

- Salt Defense Disposal Investigations (SDDI)
- Salt Disposal Investigations (SDI)
- Large-Scale Seal Demonstration
- Mining Research
- Wedge Pillar Test
- Mine-By DRZ Measurement
- International Test Bed

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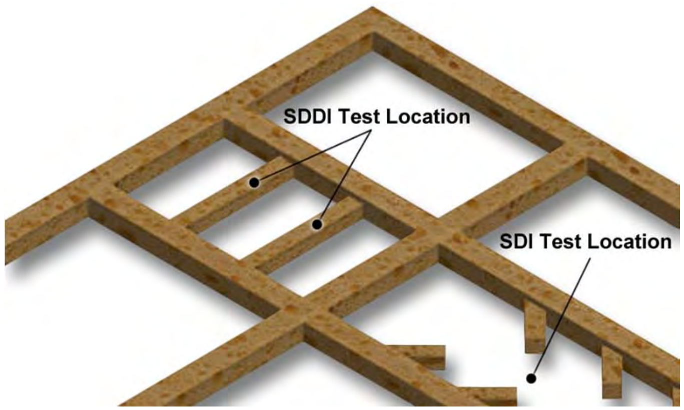
SDDI Mining Layout



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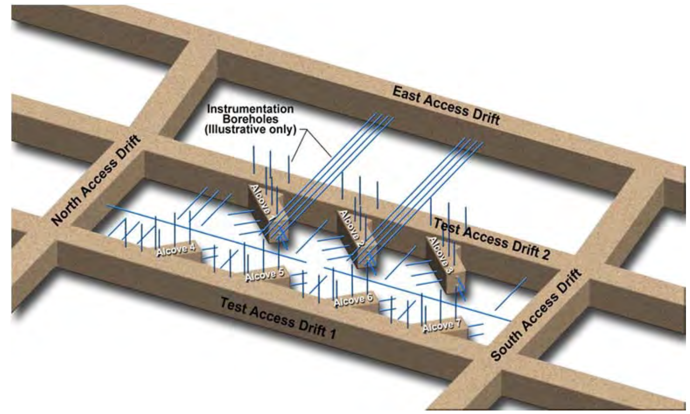
Concept for SDI Test Layout



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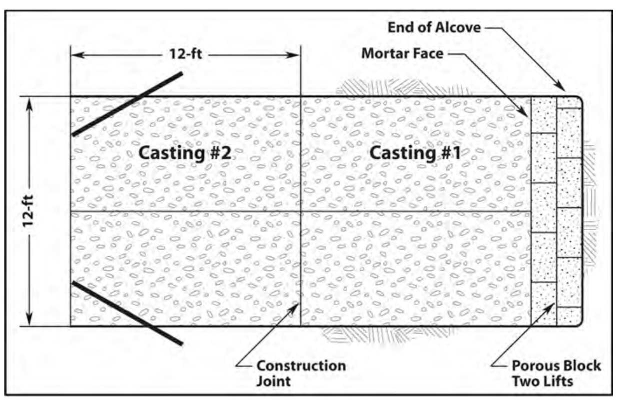
Large-scale Seal Demonstration



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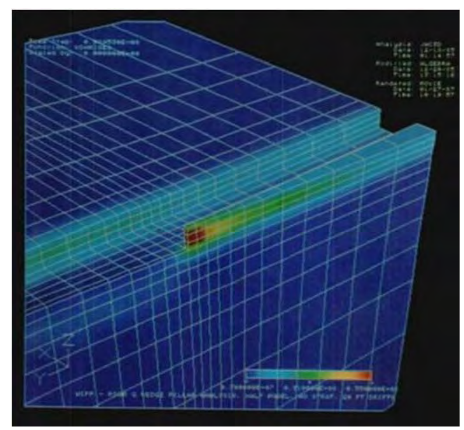
Stress Distribution in Wedge Pillar



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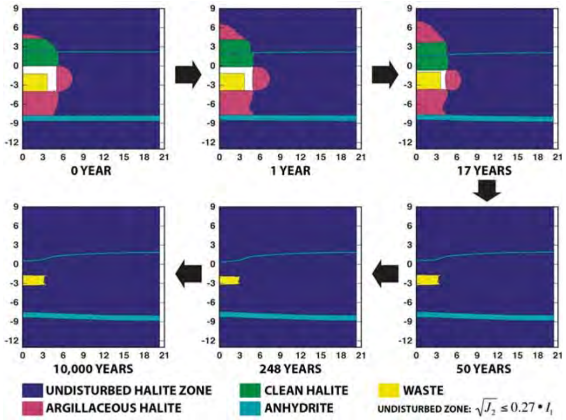
Disturbed Rock Zone Around a Disposal Room



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Elevated Temperature Tests on WIPP Salt

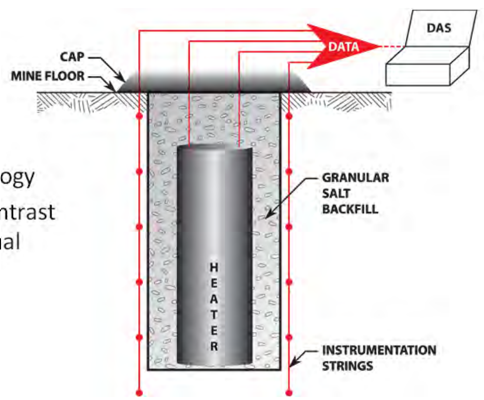
Decrepitation at 275C

Plastic flow at 250C

14

Potential Single Heater Test

- Utility
  - Overdrive experiment
  - Observe phenomenology
  - Compare/contrast bedded/domal response



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Extended RD&D Consideration

- Develop and exchange rock salt information among nations currently pursuing or considering rock salt as a candidate deep geological repository medium.
- Collaborate with international peers and stimulate interest in salt as a viable repository host medium.
- Identify and perform fundamental joint research into areas where understanding is incomplete.
- Exchange and transfer advanced methods and tools developed for salt disposal to industry
- Characterize and qualify the information available.
- Promote information exchange on approaches, methods, methodologies, and technologies
- Outreach to other salt related applications.
- Afford technical experts access to and interchanges with the latest international developments in salt mechanics sciences.
- Inform and provide advice on conceptual topics, performance descriptions and modeling.
- Publish results, models, reliability, data quality, and evaluate national and international RD&D activities.
- Develop a central library of acquired salt data, information, and knowledge with broad access provided via the Internet.
- Address the fundamental issue of knowledge management.
- Reinvigorate the science (chemistry and physics) of rock salt through education, training development of new researchers and students.
- Perform fundamental research.

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