Proceedings of the 4th US/German Workshop on Salt Repository Research, Design, and Operation

Fuel Cycle Research & Development

Prepared for
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Used Fuel Disposition Campaign
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December 13, 2013
FCRD-UFD-2014-000335
SAND 2013-10592P

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Sandia National Laboratories

Revision 2
12/20/2012

APPENDIX E
FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	4th US/German Workshop on Salt Repository Research, Design and Operation
Work Package Title and Number	DR Salt R&D – SNL, FT-14SN081801
Work Package WBS Number	1.02.08.18
Responsible Work Package Manager	Francis D. Hansen [signature] (Name/Signature)
Date Submitted	

Quality Rigor Level for Deliverable/Milestone[2]	☒ QRL-3	☐ QRL-2	☐ QRL-1 Nuclear Data	☐ Lab/Participant QA Program (no additional FCT QA requirements)

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ACKNOWLEDGEMENTS

Authors of these Proceedings are indebted to all participants and are grateful for their excellent contributions. We are delighted with the organization and assembly of these Proceedings provided by Laura A. Connolly of Sandia National Laboratories.

ABSTRACT

The 4th US/German Workshop on Salt Repository Research, Design, and Operation was held in Berlin, Germany September 17 and 18, 2013. The Workshop was preceded on September 16 by two related meetings: 1. Organisation for Economic Co-operation and Development / Nuclear Energy Agency (OECD/NEA) "Salt Club" held in Berlin, Germany, and 2. BMWi-funded US/German Joint Project on the "Comparison of Current Constitutive Models and Simulation Procedures on the Basis of Model Calculations of the Thermo-Mechanical Behavior and Healing of Rock Salt held in Leipzig, Germany. A synopsis of the two preceding meetings will be included here, but the primary focus of these Proceedings is the technical advancements made by the US/German collaborators via our series of annual workshops. As with the previous US/German Workshops, these Proceedings are posted on our Salt Repository Website (http://www.sandia.gov/SALT/SALT_Home.html)) after they have undergone review and approval for public release.

Over fifty salt repository research scientists from Europe and the US met to discuss selected key technical issues pertaining to the scientific basis for salt disposal of heat-generating nuclear waste. A list of attendees and a number of short biographical sketches are provided within this document.

The main workshop topics focus on collaborative efforts between technical peers in the US and Germany. These include 1. Selected aspects of the safety case for salt disposal of high-level waste, 2. Plugging and sealing of a salt repository, 3. Salt mechanics modeling, and 4. Repository design including potential uses of an underground research laboratory at the Waste Isolation Pilot Plant (WIPP). Ancillary discussions included geochemistry, microbiology, and hydrogeology modeling. Topical arrangement generally follows the workshop agenda, which is also provided later in this document. Main topics on the agenda and these Proceedings are organized topically as follows:

1. Safety case for heat-generating waste disposal in salt. As noted in a number of previous sources, the international salt research community has a solid foundation for a salt safety case and the associated performance/safety assessment. Workshop collaborators have extensive experience with the building blocks of performance assessment—often referred to as Features, Events, and Processes (FEPs). Subject matter experts from the US and Germany are in the process of compiling a comprehensive FEPs catalogue for disposal of heat-generating waste in salt (Freeze, et al., 2014). Indeed, Sandia is beginning to develop a generic safety case for disposal of heat-generating waste in bedded salt. Workshop partners also discussed elements of the safety case including handling uncertainties and the qualitative contribution of analogues. This progress along with Germany's preliminary safety analysis for the Gorleben site (Vorläufige Sicherheitsanalyse Gorleben or VSG) provide a strong technical basis for a safety case for salt disposal of heat-generating nuclear waste.

2. Plugging and sealing. It will be mandatory to close a repository. Therefore, it is essential to prove that it can be sealed by appropriate and integrity-proven seal systems, including both shaft and drift settings. Sealing capability has to be demonstrated in the laboratory and at full-scale in situ. Real-time and full-scale drift seal demonstrations are ongoing in the Morsleben repository, in the European project full-scale Demonstration of Plugs And Seals (DOPAS), and in the BMWi research and development (R&D) project, "Shaft seals for repositories for high-level radioactive waste" **S**chachtverschlüsse für **E**nd**l**ager für hochaktive **A**bfälle (ELSA). The ELSA project is developing concepts for shaft seals and demonstrating functional elements using laboratory and medium scale tests. One of the key overarching research areas pertaining to plugging, sealing, testing, and modeling involves reconsolidation of granular salt, particularly in the horizontal orientation.

3. Salt mechanics modeling. The Joint Project has been officially extended to include two additional benchmarking problems based on in situ full-scale tests conducted in the early 1980's at WIPP. Modeling will compare an isothermal mining development test (WIPP Room D) to a heated "overtest" for simulated defense high-level waste (WIPP Room B). In concert with benchmark modeling of the full-scale field tests, German research groups are conducting approximately 140 laboratory experiments on WIPP salt. Back-calculations of the various lab tests with different boundary conditions demonstrate the ability of the models to describe different phenomena and their dependencies under different and well-controlled conditions. This is also why the large lab test series on WIPP salt is so important for the extension of the present Joint Project. Back-calculations of these lab tests are not only performed for the parameter determination, but also as a check of model capability/ies to describe the deformation behavior of bedded WIPP salt.

4. Repository design and use of the Underground Research Laboratory (URL). As with many topics covered in these US/German workshops, practical monitoring experience has application within repository science, engineering, design, and performance. Many challenges arise in the analysis and interpretation of the captured values even with careful planning of the measurement program and installation of the monitoring devices. The international salt repository community has significant participation in collaborative monitoring projects, which were revisited in this workshop. With this experience in mind, workshop participants examined possible uses of the new URL in the WIPP underground setting. The URL provides a unique opportunity to advance the scientific basis for heat-generating waste disposal in salt. With this opportunity comes a significant responsibility to use this space as intelligently and cost-effectively as possible. Several potential activities were discussed in break-out sessions and feedback included a sense of duration, cost, and merit among the many potential uses. A more formal and rigorous review process of URL activities would be expected in order to guide development of the URL.

5. Geochemistry, hydrogeology, and microbes. A summary of actinide and brine chemistry (ABC Workshop held in Santa Fe) issues included in some performance assessment scenarios was presented. Contributions of anoxic corrosion and microbial consumption of cellulosics plastic and rubber to gas generation were quantified from the work supporting the WIPP compliance certification. Hydrogeologic modeling was put forward as a new area for collaboration. Powerful tools are able to meet the needs of far-field modeling, with applicable porous and fractured media flow.

The overriding premise for these US/German workshops is to advance the scientific bases for salt repositories as revealed in the title: *Workshop for Salt Repository Research, Design and Operation*. We recognized at the outset of this workshop series that our group could not tackle all imaginable avenues of science and engineering immediately. Therefore, we have focused on a few most significant areas that are known to be of first-order concern to the theme of our workshop. Given the political climate in the respective nations and the history of salt repository projects, acknowledgement, and documentation of the state-of-the-art and knowledge preservation are concomitant essential goals. Some of the key objectives are predicated on historical experience; for example, creation of a comprehensive FEPs database for high-level waste (HLW) disposal in salt by this working group will provide an important reference for future safety case development.

In the following Proceedings, an overall summary of key issues pertinent to the 4th US/German Workshop on Salt Repository Research, Design, and Operation is given. Additional reference detail can be acquired in the abstracts and power-point presentations, also included in this document.

CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

ACRONYMS

ABC	Actinide and Brine Chemistry Workshop (ABC)
BAMBUS	Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt / Germany
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
CPRZ	Confinement Providing Rock Zone
DBE	Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe
DOE	Department of Energy
DOPAS	Demonstration of Plugs And Seals
EDZ	Excavation Damaged Zone
ELSA	**S**chachtverschlüsse für **E**nd**l**ager für hochaktive **A**bfälle (Shaft Seals for Repositories for High-Level Radioactive Waste)
FEP	Features, Events, and Processes
HLW	High-Level Waste
IfG	Institut für Gebirgsmechanik GmbH
IGD-TP	Implementing Geological Disposal of Radioactive Waste Technology Platform
IGSC	Integration Group for the Safety Case
KIT	Karlsruhe Institute of Technology
MoDeRn	Monitoring Development for Safe Repository Operation and Staged Closure
MoU	Memorandum of Understanding
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
RD&D	Research Development and Demonstrations
REPOPERM	Restporositat und permeabilitat von Kimpaktierendem Salzgrus-Versatz
TBD	Thermochemical Database
THEREDA	Thermodynamic Reference Database
TM	Thermal-Mechanical
TSDE	Thermal Simulation of Drift Emplacement
TUC	Technical University Clausthal
TUBS	Technical University Braunschweig
URL	Underground Research Laboratory
US	United States
VSG	Vorläufige Sicherheitsanalyse Gorleben (Preliminary Safety Analysis)
WIPP	Waste Isolation Pilot Plant

Proceedings of the 4th US/German Workshop on Salt Repository Research, Design and Operation

Meeting Venue: Hollywood Media Hotel
Kurfürstendamm 202
D-10719 Berlin
September 17-18, 2013

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1. INTRODUCTION

These Proceedings of the 4th US/German Workshop on Salt Repository Research, Design, and Operation provide a summary of the sequence of presentations and discussions and provides a record of our workshop activities. Since restarting close US/German collaborations, the purpose has been to assemble invited key investigators in salt repository science and engineering and to identify a coordinated research agenda that participants can agree to pursue with the intent of maximizing individual resources for the mutual benefit of each program. The authors of these Proceedings have functioned as the primary coordinators of these workshops and they are responsible for the scientific agenda and reporting. These workshops were put together for the mutual benefit of the US and German salt repository programs, which face the challenges of preserving and improving capabilities in salt repository science and technology.

US and German researchers have intensively collaborated in salt repository research for nearly 50 years. Together their extensive research, development, and demonstration activities contribute to the profound knowledge available concerning rock salt. These achievements were manifested in laboratory and in situ experiments, including large-scale demonstrations (Steininger, et al., 2013). Particularly noteworthy progress has been made on safety assessments for heat-generating waste disposal and multiphysics modeling to capture physical processes with the next generation of computational capabilities. Owing in part to close collaboration between German and US salt researchers, comprehensive knowledge and sound expertise in salt repository science and engineering have been acquired over the years.

It is acknowledged that the enormous concept of licensing, operating, and closing a salt repository and the scientific-technological challenges connected thereto can be tackled much more efficiently by an international job-sharing effort. Collaboration helps reduce risk as well as cost while strengthening the scientific basis. International collaboration provides an opportunity to educate, train, and exchange scientists to promote development of the requisite human capital needed over repository lifetimes. The importance and the potential of the collaboration have been further supported by the responsible ministries and departments signing a Memorandum of Understanding (MoU) between the US Department of Energy (DOE) Offices of Environmental Management and Nuclear Energy and the German Ministry of Economics and Technology. German and US financial and intellectual investments in salt repositories are unique and represent state-of-the-art global assets.

On the day before the workshop, two salt-disposal related meetings were also held in Germany. The US/German Joint Project on the "Comparison of Current Constitutive Models and Simulation Procedures on the Basis of Model Calculations of the Thermo-Mechanical Behavior and Healing of Rock Salt" (hereafter Joint Project) meeting was held in Leipzig and the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA) Salt Club meeting was held in Berlin to take advantage of the large number of salt scientists arriving for the 4th US/German Workshop. The Joint Project, although separate from the US/German workshop in function, has nonetheless been intimately involved with the US/German collaborations. Since 2004, the series of Joint Projects has been considered an exemplary project. The Joint Project helps identify the best-in-class constitutive model, platform, simulation architecture, and solution algorithms appropriate for analyzing the performance of underground salt repositories, which ultimately provides permanent disposal of nuclear waste materials. The present Joint Project III, initiated October 1, 2013, will simulate isothermal and thermal-mechanical (TM) response of the Waste Isolation Pilot Plant (WIPP) Room B and Room D in situ experiments that were conducted during the late 1980s.

I am delighted that some 50 participants have made their way to Berlin from across Germany and from further afield. As Germany's capital city, Berlin is always worth a visit – particularly on account of its turbulent history over the past centuries.

As salt experts, you have come together for this U.S.-German workshop on Salt Repository Research, Design and Operation. And you will be spending the next two days discussing key issues:

- ***the safety case for repositories in salt rock formations,***
- ***specific engineering issues, such as plugging and sealing,***
- ***general issues of salt mechanics, and***
- ***repository design and operation.***

There is a long tradition of cooperation between the U.S. and Germany. We believe that our cooperation with the United States in particular offers potential synergies in research work, with the possibility of joint studies and experiments, for example in underground laboratories. I therefore hope that the existing fruitful cooperation between our countries will be continued with the same degree of intensity and commitment in the years to come.

Prof. Dr. Mager—Welcome Address Excerpt

(Complete Text in Proceedings)

The latest quarterly project meeting of the Joint Project was held at the Institut für Gebirgsmechanik GmbH (IfG) in Leipzig. An abstract summary and presentation of Joint Project progress are included later in these Proceedings of the 4th US/German workshop. To support Joint Project activities in the third phase, German research groups are conducting numerous laboratory tests on WIPP salt, which has been provided by Sandia. Questions with regard to humidity, distribution of polyhalite in the clean salt at WIPP, and differences in creep rate between 4-inch and 12-inch core were raised. One early observation that was discussed concerned the long-held claim that WIPP salt creeps much faster than Asse salt. First results of the new tests suggest that generality may not be true. To further address creep results and clarify this open question, it was proposed that an upcoming quarterly Joint Project meeting be held in the US (approximately April or May 2014). Various presentations related to the numerical modeling of damage and healing were given. The very closely related WIPP core research and numerical modeling of these tests was also discussed. In preparation for next year's start of the WIPP Rooms B & D calculations that the Joint Project partners will perform, Sandia (Argüello) was asked to provide a starting mesh for WIPP Room D. The next quarterly meeting is scheduled to be held on January 16-17, 2014, in Karlsruhe.

The second related meeting on Monday September 16, 2013 was held by the OECD/NEA Salt Club. From the NEA monthly bulletin in October the following account was provided.

> *On 16 September, the NEA "Salt Club" held its 2nd annual meeting in Berlin, Germany together with the 4th US-German Geotechnical Workshop. Thirty-two participants from Germany, the Netherlands and the United States met to discuss the status of Salt Club projects and future activities, namely the collaboration between the NEA Thermochemical Database (TDB) Project and the German Thermodynamic Reference Database (THEREDA) to build a joint international thermochemical database. In the future, it is also envisaged that the Salt Club's Features, Events and Processes (FEP) list will be incorporated into the NEA International FEP database. At the meeting, several presentations were given on studies on microbial activities in deep geological repository salt formations (such as the Waste Isolation Pilot Plant in the United States, and Gorleben and Asse in Germany). Participants decided to make microbial activities one of the future working areas of the Salt Club and to co-ordinate research activities accordingly. The next meeting will be held on 18 March 2014 in Paris.*

Presumably the FEPs list mentioned in the OECD/NEA summary is that which is being prepared by Principal Investigators from the US and Germany as a result of the US/German Workshops on Salt Repository Research, Design, and Operation. The other emphases of the OECD/NEA "Salt Club" diverge appreciably from the mission embraced by US/German collaborators on salt repository research, design and operation and from the salt club mandate itself. The Salt Club Mandate for the Integration Group for the Safety Case (IGSC) does not identify microbial studies or a reference to a thermodynamic data base as a purpose.

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

Workshop collaborators have extensive experience with the building blocks of performance assessment—often referred to as FEPs. Planned and ongoing collaboration between Principal Investigators from the US and Germany includes producing a single consolidated salt repository FEP list. Consistent progress on the consolidated FEPs list was reviewed at the 4th Workshop. As noted in a number of published sources including previous US/German Workshop Proceedings http://www.sandia.gov/SALT/SALT_Home.html the international salt research community has a solid foundation for a salt safety case and the associated performance assessment. A *safety case* is a formal compilation of evidence, analyses, and arguments that substantiate and demonstrate the safety, and the level of confidence in the safety, of a proposed or conceptual repository (Sevougian, et al., 2012a; 2012b). The central quantitative analysis of the safety case is performance assessment, which calculates the future of salt host rock for the undisturbed scenario. As acknowledged in previous US/German Workshops, a safety case for heat-generating waste will provide the necessary structure for organizing and synthesizing the existing technical bases. A safety case synthesis has the potential to identify issues and uncertainties pertaining to safe disposal of heat-generating nuclear waste in salt and thereby aid DOE plans for research development and demonstrations (RD&D) activities.

Subject matter experts from the US and Germany are in the process of compiling a comprehensive FEPs catalogue for disposal of heat-generating waste in salt. A FEP matrix approach is currently being applied to develop a comprehensive set of FEPs for a generic salt repository. The goal of the collaboration is to populate an international FEP database for salt repositories (Freeze, et al., 2014). The initial deliverable product is a Preamble document – Volume 1 of the catalog—and is expected in March 2014. Germany has completed their FEPs list for Germany's preliminary safety analysis for the Gorleben site (Vorläufige Sicherheitsanalyse Gorleben or VSG), which obviously provides a strong technical basis for a safety case for salt disposal of heat-generating nuclear waste.

At the 4th Workshop, a summary of the FEPs analysis and scenario development was given by US and German Principal Investigators. The presentations are included in Appendix E. Progress to date is appreciable, including development of a numbering scheme and an easily tractable template. Workshop partners also discussed elements of the safety case including handling uncertainties and the qualitative contribution of analogues. The noteworthy advancement in dealing with this important topic is owed to the expertise of the US/German experts and underlines the excellent and successful collaboration.

The German VSG is based on the concept of the excellent isolation capabilities of rock salt, called the confinement providing rock zone (CPRZ). Technical information supporting the salt safety case in the US has been substantial for several years, to wit: *the performance function of a salt repository would readily satisfy expected regulatory criteria for the safety case* (Hansen and Leigh, 2011). Sandia stands ready to develop a generic safety case for disposal of heat-generating waste in bedded salt, including a performance assessment and other safety arguments.

As DOE EM considers new salt emplacement schemes for heat-generating defense waste, they have initiated a program to formulate a safety case for emplacement of these waste forms. The development of this safety case is a two-year effort focused largely on identification of such waste forms and development of tools that can be used to model the WIPP safety case scenarios at temperatures above the ambient temperature. To support modeling the WIPP safety case scenarios, data are being collected on the chemical, mechanical, hydrologic, and thermal properties of major components that are part of the WIPP design modified to accommodate the heat-generating waste forms. The safety case being developed leverages existing modeling tools as much as possible and WIPP site characterization data. The collaborators agree that the use of natural analogs contributes fundamentally to the safety case.

3. PLUGGING AND SEALING

It is essential to demonstrate that a repository can be sealed. Seal systems include both shaft and drift settings. Real-time, full-scale drift seal demonstrations and concomitant monitoring are ongoing in the Morsleben repository. A research and development (R&D) project, **S**chachtverschlüsse für **E**nd**l**ager für hochaktive **A**bfälle (ELSA) is dedicated to design and construct functional components of a long-term stable sealing system for a shaft seal and eventually to demonstrate the constructability and functionality. The ELSA project as described in the presentations in these Proceedings (Bollingerfehr, et al.) is developing concepts for shaft seals in salt and clay formations and demonstrating functional elements using laboratory and medium scale tests. As can be appreciated, salt repository seal systems commonly include an element of specialty (e.g., salt-saturated) concrete, a component of bentonite (compacted or blocks), and crushed salt as primary seal materials.

In these Proceedings, design, placement, monitoring, and evaluation of a concrete drift seal in Morsleben were discussed. Specifically see presentation material in Appendix E provided by Mauke on construction and concrete placement and Stahlmann on monitoring performance. The main concerns are characteristics of the salt concrete mass itself, the contact zone between the concrete and the surrounding rock salt, and the rock salt excavation damaged zone (EDZ). As noted by the subject matter experts, the contact zone and the EDZ both profit by the creeping of the salt. Monitoring large-scale structures is a recognized challenge.

One of the key overarching research areas pertaining to plugging, sealing, testing, and modeling involves reconsolidation of granular salt, particularly in the horizontal orientation. Based on discussion during the 4th US/German Workshop, collaborators have begun developing strategy for obtaining field samples of reconsolidated granular salt, such as might be acquired from back-filled rooms and entries in operating salt mines. One high priority site for such sampling would be Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt / Germany (BAMBUS II) because US and German researchers have examined reconsolidated salt from that site nearly ten years ago (Bechthold, et al., 2004). The associated experiment was a full-scale mock-up of drift disposal called Thermal Simulation of Drift Emplacement (TSDE). The TSDE experiment represented direct drift disposal of six simulated Pollux casks placed in two test drifts backfilled with crushed salt. The decay heat of the spent fuel was simulated by electric heaters in the casks, which were heated with constant power for nine years (1990 until 1999).

The maximum temperature of 210 °C decreased to 170 °C at the termination because the backfill compacted and thermal conductivity increased (Rothfuchs and Wieczorek, 2010).

Thus, US and German collaborators have the possibility to examine dry reconsolidated salt, which has experienced some 23 years of closure. Figure 1 shows an example scanning electron image on the left and an optical thin section micrograph on the right from the BAMBUS II site taken ten years ago. Porosity of this particular sample is 29% and the permeability is 2 X 10^{-11} m^2. These types of measurements would be made on other analogue samples to explore processes involved with granular salt reconsolidation to an essentially impermeable condition. The key technical questions involve how quickly reconsolidation occurs and under what conditions.

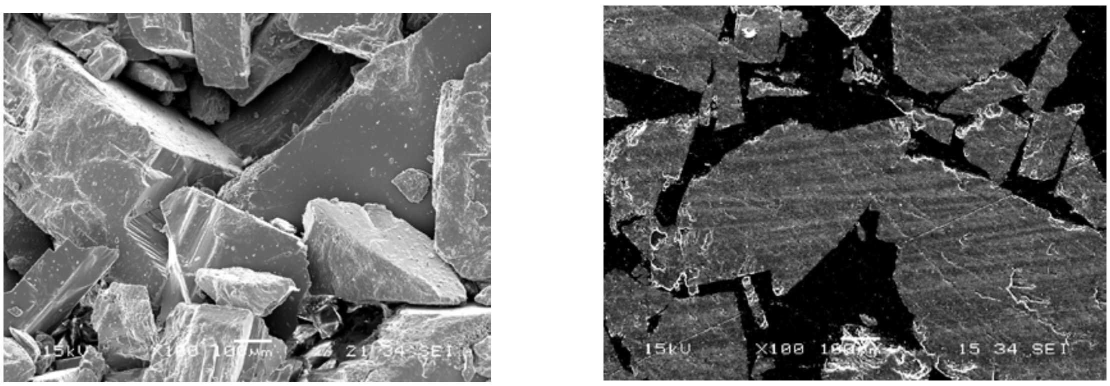

Figure 1. BAMBUS II granular salt reconsolidated about 10% from initial placement condition.

US and German Principal Investigators have made preliminary contacts regarding field sites to be explored and estimated the types of samples to be collected (if possible). Verbal acknowledgement and support for obtaining samples at the BAMBUS II site have been received. The current plan estimates that the remaining four casks (with electric heaters) associated with the experiment will be retrieved in the summer of 2014. Therefore, samples of reconsolidated salt might be acquired in the time period just before retrieval of the remaining casks. As collaborators are quite familiar with the BAMBUS II site, we can reasonably acquire field samples across the reconsolidated mass—at nominal intervals or nominal spacing. To directly facilitate laboratory testing, 100 mm X 200 mm field samples nominally one meter in length could be obtained. Field acquisition should involve dry sampling careful handling. Laboratory experimental pressure cells with capability for permeability measurements can readily accommodate specimens approximately 100 X 200 mm. Permeability tests would likely be followed by hydrostatic consolidation while continuing permeability testing in order to obtain permeability as a function of porosity. Field samples can also be sawn blocks or cubes from which laboratory samples are cored. Remnant pieces can be used for optical and scanning electron microscopy of the substructures, both before and after laboratory experiments.

4. SALT MECHANICS MODELING

In 2011, German salt modeling researchers and Sandia signed a MoU to collaborate jointly in in the 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 to formulate a strategy for generic modeling of thermomechanical field-scale tests. Progress on this collaboration will identify the best-in-class constitutive model, platform, simulation architecture, and solution algorithms appropriate for analyzing the performance of underground salt repositories, which ultimately provide permanent disposal of nuclear waste materials. This research will establish and document the most advanced modeling and simulation capability extant in the world for salt disposal options. All calculations will use highly advanced constitutive laws that mathematically describe deformational processes inherent to those found in nuclear waste repository environment.

As an example used for the modeling of sealing and healing in a real underground situation, the simulations were performed of a drift in the former Asse II salt mine that was excavated in 1911 and of which a 25 meter section was lined after 3 years with a cast-steel tube and concrete (see photograph in Figure 2). The partners are currently performing different simulations: 1) open drift, 2) drift with bulkhead: 2a) no healing assumed, 2b) healing assumed. First results demonstrate that the considered models are able to describe sealing and healing of damaged and dilatant rock salt in the EDZ. This is essential for calculations of the plugging and sealing of underground chambers, drifts, and shafts.

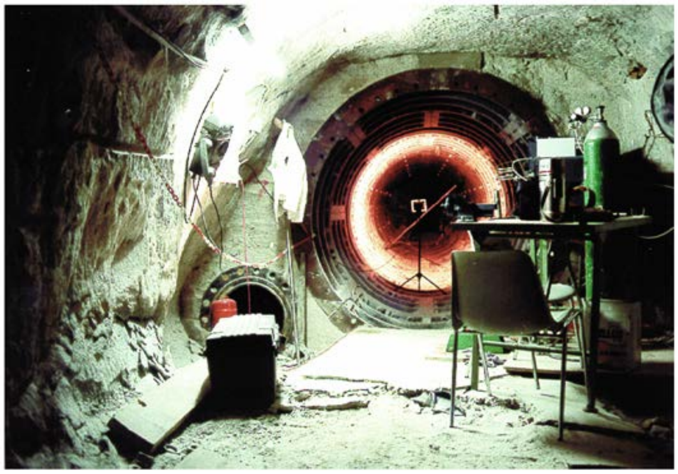

Figure 2. Joint Project models this liner configuration in the Asse Mine.

The Joint Project has been officially extended to include two additional benchmarking problems based on in situ full-scale tests conducted in the early 1980's at WIPP. Modeling will compare an isothermal mining development test (WIPP Room D) to a heated "overtest" for simulated defense high-level waste (WIPP Room B). In concert with benchmark modeling of the full-scale field tests, German research groups are conducting approximately 140 laboratory experiments on WIPP salt samples. Back-calculations of the various lab tests with different boundary conditions demonstrate the ability of the models to describe different phenomena and their dependencies under different and well-controlled conditions. Back-calculations of these lab tests are not only performed for the parameter determination, but also as a check of model capability to describe the deformation behavior of bedded WIPP salt.

Thus, the Joint Project extension comprises two large efforts: Benchmark modeling of WIPP Rooms B&D and a suite of laboratory tests on WIPP salt. A project status summary as well as a look forward was provided in separate presentations by Hampel and Argüello, which are included in Appendix E. Earlier collaboration efforts led to the conclusion that further tests on WIPP salt were needed by the partners to parameterize their respective models for the WIPP Rooms B&D benchmark effort.

After the 3rd Workshop in Albuquerque, three partners made requests for WIPP salt core for laboratory testing. Shortly thereafter (in late 2012), a first shipment of 4-inch WIPP salt core (both clean and argillaceous) from existing inventory was sent to the technical universities at Clausthal and Braunschweig (TUC and TUBS), and the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). A second large shipment of 12-inch clean salt core was sent to IfG in March 2013 followed by another shipment of 12-inch argillaceous salt sent to IfG in June 2013.These cores are shown in their packaging (left) and natural state (right) of Figure 3. The cores arrived in Germany in excellent condition. A final shipment of 4-inch core acquired from the WIPP floor and penetrating Marker Bed 139 arrived at the BGR on September 20, 2013. In addition, seven 5-gallon buckets of run-of-mine crushed salt were sent to the BGR, to be studied in the framework of the important German Restporositat und permeabilitat von Kimpaktierendem Salzgrus-Versatz (REPOPERM)-Project (Krohn, et al., 2009) in which the porosity/permeability development of crushed salt is investigated. WIPP crushed salt is used as an example to examine the influence of humidity the porosity/permeability behavior.

Figure 3. Shipment of WIPP core to German research groups.

As part of the US/German salt repository collaborations, German salt repository experts and Sandia are conducting benchmark evaluations of generic modeling of thermomechanical field-scale tests, as described above. The German researchers are conducting a large series (~ 140) of geomechanical tests on WIPP salt to derive WIPP parameters specific to physical phenomena represented within their salt models. In the US, consideration has been given to replicating a subset of these tests in US laboratories, which implement quality assurance requirements of DOE repository programs. Performing corroborating tests in this manner could avail the possibility of qualifying the entire database produced by the German research groups.

As of this writing many of the strength tests have been completed, creep tests are under way, and prepared test samples have been sent to collaborating German research centers. Technical reports regarding substructures of WIPP salt have been transmitted from Sandia to the IfG. These reports include the extensive brine sampling done at the WIPP site (Deal, et al., 1989) and several others pertaining to undeformed and deformed substructures, physical, and mechanical variability of natural rock salt, and percentages of mineral constituents. Characterization of WIPP salt was performed 25-30 years ago, when imaging and file saving techniques were not digital. New images will be helpful for corroboration and preservation. Thus far, moisture content measurements correspond well to values provided by Deal, et al., 1989).

The benchmarking collaboration and accompanying laboratory tests are of enormous value to generic salt repository science. When laboratory testing of WIPP salt and modeling of WIPP Rooms B & D are complete, the science community will possess the best-available analysis, design, and performance assessment modeling tools for salt repository investigations.

5. REPOSITORY DESIGN AND USE OF THE WIPP URL

As with many topics covered in these US/German workshops, practical monitoring experience has application within repository science, engineering, design, and performance. Many challenges arise in the analysis and interpretation of the captured values even with careful planning of the measurement program and installation of the monitoring devices. The international repository community has significant participation in collaborative monitoring projects, which were revisited in this workshop. The European Commission Joint Research Project MoDeRn (Monitoring Development for Safe Repository Operation and Staged Closure) (www.modern-fp7.eu) and Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) (http://www.igdtp.eu) were discussed. The MoDeRn project is nearing completion. Discussions within the IGD-TP concerning a follow-up project are ongoing. Further opportunity in IGD-TP for collaboration is a desirable goal.

The monitoring experience naturally extends to possible testing, and demonstration activities at the proposed WIPP Underground Research Laboratory (URL). The URL provides a unique opportunity to advance the scientific basis for heat-generating waste disposal in salt, perhaps by identifying test activities that could reduce uncertainty or advance the technical bases for such disposal. In break-out sessions workshop participants reviewed possible uses, which have been enumerated in technical publications (Hansen, et al., 2013, Hansen, 2013). A formal, independent review of potential uses of the WIPP URL has not been undertaken.

At this 4th workshop, concepts for use of the WIPP URL were discussed once again by dividing attendees into break-out groups. Several potential URL activities were reviewed in break-out sessions, including those previously identified in the reference documents as well as some new ideas. Workshop participants were asked to provide a high-level review and feedback concerning a sense of duration, cost, and merit among the many potential uses. Field testing inherently requires time to develop and review Test Plans, to perform an operational readiness review, to identify and purchase requisite instrumentation, to prepare the underground test bed, and finally to execute the action. The physical phenomena (such as thermally driven creep processes or damage healing) also require relatively large scale and time-dependent evolution. In Table 1, cost is abstracted as dollar signs ($ ~ 1 million, $$$$ > 10 million) and time is estimated in year durations. The counterpart to cost and time is perceived benefit, which can be achieved at several different levels. In these high-level considerations benefits were categorized as confirmation, demonstration, validation, and new science. In tests where "new science" was advanced as the purpose, the technical merit column identifies the nature of the advancement. Of course, this review and discussion was rather cursory and a more formal and rigorous review process of URL activities would be expected in order guide development of the URL.

Table 1. High-level review of possible WIPP URL activities.

Activity	Purpose	Duration (years)	Cost	Technical Merit
Single Heater	Confirmation	1-5	$$	Model validation
Large-scale Seal	Confirmation and demonstration	5	$$$	Confirmation, demonstration, and performance
SDI-Hot waste	New science	5+	$$$$	Accelerated results, model validation
SDDI-Defense Waste	Demonstration	5	$$$$	Demonstration
Wedge Pillar	New science	N/A	N/A	Not supported
Fluid differential pressure test	New science	3	0.5$	Intact permeability in bedded salt
In situ consolidation	New science	<3	$	Consolidation data gap, permeability
Canister movement	New science	5+	$$	Model buoyancy

Most of the proposed investigations were considered expensive and of long duration. The concept of a wedge pillar was not supported because it appears to be redundant to similar testing that was completed at the Asse Mine in the 1980s. These preliminary evaluations of the many potential uses for a URL at WIPP are based upon the experience and lessons learned in the design and management of the original underground investigations program that supported the technical basis for the WIPP as well as decades of salt experimental programs undertaken in Germany. International experience in salt and other geologies provide further insights into the proper design and operation of URL research programs for maximum utility.

6. GEOCHEMISTRY, MICROBES, AND HYDROGEOLOGY

An update of the Actinide and Brine Chemistry Workshop (ABC) held in Santa Fe, New Mexico in April 2013 was provided. Although water intrusion is clearly a less probable scenario in salt repositories, prediction of radionuclide/brine interactions are part of performance assessment (see Altmaier and Reed presentation in Appendix E). As described by Van Luik (2013): *the only way to remove materials from the repository is via human intrusion scenarios involving brines introduced by drilling, or by striking a pressurized brine pocket that sends brine up along the drill-hole into and through the repository. Brines in contact with the waste, with a loading of actinides in solution or carried on particulates, may be removed by such a brine flow. Although the scenarios are unlikely, several (*are modeled to*) occur in every 10,000-year system performance calculation.* In the WIPP scenarios, pore pressure within repository rooms is postulated to increase by anoxic corrosion and microbial consumption of cellulosics, plastic, and rubber. Conditions for microbial activity include presence of sufficient brine, nutrients, and microbes. The expected evolution of a room within a salt repository, especially a repository for heat-generating waste, is complete encapsulation by the salt.

US/German salt repository geohydrologists explored possibilities for a new area of collaboration in hydrogeologic modeling. In particular, this modeling involves far-field circulation systems, for which Sandia and the GRS presented an update at this workshop (see Kuhlman and Schneider presentations in Appendix E). These powerful tools are able to meet the needs of far field modeling, with applicable porous and fractured media flow. Further collaboration on far-field hydrology is planned in upcoming US/German workshops.

7. 5th US/GERMAN WORKSHOP

The next US/German workshop is planned to be held in Santa Fe, New Mexico, USA. Tentative dates include the week of September 8-12, 2014. Sandia will be the primary host for this workshop. Topics include

- Modeling of healing – Comparison of simulation results of a lined drift in the Asse Mine (Joint Project)
- Modeling of WIPP Rooms B & D
- Laboratory testing of WIPP salt
- Characterization of WIPP salt by German colleagues and existing information from the USA
- Operational safety
- Analogues for reconsolidation
- Far-field hydrology
- Uses of the WIPP URL
- IGD-TP
- Safety Case for HLW disposal in salt
- Quantifying and handling of uncertainty http://www.eurunion.org/FP7-USGuide-12-09.pdf
- VIRTUS (modeling BGR/GRS/DBE TEC) and PFLOTRAN (modeling Sandia)
- Retrievability, container design, long-term storage
- Others
- Summary – review and status of completed tasks (FEPs, reconsolidation)

These Proceedings provide participants and sponsors of a sense of the progress attained via these collaborations. As noted in previous Proceedings (Hansen, et al., 2013) and at the Waste Management

Symposia (Steininger, et al., 2013), the salt repository science community is making significant progress toward some of the important early goals (e.g., FEPs and the safety case, model benchmarking, seal systems). We continue to add depth and detail to these collaborations. We also have naturally embraced other key activities identified in our mission statements, and embarked on additional collaborations (such as analogues, hydrology, and uses of the URL). Collaboration within our US/German workshop venue continues to advance salt repository science, while most efficiently summarizing, documenting, and transferring knowledge.

8. REFERENCES

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APPENDIX A: AGENDA

Final Agenda September 17-18, 2013

4th US/German Workshop on Salt Repository Research, Design, and Operation

Venue: Hollywood Media Hotel Berlin, Kurfürstendamm 202

DAY 1—September 17— Tuesday

08:00	Registration	
08:30 – 09:30	Welcome Address	D. Mager, Deputy Head (BMWi)
	US-National Program	N. Buschman (US DOE/EM) T. Gunter (US DOE/NE)
	German Situation and Developments “Salt Club-Meeting” Report	J. Mönig (GRS) J. Mönig, Chairman

Selected Aspects of the Safety Case for Salt Disposal of HLW/SNF

09:30-10:15	FEP-Catalogue & Scenario Development	Ch. Leigh, G. Freeze (SNL) J. Wolf, J. Mönig (GRS)
10:15-10:45	Handling of Uncertainties in a Safety Case	U. Noseck (GRS)
10:45-11:15	**Coffee Break**	
11:15-11:45	Discussion on Specific Rock Salt Analogues	U. Noseck (GRS), N. Rempe
11:45-12:15	Operational Phase Safety	W. Bollingerfehr (DBE TEC), E. Hardin (SNL)
12:15-13:30	**Lunch at the Hotel**	
13:30-14:00	Report on WIPP	A.van Luik (US DOE/EM)

Plugging and Sealing

14:00-14:30	BMWi-Project ELSA	W. Kudla (TU BAF) W. Bollingerfehr (DBE TEC)
14:30–15:00	Plugging & Sealing	F. Hansen (SNL)
	SITED-Project	K. Kuhlmann (SNL)
15:00-15:30	ERAM Plug Experiment	R. Mauke (BfS)
15:30-16:00	**Coffee Break**	

Cont. 4th US/German Workshop on Salt Repository Research, Design, and Operation

Geochemical Issues

16:00-16:30	Report on the ABC-Salt II Workshop	M. Altmaier (KIT/INE), D. Reed LANL)
16:30-17:15	Microbial Effects	J. Swanson (LANL), Ch. Leigh (SNL)
17:15-17:45	Summary	SNL/PTKA/DBE TEC
	Workshop Photo	
19:00	**Dinner Hosted by BMWi/PTKA**	

DAY 2— September 18 —Wednesday

Rock/Salt Mechanics (THM-Modeling)

08:30-09:15	Status of the US-German "Joint Project"	A. Hampel (Scientific Consultant) L. Argüello (SNL)
09:15-10:00	Laboratory Tests on WIPP Salt	T. Popp (IfG) K. Mellegard (RESPEC)
10:00-10:30	**Coffee Break**	
10:30-11:30	Reconsolidation of Crushed Salt	T. Popp (IfG), D. Stührenberg (BGR) K. Wieczorek (GRS), F. Hansen (SNL)

Repository Design and Operations

11:30-12:00	Practical Monitoring Experiences	J. Stahlmann (TU Braunschweig) F. Hansen (SNL)
	IGD-TP	W. Steininger (PTKA)
12:00-13:00	**Lunch at the Hotel**	
13:00-14:00	Future URLs in Rock Salt	F. Hansen (SNL), C. Leigh (SNL)
14:00-14:30	**Coffee Break**	

Miscellaneous Important Issues

14:30-15:30	Hydrogeology (Modeling, Testing, Validation)	K. Kuhlmann (SNL) A. Schneider (GRS)
15:30-16:00	Outlook on SaltMech8	L. Roberts (RESPEC)
	Summary and Outlook	SNL/DBE TEC/PTKA
16:00	**Adjourn**	

APPENDIX B: WELCOME ADDRESS:

Prof. Dr. Mager—Welcome Address

Ladies and Gentlemen,

At the start of the fourth joint US-German workshop co-organized by Sandia National Laboratories, DBE Technology and our project management organization at the Karlsruhe Institute of Technology (KIT), I would like to extend a warm welcome to you here in Berlin and pass on a message of greeting from the Federal Ministry of Economics and Technology. I would particularly like to welcome our guests from the United States and the OECD/NEA representatives.

I am delighted that some 50 participants have made their way to Berlin from across Germany and from further afield. As Germany's capital city, Berlin is always worth a visit – particularly on account of its turbulent history over the past centuries.

Looking beyond historical times, you will all be aware that in geological terms, Berlin is located in the Southern Permian Basin. This is the region where, some 255 million years ago, today's salt formations were created by cyclic evaporation processes. And nowadays, these important formations are potential host rock formations for the final disposal of hazardous waste in general, and radioactive waste in particular.

As salt experts, you have come together for this US-German workshop on Salt Repository Research, Design and Operation. And you will be spending the next two days discussing key issues:

- the safety case for repositories in salt rock formations,
- specific engineering issues, such as plugging and sealing,
- general issues of salt mechanics, and
- repository design and operation.

There is a long tradition of cooperation between the US and Germany. Some of you may know that, in the past thirty years, American colleagues have conducted and participated in experiments in our underground laboratory in the Asse salt mine. These Asse experiments included the "BAMBUS" project, the world's first long-term demonstration experiment.

In 1999, the United States gave a clear signal to the international radioactive waste management experts community: the commencement of operations at the WIPP site, the Waste Isolation Pilot Plant near Carlsbad / New Mexico. WIPP is the world's first operating geological repository for radioactive waste in rock salt, and WIPP continues to be a success story.

Until mid-2001, there were various cooperation projects. The expertise gathered in these projects enabled both countries to conclude that it was possible and feasible to construct and operate underground repositories in salt rock formations.

Since then, however, priorities in waste management policies in Germany and in the US have somewhat shifted the emphasis of our cooperation.

It was not until the end of 2009 that both countries' waste management philosophies reverted back to a more open attitude to salt. This was the starting point for reviving our collaboration. The upshot of this was the first joint workshop in Canton (Mississippi) in May 2010, which was co-organized by Sandia National Laboratories, DBE Technology and our research project management organization at the Karlsruhe Institute of Technology (KIT). The second workshop held in Peine / Germany in 2011 resulted in the initiative to form the OECD/NEA Salt Club.

In addition to the United States and Germany, the official founding members of the Salt Club in 2012 were the Netherlands and Poland, where salt is also an important option as host rock for a radioactive waste repository.

This year's meeting of the Salt Club took place yesterday and covered important issues like

- the relevance of microbes to the salt safety case,
- the thermochemical and thermodynamic databases, and
- the FEP catalogue

An important milestone in the US-German cooperation was the signing of the agreement between the Federal Ministry of Economics and Technology and the two Offices of the US Department of Energy – Environmental Management and Nuclear Energy – in 2011. This agreement on salt research forms an important basis for our future bilateral cooperation.

Allow me to say a few words about the new political situation here in Germany regarding the repository for high-level radioactive waste.

The adoption of the new Act on Site Selection by the Bundestag and Bundesrat this summer created the legal framework for a political consensus on radioactive waste management and thus calmed our national debate on nuclear power. The new legislation stipulates a staged site selection process, starting from a "white (blank) map" of Germany.

This means that, during this site selection process, potential rock salt sites, like Gorleben, will have to compete in the evaluation process with suitable sites in alternative rock formations. At the same time, the implementation of the Site Selection Act means that

- alternative sites and different host rock formations have to be considered for the final disposal of radioactive waste, and, at the same time,
- further scientific and engineering research has to be conducted in order to enhance and further develop the state of science and technology regarding the suitability of salt rock formations.

Here, we particularly need to draw on international networks and experience. Therefore, in our view the continuing cooperation between the United States and Germany, such as the network of the Salt Club, remains both necessary and useful.

Not least, the broad range of topics covered by this year's workshop shows how topical the theme of rock salt is. As we tackle the challenges that lie ahead of us, Germany will be feeding in its many years of "salt" expertise.

We believe that our cooperation with the United States in particular offers potential synergies in research work, with the possibility of joint studies and experiments, for example in underground laboratories. I therefore hope that the existing fruitful cooperation between our countries will be continued with the same degree of intensity and commitment in the years to come.

On this note, I wish the workshop every success.

APPENDIX C: LIST OF PARTICIPANTS AND OBSERVERS

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APPENDIX D: BIOS

Marcus Altmaier

Hiroomi Aoki

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.

Thilo von Berlepsch

Enrique Biurrun

Enrique Biurrun was born and grew up in the vast plains of western Argentina. There, he used to look every day through the cleanest air he ever saw to the 120 km distant Nevado, a 4000m high volcano, to guess how weather would develop. In this impressing landscape he could well have become a volcanologist, but Nevado is silent for now, and he is 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 he got in Nuclear Engineering at RWTH Aachen University in Germany in 1980. And once there Enrique stayed to get a PhD in Radioactive Waste Disposal. After 8 years working on final repositories R&D Enrique 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 Enriguq represents both companies in international forums and events and participates and leads engineering repository related work, at present for customers in Ukraine Bulgaria, Belgium, and Japan.

Stephan Bödecker

Wilhelm Bollingerfehr

Diplom-Bauingenieur (M.Sc.eq) –civil engineer, Head of Research and Development Department at DBE Technology GmbH, in Peine, Germany

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 high-level waste (HLW) repository in salt formations in the context of a preliminary safety case.

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.

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

Ralf Eickemeier

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 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.

Werner Gräsle

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.

Jörg Hammer

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 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 Labs 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 of 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.

Benno Haverkate

Michael Hofmann

Bernhard Kienzler

Bärbel Kleinefeld

Kris Kuhlman

Kris Kuhlman is a hydrogeologist at Sandia National Laboratories, where he is the technical lead for the hydrology program at the US Department of Energy’s Waste Isolation Pilot Plant (WIPP) in Carlsbad. Kris received his PhD in Hydrology from University of Arizona, and his Bachelor’s degree in Geological Engineering from Colorado School of Mines. Before Sandia, Kris worked several years as a groundwater consultant in the Los Angeles area.

Gloria Kwong

Gloria Kwong is a project manager at the OECD/NEA, supporting the Integration Group for the Safety Case (IGSC). The IGSC is a main technical advisory body to the Radioactive Waste Management Committee (RWMC) of the OECD/NEA. She has the role of liaising members of the IGSC from 28 member countries and manages projects and technical programmes related to safety cases and safety assessments for radioactive waste disposal. Such liaison provides a platform for international dialogues and technical expertise exchanges among the member countries. PhD in Materials Science from Imperial College, London, UK. Masters of Engineering in Chemical Engineering from the University of Toronto, Canada. Licensed professional engineer in Canada.

Christi Leigh

Karl-Heinz Lux

Diethard Mager

Prof. Dr. Mager is Deputy Director General of the Federal Ministry of Economics and Technology, Berlin. He holds an honorary professorship for the field of Applied Geology at the University of Erlangen-Nürnberg and provides lectures and seminars on Energy Politics, Mineral Economics, Waste Management and Mine Decommissioning. He performed his academic education in geology at the University of Erlangen-Nürnberg; PhD thesis on granite intrusions. From 1985-1987 Dr. Mager was an advisor for Mineral Economics at the German Federal Institute for Geosciences and Natural Resources, BGR in Hannover. Since 1987 he has served the Federal Ministry of Economics and Technology in Bonn and Berlin as a senior advisor and division head with technical emphasis in mineral economics, geoscience research, radioactive waste management, decommissioning & remediation of uranium mine and milling sites, mine safety, and mining research. Presently he is deputy director general within the ministry’s Energy Department, responsible for strategic issues of energy policy and for energy research.

Ralf Mauke

- 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 Labs

- 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.

Kirby Mellegard

Mr. Mellegard has 40 years of experience in energy-related engineering tasks. Since 1977, Mr. Mellegard has been involved with a variety of programs in the area of materials testing provided by the RESPEC laboratory. Mr. Mellegard’s work in the laboratory includes designing, implementing, and using sophisticated mechanical test systems to characterize the behavior of natural rock salt in support of projects sponsored by nuclear waste isolation programs, commercial and government cavern storage projects (both gas and liquid), and potash mines in Saskatchewan and South America. Those salt research investigations were funded by a variety of both commercial and government clients including Sandia National Laboratories, National Energy Technology Laboratory, and the Solution Mining Research Institute. Mr. Mellegard has also provided laboratory research expertise in the hard rock arena where he served on the American Society for Testing and Materials (ASTM) Steering Committee that directed an interlaboratory research program to investigate the uncertainty levels in brittle rock strength and elastic properties determined within and between laboratories. He also led the effort to determine anisotropic properties of the brittle rock formations hosting the U.S. National Science Foundation facility for advanced study of neutrinos known as the Deep Underground Science and Engineering Laboratory (DUSEL) located in the former Homestake Gold Mine in Lead, South Dakota.

Wolfgang Minkley

Jörg Mönig

Nina Müller-Hoeppe

Erika Neeft

Ulrich Noseck

Jane Perrone

Thomas Pick

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.

Maximilian Pusch

Norbert Rempe

Lance Roberts

Lance A. Roberts, Ph.D., P.E. is currently the Vice President of RESPEC's Mining & Energy Division in Rapid City. Dr. Roberts' responsibilities include operations, project management, and client development within the mining and energy market sectors, specifically related to salt mechanics, rock mechanics in mining, and underground cavern storage. Before joining RESPEC, Dr. Roberts served as an Assistant Professor in the Civil Engineering Department at the South Dakota School of Mines and Technology (SDSM&T) where he taught geotechnical engineering courses. While at SDSM&T, Dr. Roberts' research was focused within the field of reliability-based design and risk assessment for geotechnical and geostructural engineering applications, along with specialty laboratory testing of soil and pavement materials. Dr. Roberts has published nearly 40 technical papers in national journals, international journals, and conference proceedings and has presented his research results at numerous forums. In addition, Dr. Roberts has numerous years of experience in the private sector focusing on the design of foundations, earth retention systems, slope stability, and other geotechnical and geostructural-related projects.

Klaus-Jürgen Röhlig

Anke Schneider

Pascale Semmler

Joachim Stahlmann

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

Walter Steininger

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

Dieter Stührenberg

Julie Swanson

Abraham Van Luik

Dr. Abraham (Abe) Van Luik is a Senior Physical Scientist and the Director of International Programs at the Carlsbad Field Office (CBFO) of the US Department of Energy. CBFO oversees and owns the Waste Isolation Pilot Plant (WIPP). Abe joined CBFO after several decades of working on the Yucca Mountain Project in Nevada, where he served as Senior Policy Advisor for Performance Assessment. With CBFO, Abe works with other staff to set up cooperation between the US repository program and other international agencies. Cooperative activities are formalized in a Memorandum of Understanding between the Department of Energy and its German counterpart, which is especially useful since the German repository program is also working in salt.

Abe's nuclear-waste career began at Argonne National Laboratory in Illinois, continued at Rockwell Hanford Operations in Washington, with Roy F. Weston and Rogers Engineering in Washington, DC, with the Pacific Northwest National Laboratories (PNNL) in Washington State, and with Intera, Inc. in Las Vegas, Nevada. Finally, he joined the Department of Energy in Nevada, where he oversaw the science and engineering side of the proposed Yucca Mountain repository's license application to the Nuclear Regulatory Commission.

Van Luik has a bachelor's degree in chemistry from the University of California at Los Angeles and both a master's and doctorate from Utah State University. His dissertation involved studying and modeling the solubility of heavy metals in the brines of Utah's Great Salt Lake.

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 and is head of GRS' geotechnical sector. His main expertise is in field testing in underground laboratories in different types of rock, especially salt and argillaceous formations.

Max Wippich

Holger Wirth

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 key emphasis has been the preliminary safety analysis for the salt dome Gorleben.

APPENDIX E: PRESENTATIONS

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Used Nuclear Fuel Disposition Research and Development

Timothy C. Gunter

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

4th US/German Workshop on Salt Repository Research, Design and Operations
Berlin, Germany
September 2013

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 United States 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.**

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.**

U.S. DEPARTMENT OF ENERGY Nuclear Energy

Summary of the Administration's UNF and HLW Strategy

- **Statement of Administration policy regarding the importance of addressing the disposition of used nuclear fuel and high-level radioactive waste**
- **Response to the final report and recommendations made by the *Blue Ribbon Commission on America's Nuclear Future***
- **Initial basis for discussions among the Administration, Congress, and other stakeholders**
- **10-year program of work that:**
  - Sites, designs, licenses, constructs, and begins operations of a pilot interim storage facility
  - Advances toward the siting and licensing of a larger interim storage facility
  - Makes demonstrable progress on the siting and characterization of geologic repository sites

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Legislation Needed for Implementation

- Active engagement in a broad, national, consent-based process to site storage and disposal facilities
- Siting, design, licensing, and commencement of operations at a pilot-scale storage facility
- Significant progress on siting and licensing of a larger consolidated interim storage facility
- Development of transportation capabilities to begin movement of fuel from shut-down reactors
- Reformation of the funding arrangements
- Establishment of a new organization to run this program

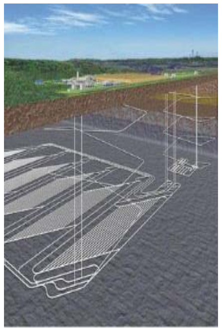
5

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

R&D Disposal

Objectives:

1. Provide a sound technical basis for the assertion that the U.S. has multiple viable disposal options
2. Increase confidence in the robustness of generic disposal concepts
3. Develop a plan for taking the deep borehole disposal concept to the point of a demonstration



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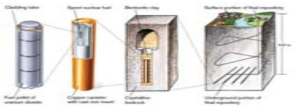
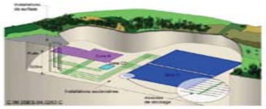
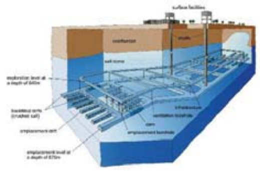
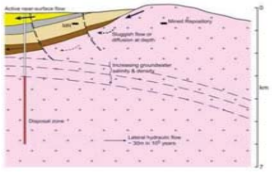
Disposal Options

- 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

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R&D Activities in Disposal

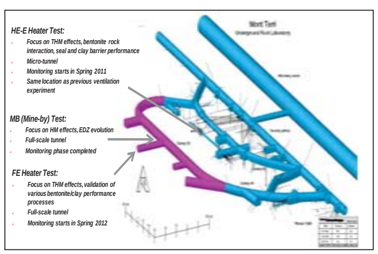
- R&D on generic geological media
  - Evaluate the performance of repositories in various geologic environments
  - Advance understanding of various disposal concepts in geologic media
- Work on geologic disposal will include:
  - Finalize an R&D and Demonstration plan and roadmap for the deep borehole disposal concept
  - Work with international partners for disposal in salt, granite and clay rocks
  - Evaluate feasibility of direct disposal of Dual-Purpose Canisters

8

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Disposal R&D International Collaboration

Formal collaborative R&D arrangements with ongoing programs in Europe and Asia



- Mont Terri: Underground research laboratory in clay (Switzerland)
- Grimsel: Colloid Formation and Migration Project in granite (Switzerland)
- DECOVALEX: (Development of Coupled Models and their Validation against Experiments)
- KAERI Underground Research Tunnel: Borehole Geophysics (South Korea)
- SKB: Task Forces on Groundwater Flow and Engineered Barriers at Äspö Hard Rock Laboratory (Sweden)
- BMWi: Data exchange for salt repositories at Gorleben and WIPP (Germany)
- ANDRA: Natural and Engineered Barriers in clay and shale (France)

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Please visit the Office of Nuclear Energy website for further program activities and information

http://energy.gov/ne/

German Situation

Jörg Mönig

4th US/German Workshop on Salt Repository Research, Design and Operations
Berlin, Sept. 17-18, 2013

Bill on Site Selection Process

- Bill has been enacted in July 23, 2013 on selecting a repository site for heat-producing radioactive waste
  - objectives: science-oriented and transparent site selection process
- Expert group will be convened, recommendations due by the end of 2015 (half a year extension possible)
  - 33 members incl. 1 chairperson; 16 members from parlament, 8 from science, 2 members each from religious groups, unions, industry & environmental groups
  - assessment of alternatives to disposal in deep geologic formation
  - recommendations concerning the selection process itself & site selection criteria (host rock specific exclusion criteria & minimum requirements for salt, clay, granite, host rock independent weighing criteria)
  - Criteria for error correction (design requirements concerning retrievability) and reversibility of decisions
  - Recommendations with respect to involving and informing the public

German Working Group on Repository Research (DAEF)

- Established Jan. 16, 2013, members are leading German institutions
  - DBE Technology
  - FZ Jülich
  - GRS
  - Helmholtz-Zentrum Dresden-Rossendorf
  - IfG
  - ISTec
  - KIT
  - Öko-Institut
  - TU BA Freiberg (Institut für Bergbau und Spezialtiefbau)
  - TU Clausthal (Institut für Endlagerforschung)
  - TU Braunschweig
- Chairperson: Horst Geckeis (KIT-INE)

DAEF - Objectives & Activities

- to contribute to the safe disposal of radioactive waste
- to render the associated research more effective.
- to provide advisory support to political institutions and the competent federal and Länder authorities as well as other interested organisations
- to inform the general public about developments and results in the field of repository research
- to promote and intensify exchange between specialists
  - International Conference will be held in autumn 2014
- Currently a position paper is developed on scientific-technical and social-science aspects of repository site selection (December 2013)

Preliminary Safety Case Gorleben (Project VSG)

Basics
- Site characterization and long-term prediction
- Waste characteristics and quantities
- Safety concept and Demonstration concept

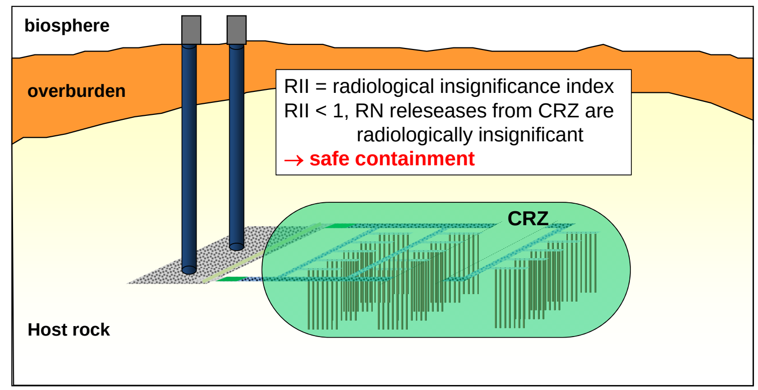
Repository design
- Repository concept
- Repository design & optimization

System analyses
- FEP catalogue and scenario development
- Integrity assessment geol. /geotechnical barriers
- Modeling of RN release scenarios
- Human Intrusion Scenarios

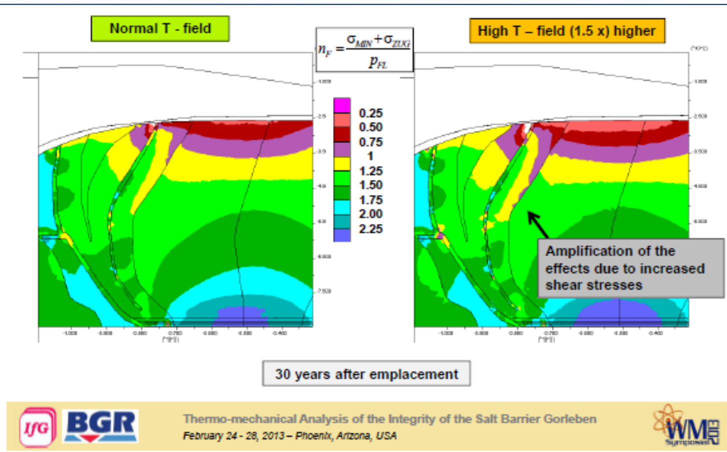
Synthesis
- Bewertung der Ergebnisse
- Empfehlungen

GRS, BGR Bundesanstalt für Geowissenschaften und Rohstoffe, GEOZENTRUM HANNOVER, DBE TEC DBE TECHNOLOGY GmbH, iSTec, IfG, KIT, nse international, GOETHE UNIVERSITÄT FRANKFURT AM MAIN, TU Clausthal

Containment-providing Rock Zone



Minimum stress criterion



Modeling of Radionuclide Releases - Overview

Modeling of solute transport (1D)

- **No** RN release from CRZ at 1% final porosity in compacted crushed salt backfill
- **Very low** RN release at 2 % porosity via diffusion, safe containment shown

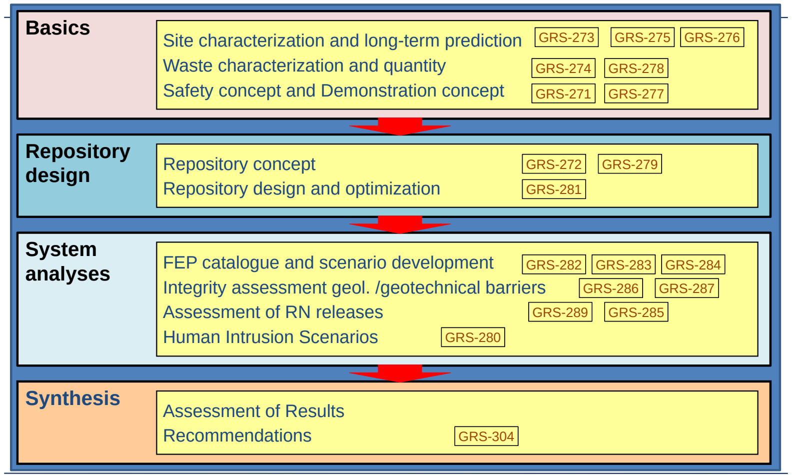
2-Phase modeling (3D)

- Independent of final porosity, relevant C-14 release in the gas phase via drift seal
  - Convergence with associated compaction of crushed salt backfill is driving factor for gas flow
  - Gas formation enhances gas flow due to salt convergence
  - Results are affected by position of the waste in the repository (-> optimization)

Release via gas phase main pathway for RN release from CRZ, in some cases RII > 1 (radiological insignificance index)

Properties of compacted crushed salt are relevant for results and their interpretation -> R&D-Bedarf, esp. at low porosities

VSG Reports



Literatur (1)

- GRS-271: Grundzüge des Sicherheits- und Nachweiskonzeptes
- GRS-272: Endlagerkonzepte
- GRS-273: Salzgeologische Untersuchungen der Integrität der geologischen Barriere des Salzstocks Gorleben (2012)
- GRS-274: Abfallspezifikation und Mengengerüst: Basis der Laufzeitverlängerung der Kernkraftwerke
- GRS-275: Geowissenschaftliche Langzeitprognose
- GRS-276: Sichtung und Bewertung der Standortdaten Gorleben
- GRS-277: Sicherheits- und Nachweiskonzept (*report replaces GRS-271*)
- GRS-278: Abfallspezifikation und Mengengerüst: Basis Ausstieg aus der Kernenergienutzung (*Update of Report GRS-273 after Fukushima*)
- GRS-279: Einschätzung betrieblicher Machbarkeit von Endlagerkonzepten
- GRS-280: Human Intrusion

Literatur (2)

- GRS-281: Endlagerauslegung und –optimierung
- GRS-282: FEP-Katalog für die VSG: Konzept und Aufbau
- GRS-283: FEP-Katalog für die VSG: Dokumentation
- GRS-284: Szenarienentwicklung
- GRS-285: Berücksichtigung der Kohlenwasserstoffvorkommen in Gorleben
- GRS-286: Integritätsanalyse der geologischen Barriere
- GRS-287: Integrität geotechnischer Barrieren Teil 1 - Vorbemessung
- GRS-289: Radiologische Konsequenzenanalyse
- GRS-304: Forschungs- und Entwicklungsbedarf auf Basis der Erkenntnisse aus der VSG sowie Empfehlungen
- All reports available via http://www.grs.de/german-publications?page=1&title=VSG&field_author_value=&field_year_value=&tid_1=&tid=All

FEP Catalogue and Scenario Development

Geoff Freeze (SNL), Jens Wolf (GRS)

2nd Meeting of the NEA Salt Club

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany
September 2013

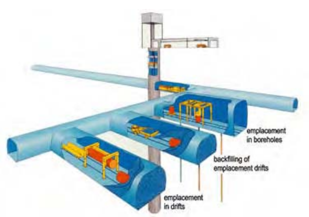
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2013-7511P.

Outline

- Joint U.S.-German Objective
- U.S. FEP Analysis and Scenario Development Approach
  - SNL: Geoff Freeze, S. David Sevougian, Michael Gross, Christi Leigh
- German FEP Analysis and Scenario Development Approach
  - GRS: Jens Wolf, Jörg Mönig, Dieter Buhmann
- Collaborative Results to Date
  - FEP numbering scheme
  - FEP template
- Future Work

Objectives

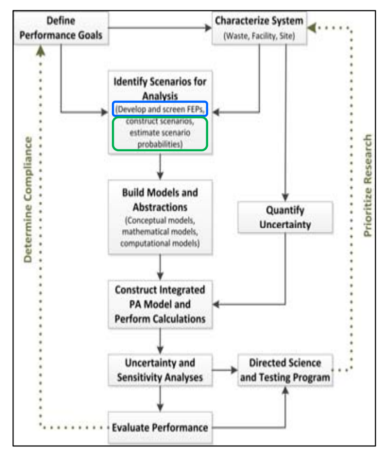
- U.S. – German collaboration to produce a common FEP list
  - Identify relevant features, events, and processes (FEPs) for disposal of heat-generating waste (SNF and HLW) in salt
    - Applicable to all potential salt concepts and sites
  - Review FEP analysis approach
- Salt Club
  - FEP Catalogue for use by all Salt Club members
  - Inform new NEA FEP database



U.S. FEP Analysis

- FEP Identification
  - Generic DOE Used Fuel Disposition (UFD) FEPs
  - Generic bedded salt FEPs
  - US-German Salt FEPs
    - FEP Matrix
    - FEP Content
- FEP Screening
- Scenario Development

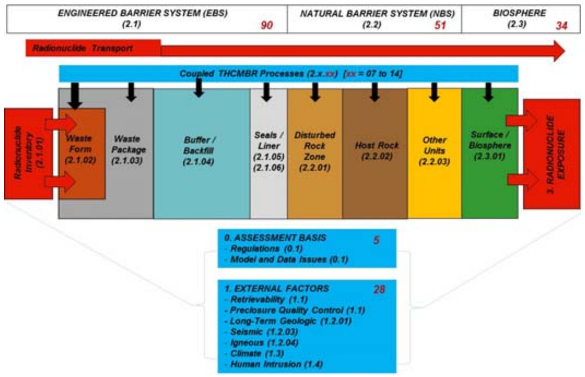
Safety Assessment Methodology



U.S. Generic UFD FEPs

Freeze et al. (2010, 2011)

- 208 FEPs – derived from the NEA FEP Database (1999, 2006) to be broadly applicable to a range of SNF/HLW disposal concepts



U.S. Generic UFD FEPs

- Example of a single UFD FEP

Broad FEP description provided in the "Description" column

Additional detail provided in the "Associated Processes" column

"Screening Decision" is dependent on design and siting

UFD FEP Number	Description	Associated Processes	Related FEPs	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	

2.1 = EBS
08 = Hydrologic

2.1.03 = EBS Waste Package
2.1.04 = EBS Buffer/Backfill
2.1.07 = EBS Mechanical
2.1.08 = EBS Hydrologic
2.1.09 = EBS Chemical

U.S. Generic Bedded Salt FEPs

Sevougian et al. (2012)

- Reviewed generic UFD FEP list
  - Broadly applicable to four different concepts
    - Granite/crystalline, Clay/argillite, Salt, Deep borehole
- Modified UFD FEPs to be more salt-specific, as necessary
  - Assumptions about design and geologic setting for bedded salt repository "generic reference case"
  - Cross-check against WIPP FEPs catalogue
  - Cross-check against German (Gorleben) FEP catalogue
- Further modified as part of "FEP Matrix" approach
  - Better identify related FEPs
  - Eliminate redundancies

U.S. Generic Bedded Salt FEPs

- Example of a single Bedded Salt FEP
  - Site and design-specific considerations:
    - crushed salt backfill
    - salt creep closure
    - disturbed scenario FEPs (e.g., seismic ground motion, fault displacement)

Salt-specific detail shown in red text

UFD FEP Number	Description	Associated Processes	Related FEP Number	Screening Decision
2.1.07.03	Mechanical Effects of Backfill	- Consolidation of crushed salt backfill during room closure process - Static and dynamic loading on other EBS components - Backfill restricts displacement of other 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	

2.1 = EBS
07 = Mechanical

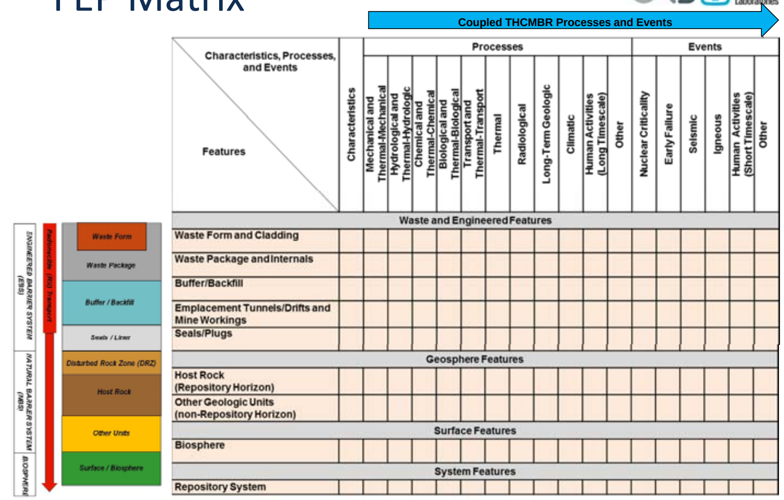
2.1.04 = EBS Buffer/Backfill

FEP Matrix

Freeze et al. (2013b)

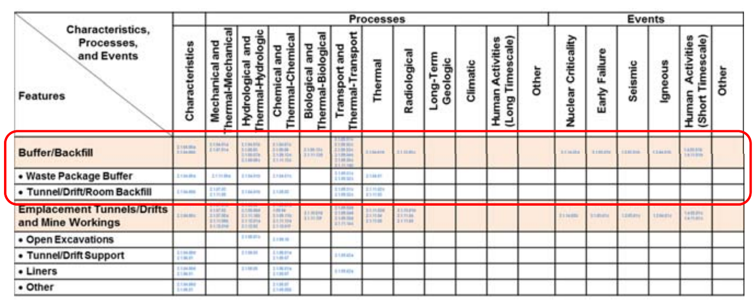
- Two-dimensional FEP organizational structure
  - Matrix Rows = Feature Categories
  - Matrix Columns = Process and Event Categories
- Matrix Cell contains all FEPs related to the "Process/Event" acting upon or within the "Feature"
- Related FEPs are grouped by Matrix Cell (or by Row or Column)
  - Not distributed among various locations as in the NEA-based hierarchical list
- FEP Numbering
  - Developed a new numbering scheme consistent with FEP Matrix
    - Can still be mapped to NEA Database numbering for traceability

FEP Matrix



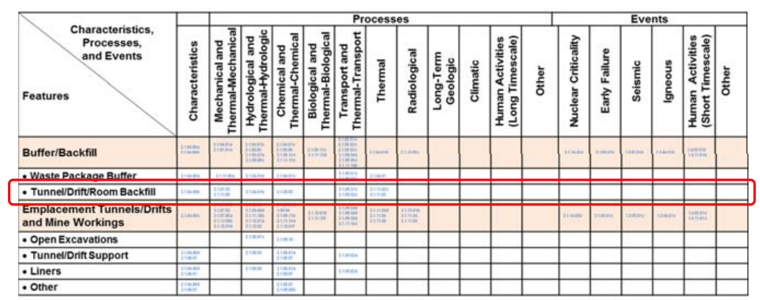
FEP Matrix

- All FEPs relevant to Buffer and Backfill
  - Some are broadly applicable to both
  - Some are specific to Buffer or Backfill



FEP Matrix

- All FEPs relevant only to Backfill



FEP Matrix

- All Thermal-Mechanical FEPs relevant to Buffer/Backfill and Emplacement Tunnels/Drifts

Features \ Characteristics, Processes, and Events	Characteristics	Processes: Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Events: Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
• Waste Package Buffer	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]											
• Tunnel/Drift/Room Backfill	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]											
Emplacement Tunnels/Drifts and Mine Workings	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
• Open Excavations			[illegible]	[illegible]														
• Tunnel/Drift Support	[illegible]		[illegible]	[illegible]		[illegible]												
• Liners	[illegible]		[illegible]	[illegible]		[illegible]												
• Other	[illegible]			[illegible]														

FEP Matrix

- All Thermal-Mechanical FEPs relevant to Backfill only

Features \ Characteristics, Processes, and Events	Characteristics	Processes: Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Events: Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
• Waste Package Buffer	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]											
• Tunnel/Drift/Room Backfill	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]											
Emplacement Tunnels/Drifts and Mine Workings	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
• Open Excavations			[illegible]	[illegible]														
• Tunnel/Drift Support	[illegible]		[illegible]	[illegible]		[illegible]												
• Liners	[illegible]		[illegible]	[illegible]		[illegible]												
• Other	[illegible]			[illegible]														

FEP Matrix

- Characteristic FEPs
  - FEPs containing properties and parameter values that describe a feature or group of features
  - No phenomena (i.e., process or event) to be screened

Features \ Characteristics, Processes, and Events	Characteristics	Processes: Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Events: Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
• Waste Package Buffer	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]											
• Tunnel/Drift/Room Backfill	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]											
Emplacement Tunnels/Drifts and Mine Workings	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
• Open Excavations			[illegible]	[illegible]														
• Tunnel/Drift Support	[illegible]		[illegible]	[illegible]		[illegible]												
• Liners	[illegible]		[illegible]	[illegible]		[illegible]												
• Other	[illegible]			[illegible]														

U.S. FEP Screening

Sevougian et al. (2012)

- FEP screening requires “generic” assumptions
  - Bedded salt
  - Waste package (UNF and HLW) barrier does not provide significant performance credit
  - Crushed salt backfill
  - 10,000 year screening period
- Assumptions captured in a salt reference case design
  - Sevougian et al. (2012)
- Preliminary FEP screening decisions based on generic reference case design
  - Included / Excluded: low probability, low consequence, by regulation
  - Site- or Design-Specific: requires detailed site or design information
  - Evaluate: further evaluation needed

U.S. Scenario Development

Freeze et al. (2013a)

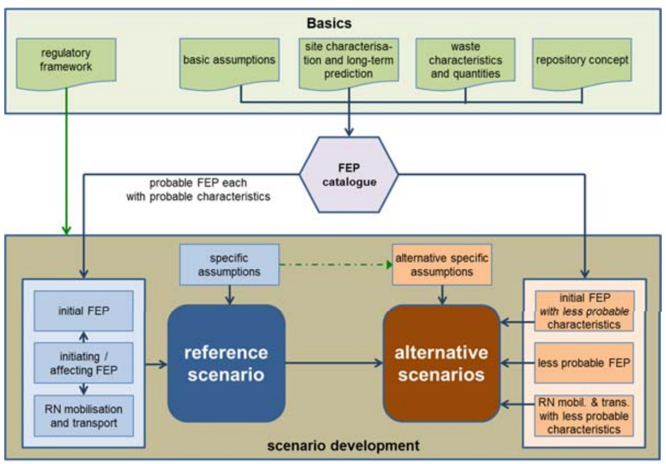
- Initial generic scenario development performed independent of FEP screening
  - Scenario "overview" based on qualitative description of salt repository initial state and evolution
  - Scenario details supported by FEP screening
- Generic scenario development focused on undisturbed scenarios
  - Disturbed scenarios require site-specific and design-specific knowledge
- Safety Assessment Model development focused on high-performance computing (HPC)-based numerical implementation to better represent coupled THCM processes
  - Multiple realization probabilistic analyses

German FEP Analysis

Wolf et al. (2012a, 2012b)

- 2008-2010:
  General FEP-Catalogue for domal salt (reference Gorleben)
  - based on NEA (1999)
  - combination of top-down and bottom-up approach
- 2010-2012: Gorleben FEP-Catalogue
  - status of knowledge on the Gorleben site
    → basis of system analysis
  - transparency and comprehensiveness
  - fundamental basis for scenario development

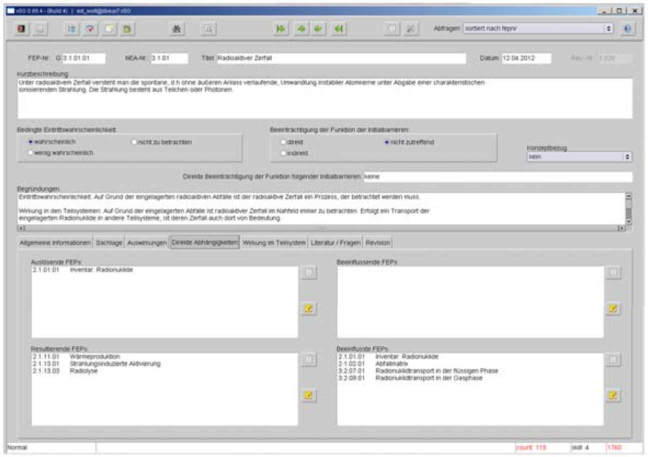
German Scenario Development



German FEP Description

- definition of FEP
- situation at site
- consequences at site
- temporal boundaries
- conditional probability
- interactions of FEP
- adverse effect on initial barriers
- open question
- literature

German FEP Data Base



Gorleben FEP Analysis

- 115 FEPs
- statement on probability:
  probable: 98, less probable: 4, not to consider: 13 (Screening I)
- FEP-Screening (II):
  6 probable FEP are classified as not relevant
- FEP list for scenario development:
  92 probable and 4 less probable FEP
- 17 alternative scenarios (all less probable)

Collaborative Results

- FEP numbering scheme: F.XX.EP.XX

F: Compartment (Features):

Waste Form:	WF
Waste Package:	WP
Buffer/Backfill:	BB
Mine Workings:	MW
Seals/Plugs:	SP
Host Rock:	HR
Other Geologic Units:	OU

Compartment Type XX:

Overall FEP: 00

Subcompartment (e.g. shaft seal, drift seal, borehole plug, …): 01, 02, 03, ….

Colloraborative Results

- FEP numbering scheme: F.XX.EP.XX

FEP type EP:

Physical-chemical characteristics: CP
Mechanical and thermal-mechanical processes: TM
Hydrological and thermal-hydrological processes: TH
Chemical and thermal-chemical processes: TC
Biological and thermal-biological processes: TB
Transport and thermal-transport processes: TT
Thermal: TR
Radiological: RA
Long-Term Geologic: LG
Climatic: CL
Human Activities (Processes): HP
Other (Processes): OP
Nuclear Criticality: NC
Early Failure: EF
Seismic: SM
Igneous: IG
Human Activities (Events): HE
Other (Events): OE

Collaborative Results

- FEP Template

1. Definition
2. Description and Related FEPs
   - 2.1 General
   - 2.2 Concept specific (bedded salt vs. domal salt)
   - 2.3 Properties and parameter values
   - 2.4 Related FEPs
3. Processes and Screening Decision
4. Screening Justification
5. Open Issues
6. References

Ex1

Ex2

Future Work

- FEP descriptions
  - Applicability of presented FEP template
  - Schedule for FEP descriptions
- Preamble for FEP catalogue
  - Definitions
  - Explanations of Screening process etc.
- Information exchange on scenario development

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Handling of uncertainties in a Safety Case
Planning of an international project

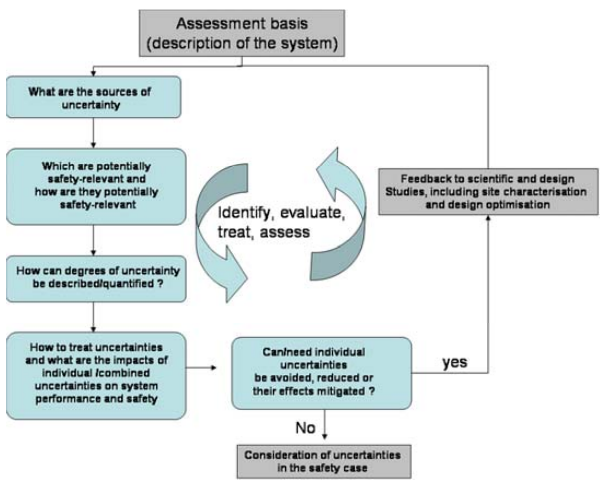
Ulrich Noseck, Dirk Becker, Dan Galson

Uncertainties in a Safety Case

Treatment of uncertainty needs to be an integral part of PA and the Safety Case development

- "A key output from safety assessment and safety case compilation is the identification of uncertainties that have the potential to undermine the understanding of the degree of safety the system offers. Based on this information, a strategy for addressing uncertainties and open issues must be developed and a decision made about whether and how to move forward to the next step in a repository programme"
  (The Nature and Purpose of the Post-closure Safety Cases for Geological Repositories, NEA 2013)

Iterative management of uncertainties (Posiva, 2009)



Classification of uncertainties

Uncertainties in safety assessment

- _Scenario uncertainties_ are associated with significant changes that may occur within the engineered and natural systems over time, and the uncertainties concerning physical and chemical processes accompanying those changes
- _Model uncertainties_ arise from an incomplete knowledge or lack of understanding of the behavior of natural and engineered systems, physical processes, site characteristics and their representation using simplified models and computer codes
- _Data and parameter uncertainties_ are associated with the parameter values used in the implemented assessment models, since data may be incomplete, cannot be measured accurately or are not available

Irreducible and reducible uncertainties

- _Irreducible or aleatory uncertainties_ are those related to the inherent randomness of events that may occur in the future (e.g. the timing of major earthquakes). These uncertainties are irreducible because no amount of knowledge will determine when or if a chance event will occur.
- _Reducible or epistemic uncertainties_ reflect the state of knowledge about relevant processes and the appropriate values to use in quantifying those processes in safety or performance assessment. In principle, such uncertainties can be reduced by carrying out more site characterization activities, laboratory experiments, making more measurements etc.

Outcomes and recommendations from PAMINA

Performance Assessment Methodologies in Application to Guide the Development of the Safety Case (PAMINA, EC 2011)

- Uncertainty analysis
  - Proposal for a systematic procedure to derive PDFs
  - Protocol to treat model uncertainties
  - These procedures should be applied and further developed in an international framework
  - Experiences shared with other institutions could provide valuable guidance
- Sensitivity analysis (SA)
  - Principle considerations of conventional and some modern methods for sensitivity analyses within the post-closure safety assessment of DGR
  - Robustness of various methods to handle non-linearities is quite different and the results are not always the same for all methods
  - More research work is needed to establish a reliable procedure for SA
  - An international frame would be needed for an efficient treatment of this task

Recommendations from MeSA project

Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste (MeSA, OECD/NEA 2012)

- "In the context of PAMINA, protocols were developed and applied to conceptualize a scenario in which a repository is abandoned without proper closure (Grupa 2006), and to characterize uncertainty in solubility limits for a generic Spanish repository (Bolado *et al.* 2009). In general, however, formal procedures have not commonly been used to date in safety assessments, other than those in the UK and US."
- "A review of approaches to guide expert judgement was made in the frame of the PAMINA project (Bolado *et al.* 2008). However, it could be interesting to examine such guidelines further to determine whether and when more formal approaches to expert judgement are warranted for safety assessment and in particular for system description and scenario derivation."
- Probabilistic sensitivity analysis: "Some methods (e.g. Sobol, FAST) have been applied to repository systems for the first time during recent years. Specific problems have surfaced that are not explicitly addressed in the relevant literature, but which seem to be essential for repository performance models. More research is necessary and planned."

4th US/German Workshop on Salt Repository Research, Design and Operation, Berlin, Germany 17.-19. September 2013

History of project preparation

June 2012: IGD-TP Deployment Plan

- Definition of JA8:
  - „Benchmarking" for confidence in Long Term Safety in Safety Cases: TSWG
  - Topic 1.3: Increase confidence and further refinement of methods to make sensitivity and uncertainty analyses
  - Priority: M

May 2013: Meeting of interested organizations

- Foundation of a TSWG
  - GRS, Galson, NDA, Nagra, ANDRA, Enresa, NIRAS-ONDRAF, SKB, SANDIA, UJC, RAWRA, NRG, Posiva, TUC
- Definition of project contents
- Elaboration of an outline project structure

July 2013: First draft outline proposal (Dan Galson)

- 8 tasks

August 2013: Second draft outline proposal (GRS)

- 4 WPs with 13 tasks, altogether

4th US/German Workshop on Salt Repository Research, Design and Operation, Berlin, Germany 17.-19. September 2013

Draft project proposal: Confidence Building and Handling of Uncertainties in Safety Assessment for Geological Disposal Facilities

WP 1: Management of uncertainties

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

WP 2: Uncertainty identification and quantification

- Task 2.1: Expert judgement
- Task 2.2: PDF derivation
- Task 2.3: Identification and quantification of correlations

WP 3: Sensitivity analysis

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

WP 4: Co-ordination

- Task 4.1: Work co-ordination
- Task 4.2: Training
- Task 4.3: International conference

4th US/German Workshop on Salt Repository Research, Design and Operation, Berlin, Germany 17.-19. September 2013

WP 1: Management of uncertainties (1/4)

General aspects of addressing uncertainties in PA (proper and traceable)
Provide a basis for regulatory guidelines concerning uncertainty management

Task 1.1: Strategies for managing uncertainty

- Phase 1: Explore practical examples identified in the PAMINA and MeSA projects:
  - Demonstrating that uncertainty is not important to safety (does not or only to a very low extent influence risk)
  - Bounding the uncertainty and showing the bounding case gives acceptable safety
  - Addressing the uncertainty explicitly (e.g. with an appropriate PDF in PA)
  - Ruling out uncertainty
    – very low probability of occurrence,
    – other consequences would far outweigh safety concerns
  - Stylised approach to handling an irreducible uncertainty
    (options to mitigate consequences in case of unfavourable developments)

WP 1: Management of uncertainties (2/4)

- Compare use of different strategies across different national WMO programmes
  – Depending on the stage of safety case development
  – Relative significance of the uncertainties
  – PDFs in comparison to 'best' and 'worst case' parameters
- Explore significance of the differences in the results from the different approaches
  – To build on existing work
  – Did national WMO programmes test theoretical studies made in PAMINA and MeSA
- Expected outcome
  – Synthesis of the development and application of uncertainty treatment over the last few years (pros & cons, what worked, what did not work)
  – Identification of future needs
- Discussion at a project workshop,

- Phase 2: Take forward identified needs

WP 1: Management of uncertainties (3/4)

Task 1.2: Management of uncertainties in different time frames of disposal system evolution

- Assessment strategies often account for different time frames based on
  - Considerations of radioactive decay
  - Ability to predict future evolution (including human habits)
  - The timescales of geological, hydrogeological, geographical or biological changes
  - The periods of monitoring, institutional control and knowledge preservation
- Aim and work content
  - Set out approaches to consideration of time frames of disposal system evolution
  - Consider the different approaches to uncertainty quantification and management in relation to different time frames
  - Evaluate and document the kinds of "complementary considerations"
  - Case study
    – Compare different approaches to treatment of uncertainty in different timeframes
    – Pros and cons of communicating uncertainty using the different approaches

WP 1: Management of uncertainties (4/4)

Task 1.3: Regulatory decision-making under uncertainty

- Views of regulators on the different uncertainty management strategies
- Certain strategies or approaches to uncertainty management may be more or less useful in terms of regulatory decision-making
- Feedback of regulatory bodies on recent submissions by WMOs (e.g. Finland, Sweden, Switzerland, UK)

Task 1.4: Communication of uncertainty

- Communication of PA and safety case to stakeholders and the public
  - Different degrees of understanding and/or different frameworks for understanding
  - Considered in several programmes and still an area of considerable difficulty
  - Communication of uncertainty identified as an area for further work in PAMINA

WP 2: Uncertainty identification and quantification (1/3)

Relevant uncertainties of the system need to be known and properly quantified

PAMINA project results:

- Influence of uncertainties on PA results to a high degree depend on parameter bandwidths, probabilistic density function (PDF) types and PDF parameters
- Consistent quantification of uncertainties according to available knowledge not trivial

Uncertainty quantification as two-step process

- Available knowledge about parameters under consideration has to be collected
- Knowledge to be assessed in view of its sources and transformed into pdfs

Aim of WP2

- Create some guidance for identification of the main parameter uncertainties of the system as well as their adequate quantification

WP 2: Uncertainty identification and quantification (2/3)

Task 2.1: Expert judgement

- MeSA recommendation: develop guidance
  - when formal approaches to expert judgement and elicitation may be warranted in safety assessment
  - when uncertainties is large and the assessment outcome is sensitive to uncertainty in the parameter value
- Essential element for uncertainty quantification if no / little literature is available
- PAMINA exercise showed expert elicitation can be expensive and time-consuming
- Aim: develop some guidance for a problem-oriented, effective expert elicitation process

Task 2.2: PDF derivation

- For uncertainty/sensitivity analysis experts views of uncertainty to be quantified in PDFs
- Evaluate and further develop NDA methodology for this purpose
  - Include a number of levels, with increasing resource requirements
  - Basic elicitation approach vs. more detailed approach
  - Definition of various roles in elicitation (facilitator, expert, recorder, customer, …)
  - Guidance on appropriate training for these roles

WP 2: Uncertainty identification and quantification (3/3)

Task 2.3: Identification and quantification of correlations

Correlations (dependencies) between uncertain parameters often exist

- Require specific handling in uncertainty and sensitivity analysis
- Still a topic of research
- Correlated uncertainties need to be identified in time
- Linear correlation coefficient often used (value more or less arbitrarily)
- Aim: more scientifically satisfying procedure of quantifying correlations
  - Selection of typical pairs of correlated parameters (e.g. porosity, permeability)
  - Analysis in view of a quantification of their correlation
  - Consistence with knowledge basis

WP 3: Sensitivity analysis (1/4)

Probabilistic uncertainty and sensitivity analysis

- Increasingly important in the safety case.
- After identification and quantification of uncertainties investigation
  - How these uncertainties affect the overall uncertainty of the model output
  - Which of them are the most relevant
- Models for final repository PA
  - Often show a non-linear, non-monotonic or even non-continuous behaviour

  → Challenging task to perform a reliable and numerically effective sensitivity analysis
- Sensitivity analysis a field of current interest in mathematical research
  - Existing methods improved and new, promising ideas are being developed
  - Test cases used by mathematicians normally different to typical PA models
  - Tests with “realistic” models are necessary to identify the methods most adequate for final repository PA

WP 3: Sensitivity analysis (2/4)

Task 3.1: Survey and assessment of methods in view of PA

- The methods for sensitivity analysis can be classified into several types, like (among others):
  - Correlation-based methods
  - Regression-based methods
  - Non-parametric methods
  - Variance-based methods
  - Graphical methods
- Planned work
  - Survey of the available methods of sensitivity analysis
    - Reviewing the methods evaluated in projects such as PAMINA
    - How applied in safety cases and WMO programmes
  - Documentation
    - Compilation of existing methods, their properties, limitations
    - Assessment how promising in view of typical properties of final repository models

4th US/German Workshop on Salt Repository Research, Design and Operation, Berlin, Germany 17.-19. September 2013

WP 3: Sensitivity analysis (3/4)

Task 3.2: Comparison of methods by numerical experiments

- Little experience about the performance of sophisticated sensitivity analysis methods applied to mathematically complex final repository PA models
- Planned work
  - Testing of several methods
    - of different types
    - with different PA models
    - for repository systems with different particularities
  - Topics to be addressed in the exercises
    - parameter sampling
    - treatment of parameter correlations
    - application of transformations to improve the robustness of sensitivity analysis
  - Integration with the evaluation of performance and safety function indicators
  - Develop and document “good practice” in applying sensitivity analysis to identify potentially important uncertainties

4th US/German Workshop on Salt Repository Research, Design and Operation, Berlin, Germany 17.-19. September 2013

WP 3: Sensitivity analysis (4/4)

Task 3.3: R&D triggering

- Comprehensive evolving R&D programmes in any country developing a final repository project
  - deepen the understanding of FEPs
  - identify relevant scenarios
  - improve models

  → reduce the epistemic uncertainties
- Optimal utilization of available research resources
  - Identification of those uncertainties that
    - have a relevant impact on the overall uncertainty of the safety assessment
    - can be effectively reduced
- Aim of the task: optimisation of R&D strategies in view of sensitivity analysis results
- Outcome: guideline for substantiating R&D requirements in a traceable manner

4th US/German Workshop on Salt Repository Research, Design and Operation, Berlin, Germany 17.-19. September 2013

WP 4: Co-ordination

Task 4.1: Work co-ordination

- Management issues
- Controlling the work of the scientific WPs
- Organisation and moderation of meetings
- Collecting and disseminating of reports and deliverables

Task 4.2: Training

- Provide training on the topic of uncertainty management in safety assessment for deep geological repositories to scientists who are new in this subject.
- Training workshop open to everyone

Task 4.3: International conference

- Open to everyone
- Presentation of results
- Identification of open questions.
- Conference report

4th US/German Workshop on Salt Repository Research, Design and Operation, Berlin, Germany 17.-19. September 2013

Current status

Discussion at Executive Group of IGD-TP:

- Proposal cannot be considered in next Call (End 2013)
- Proposal to be sent in for 2. Call of Horizon 2020 (Late 2015)

- 2. TSWG Meeting in Berlin (12 September 2013)
  - Clarification of further procedure
  - Define contributions of each participants
  - Agree on schedule

Planned contributions of participants in 2014 and 2015

Work in2014/2015	Active support
WP 1: Management of uncertainties (Leader: Galson)	
Task 1.1: Strategies for managing uncertainty	NDA, NIRAS?, Galson, Input by: Andra, SKB, TUC, Posiva
Task 1.2: Management of uncertainties in different time frames of disposal system evolution	NDA, Galson, Input by: Andra, SKB, Posiva, GRS?
Task 1.3: Regulatory decision-making under uncertainty	Comment: to be done within EC project, in 2 years SSM and STUK finalized review
Task 1.4: Communication of uncertainty	NDA (test in stakeholder dialogue), Galson, GRS?, Surao,
WP 2: Uncertainty identification and quantification (Leader: NDA)	
Task 2.1: Expert judgement	NDA, Nagra? Provide input: BfS?,Surao, Galson
Task 2.2: PDF derivation	NDA, GRS, Provide input: SKB, Posiva, Andra, NRG(2015), Surao
Task 2.3: Identification and quantification of correlations	NDA, GRS, Provide input: Andra, SKB
WP 3: Sensitivity analysis (Leader: GRS)	
Task 3.1: Survey and assessment of methods in view of PA	GRS: distribute overview report second half 2014
Task 3.2: Comparison of methods by numerical experiments	GRS, Sandia, Andra, TUC: distribute overview report second half 2014
Task 3.3: R&D triggering	Surao

Further procedure

Continue co-operation work within the TSWG on own cost until 2015

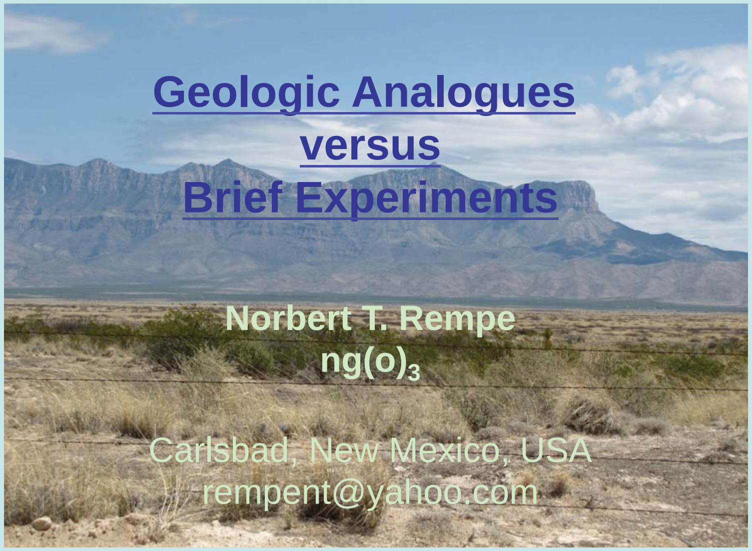
- Specific sub-groups with common interest
- Topics as identified (cf. Table)

Contact other potential partners

Working group at 5th IGD-TP Exchange Forum

Schedule

- June2014: Information exchange on status of sub-groups in the TSWG by e-mail
- February 2015: Next Technical meeting
- September 2015: Meeting for final discussion of the proposal



Geologic Analogues versus Brief Experiments

Norbert T. Rempe
ng(o)$_3$

Carlsbad, New Mexico, USA
rempent@yahoo.com

General Caution

1. Presentations are open to misinterpretation without (or likely even with) the presenter's interaction with his audience.
2. Data, ideas, and conclusions that are extracted may be in error outside the original context or intent.
3. The presenter or provider of this material is not liable for inappropriate or erroneous use of the material or its consequences.
4. None of the material should be assumed to be be original.

Special Note

Norbert T. Rempe prepared this presentation as a private individual, not for profit. This work was *NOT* sponsored by any private organization or government agency.

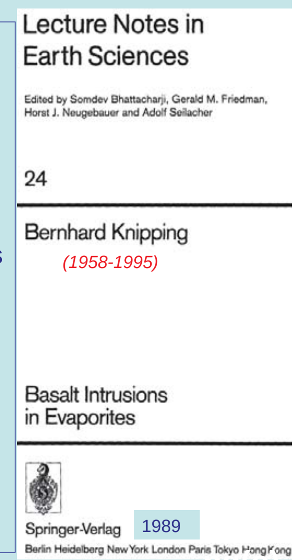
ng(o)$_3$

After half a century of experimental research on salt repositories for hot radioactive waste…

ng(o)$_3$

The quantitative study of natural processes is by far more important than experiments in the lab which are more or less in the present. Therefore it is necessary to conduct on-site comparative studies of different evaporite occurrences…
In rock salt the effect of high temperatures and solutions in the vicinity of basaltic dikes is limited to a few centimeters.
…should it be found that the chemical and mineralogical composition of a potash salt seam has not changed since its formation 250 million years ago, important conclusions could be drawn regarding the long-term safety of an underground repository.

Bernhard J. Knipping, *Evaporites and Waste Disposal – Criteria for Long-Term Safety*, Proceedings, WM '90



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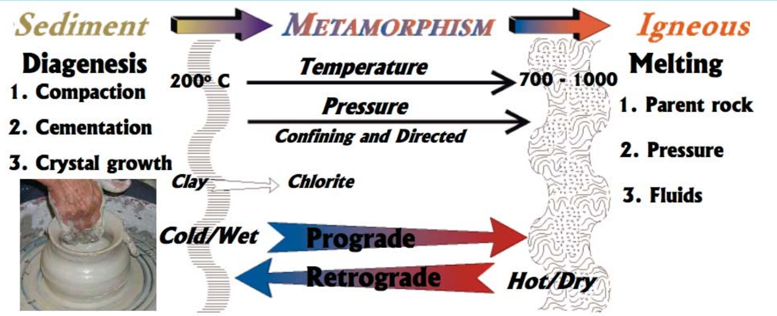

http://csmres.jmu.edu/geollab/fichter/GS102/2008PowerPoints/11-Metamorphism.pdf

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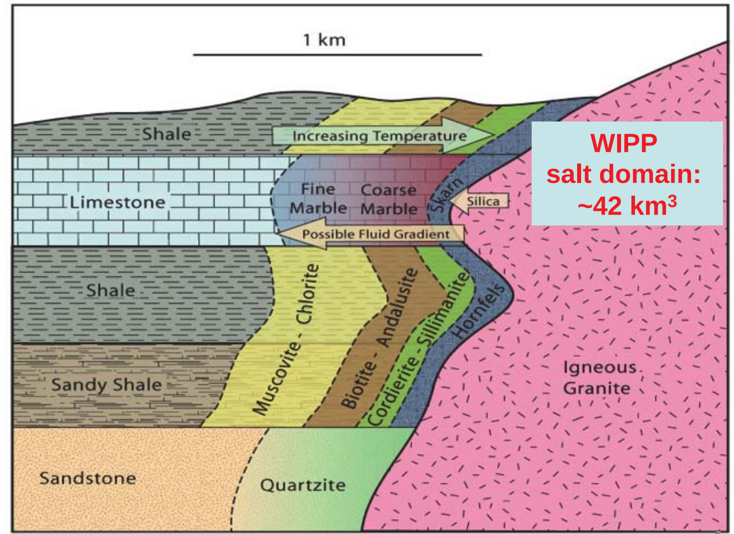

http://www.whitman.edu/geology/winter/ (Chapter 21: Introduction to Metamorphism)

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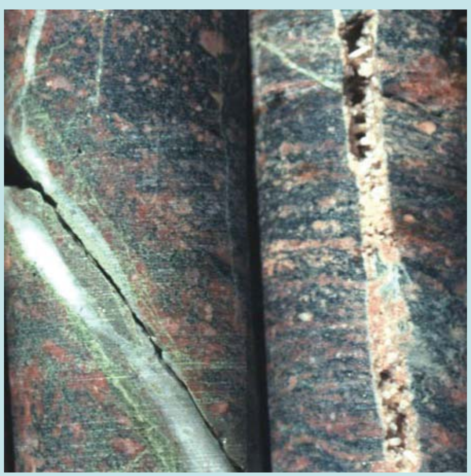
Hot fluids from cooling magma precipitated hydrothermal minerals in veins



Basement rock cores from the Savannah River Plant in South Carolina, USA

http://maps.unomaha.edu/Maher/geo117/117hydro.html

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Abb. 10: Gangartige vulkanische Brekzie im geschichteten Steinsalz in Dallol | *Volcanic breccia in the stratified salt of Dallol, main fragments are halite*

Abb. 11: Vulkanitgestein des Ringvulkans, Brekzie zumeist aus Steinsalz | *Breccia from the Skating Ring volcano, mainly of broken halite fragments*

Karl-Christian Kaeding, *Das Salinar der Danakil Senke in NE-Aethiopien*, Kali und Steinsalz 1/2008

ng(o)$_3$

Homogenization* temperatures

of brine-gas inclusions
in langbeinite samples
from Bernburg/Groena und Giersleben/Kleinschierstedt
(Stassfurt District)

range from 93 to 162°C

*minimum entrapment

Graupner, Reutel, & Pilot, *Charakterisierung von Langbeiniten mit Hilfe einschlussanalytischer Untersuchungen*, Kali und Steinsalz, Band 12, Heft 3, Dezember 1996

WIPP plan, DOE

One drift will mimic the emplacement of typical DOE Defense High-Level Waste (DHLW) (< 200 Watts per canister). The test in the second drift will simulate emplacement of hotter wastes (1500 watts per canister) to confirm the impact of higher temperatures.

Test Specification (planned)	SDDI Test Drift	
	SDDI Drift #1	SDDI Drift #2
Drift Location	see figure 2-6	see figure 2-6
Drift Length (ft)	80	80
Drift Width (ft)	16	16
Drift Height (ft)	10	10
Number of Heater Canisters	5	5
Wattage of Each Heater (W) (nominal)	200-300	1500
→ Approx Average Drift Wall Temp (C)	40	75 ←
Planned Length of Test	2 years heating	2 years heating

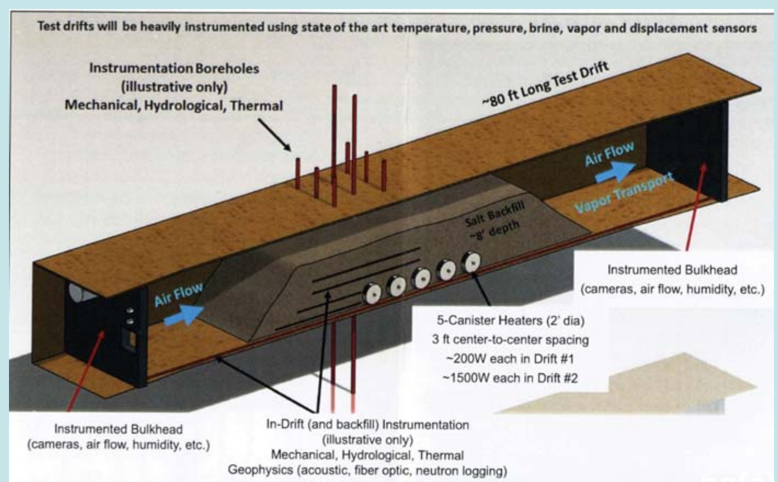
Excerpt from WIPP brochure, July 2013

WIPP plan, LANL

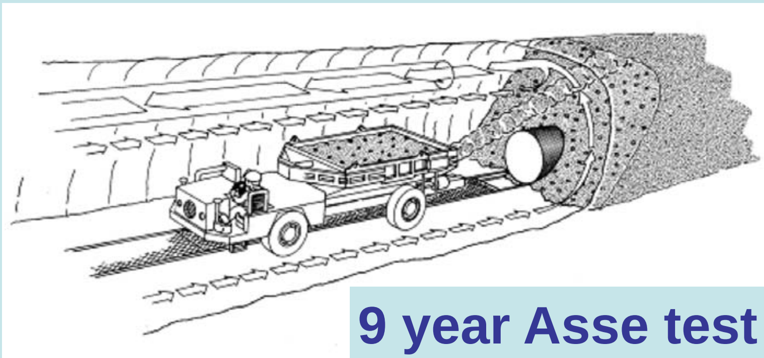
WIPP – Proposed Testing Program				
SDDI		X	Bedded salt	• Peak salt T ~80-150°C • 1-2 year heating duration • Power – 0.5-2 kW/heater
SDI		X	Bedded salt	• Peak salt T >200°C • 4 year heating/cooling duration • Power – 8.5 kW/heater

LA-UR-12-24853 (2012)
http://public.lanl.gov/dlevitt/papers/Levitt_2012.pdf

2 / 4 / 6? year WIPP plan



Excerpt from WIPP brochure, July 2013



9 year Asse test

Prinzipskizze zur Einbringung von Salzgrus in eine POLLUX-Lagerstrecke

Anhang zu GRS-247, ISBN 978-3-939355-22-9
http://www.ptka.kit.edu/downloads/ptka-wte-e/WTE-E-BPub-EwrAD_Anhang_Endlagerbetrieb.pdf

Fundamental **objections** to proposed WIPP experiments:

- No documented specific request or demand by regulators or stakeholders*
- No external independent review
- Little to no open discussion or debate on the merits

Falling into the old "DADA" trap:

Decide
Announce
Defend
Abandon

*George Dials (WIPP DOE manager) advanced the start of disposal operations by focusing on, and completing, only those experiments needed for demonstrating satisfactory repository performance (and by terminating "science fair" stuff).

Unexamined (and impossible) Supposition:

We must understand everything "perfectly"
down below the yocto (10^{-24}) scale
up above the n^{th} dimension
before deciding to do anything

Mandated by the

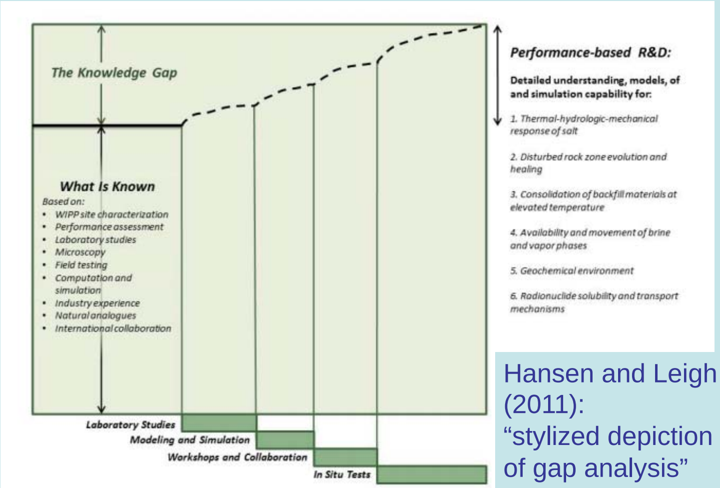
Precautionary Principle

Precautionary Principle

In Action

Anneken Hendriks, anabaptist/Mennonite burned in Amsterdam November 10, 1571

Supplemental slides

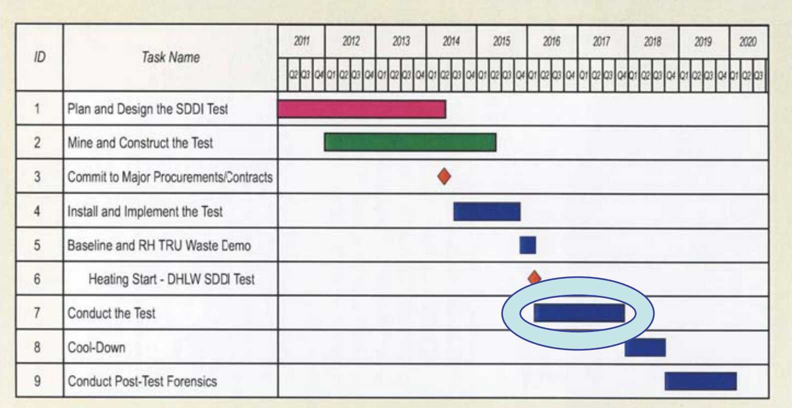


Hansen and Leigh (2011): "stylized depiction of gap analysis"

Figure 10. Gap analysis for a HLW repository in salt.

http://prod.sandia.gov/techlib/access-control.cgi/2011/110161.pdf

WIPP plan, DOE



Excerpt from WIPP brochure, July 2013

ng(o)$_3$

GEOLOGIC DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE IN SALT FORMATIONS

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–02–07–006

Prepared by

J. Winterle,[1] G. Ofoegbu, R. Pabalan, C. Manepally, T. Mintz, E. Pearcy, K. Smart, J. McMurry, and R. Pauline

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

and

R. Fedors

U.S. Nuclear Regulatory Commission
Washington, DC

March 2012

http://pbadupws.nrc.gov/docs/ML1206/ML12068A057.pdf

ng(o)$_3$

Table 3-1. Thermal Tests in Salt

Site	Name of Test	Description and Focus	Maximum Temperature
Waste Isolation Pilot Plant (WIPP)*†	Defense High-Level Waste Mockup	Vertical boreholes in floor; evaluated mechanical response to thermal load	—
WIPP*†	Defense High-Level Waste Overtest	Vertical boreholes with heaters at two different supplied power levels; evaluated of crushed backfill and collection of brine for periods up to 600 days	250 °C [482 °F]
WIPP*†	Heated Axisymmetric Pillar Test	Evaluated scale effects for thermal-mechanical processes	70 °C [158 °F]
WIPP‡	Crushed Rock Reconsolidation Test	Evaluated extent and rate of reconsolidation of crushed salt backfill in the laboratory	250 °C [482 °F]
Louisiana*	Avery Island Salt Mine	Heated borehole test with supporting laboratory analyses; evaluated migration of brine inclusions; collected moisture released during test; concluded water released during cooling stage	51 °C [123 °F]
Asse Mine§	Thermal Simulation of Drift Emplacement (TDSE)	Two heated drifts, posttest excavation of one drift; evaluated healing rate and extent of damage zone and backfill	170 to 210 °C [338 to 410 °F]
Asse Mine‖	Development of Borehole Seals for Radioactive Waste (DEBORA)	Deep borehole concept, performance of crushed salt; evaluated rate of compaction, change in permeability, and extent of porosity reduction	140 °C [284 °F]
Russian Lab Test¶	—	Two intermediate-scale laboratory tests designed to study brine and vapor distribution and migration around heater and in backfill	200 °C [392 °F]

*Hansen, F.D. and C.D. Leigh. "Salt Disposal of Heat-Generating Nuclear Waste." SAND2011-0161. Albuquerque, New Mexico: Sandia National Laboratories. 2011.
†Matthews, M.L., and L.G. Eriksson. "The Waste Isolation Pilot Plant—An International Center of Excellence for Training in and Demonstration of Waste Disposal Technologies." Proceedings From the WM'03 Conference, February 23–27, 2003, Tucson, Arizona. 2003.
‡Clayton, D.J., M.Y. Lee, D.J. Holcomb, and D.R. Bronkowski. "Crushed Salt Reconsolidation at Elevated Temperatures." ARMA 10-236. Proceedings from the 44th U.S. Rock Mechanics Symposium, June 27–30, 2010, Salt Lake City, Utah. 2010.
§Rothfuchs, T., W. Gollingerfehr, and W. Bechthold. "Lessons Learned From Large-Scale Experiments at the Asse Mine/Germany." Paper 6-7. Proceedings From Invited Lecture EURADWATE '40, Luxembourg, March 29–31, 2004.
‖Bechthold, W. and F. Hansen, eds. "Final Report—Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt, Phase II (BAMBUS II)." EUR 20621. European Commission, Nuclear Science and Technology. 2003.
¶Schneider, L.R. "*In-Situ* Experiments, HLW-Investigations: Russian Salt Experiments." Presentation at U.S.-German Workshop, Jackson, Mississippi, May 25–28, 2010.

http://pbadupws.nrc.gov/docs/ML1206/ML12068A057.pd

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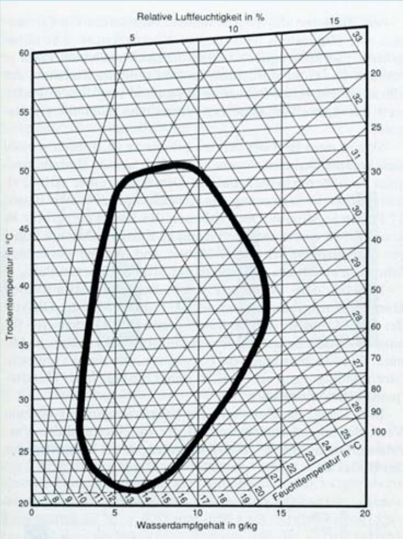
Natural atmosphere in deep Lower Saxony salt mines



Thomas Wolperding, *Untersuchungen in einem Klimaraum zur Beurteilung der Beanspruchung hitzeexponierter Bergleute*, Kali und Steinsalz, Band 11, Heft 1/2, Mai 1992

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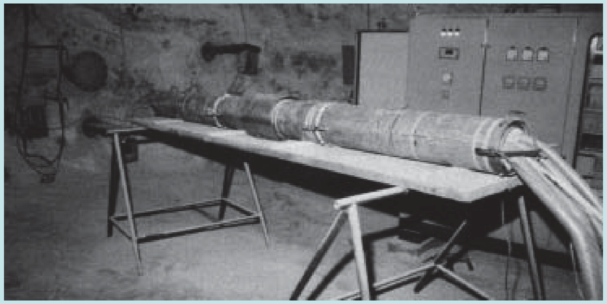
Asse TV 5 experiment

In a horizontal drill hole (3m long, 20cm diameter) successive temperature levels of 100, 150, 200, 230, and 270°C were maintained for 60 days each.



tu-freiberg.de/fakult3/gt/studium/exk-00.pdf

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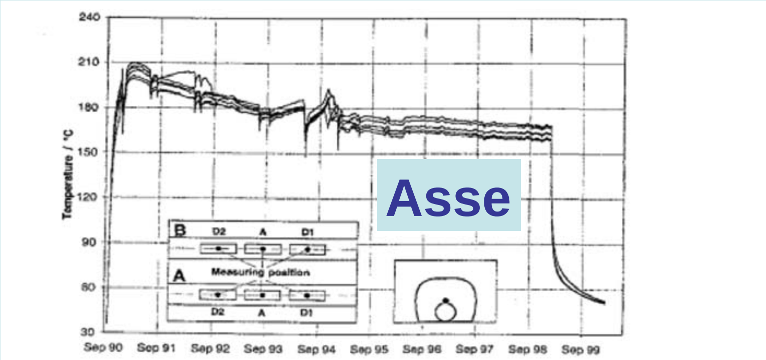

Asse

TSS-Versuch - Gemessener Temperaturverlauf an der Behälteroberfläche, aus: /BEC 03/

Temperatures measured at the Pollux container surface

Anhang zu GRS-247, ISBN 978-3-939355-22-9
http://www.ptka.kit.edu/downloads/ptka-wte-e/WTE-E-BPub-EwrAD_Anhang_Endlagerbetrieb.pdf

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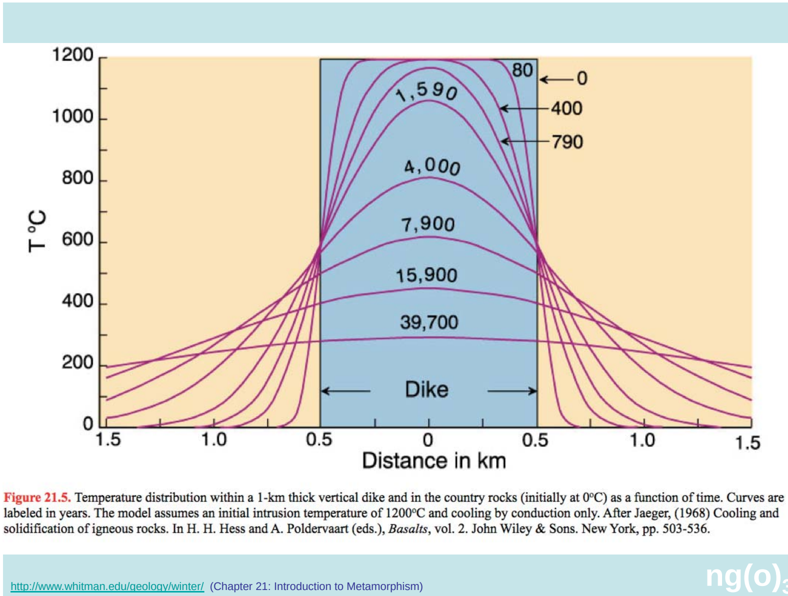
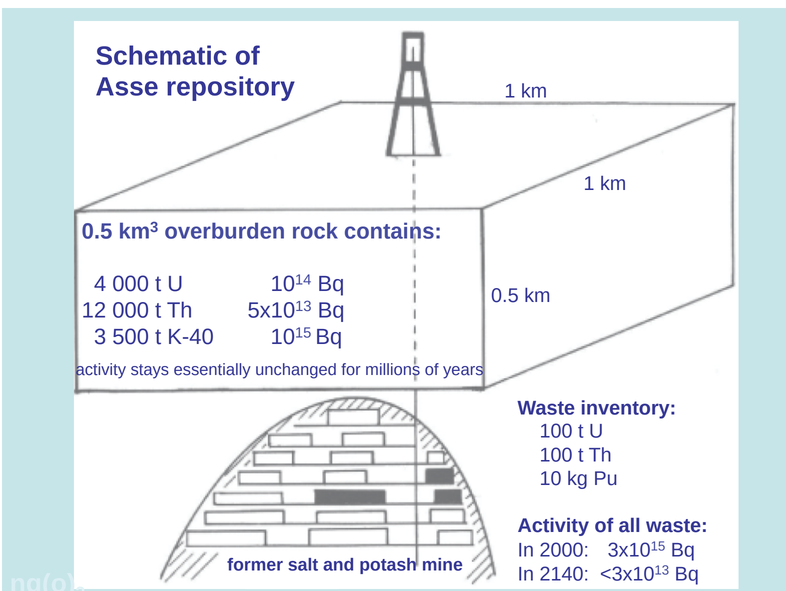
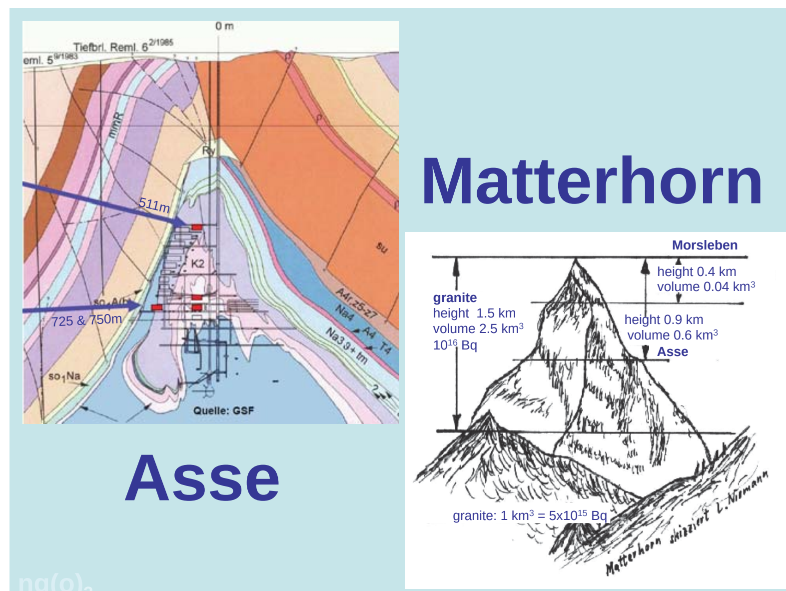

1200
1000
800
600
400
200
0
T °C
80
0
400
790
1,590
4,000
7,900
15,900
39,700
Dike
1.5 1.0 0.5 0 0.5 1.0 1.5
Distance in km
Figure 21.5. Temperature distribution within a 1-km thick vertical dike and in the country rocks (initially at 0°C) as a function of time. Curves are labeled in years. The model assumes an initial intrusion temperature of 1200°C and cooling by conduction only. After Jaeger, (1968) Cooling and solidification of igneous rocks. In H. H. Hess and A. Poldervaart (eds.), Basalts, vol. 2. John Wiley & Sons. New York, pp. 503-536.
http://www.whitman.edu/geology/winter/ (Chapter 21: Introduction to Metamorphism)
ng(o)3


Miozäner Basaltgang im K1ThH – Kaliwerk Wintershall.
Miocene basalt dike in Wintershall potash mine, Heringen, Germany
Kokorsch, Kali und Steinsalz, Band 11, Heft 3/4, April 1993
ng(o)3


Schematic of Asse repository
1 km
1 km
0.5 km
0.5 km³ overburden rock contains:
4 000 t U 10¹⁴ Bq
12 000 t Th 5x10¹³ Bq
3 500 t K-40 10¹⁵ Bq
activity stays essentially unchanged for millions of years
Waste inventory:
100 t U
100 t Th
10 kg Pu
Activity of all waste:
In 2000: 3x10¹⁵ Bq
In 2140: <3x10¹³ Bq
former salt and potash mine
ng(o)3
translated from: http://www.novo-argumente.com/artikel/99/novo9943.pdf


Matterhorn
Asse
511m
725 & 750m
Quelle: GSF
Morsleben
height 0.4 km
volume 0.04 km³
granite
height 1.5 km
volume 2.5 km³
10¹⁶ Bq
height 0.9 km
volume 0.6 km³
Asse
granite: 1 km³ = 5x10¹⁵ Bq
ng(o)3

Background Radiation and EPA and NRC Regulations

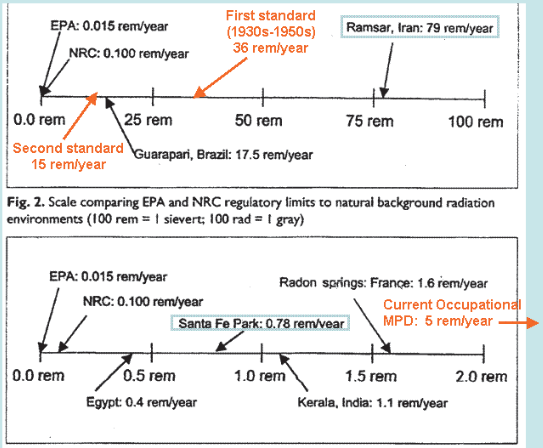


Fig. 2. Scale comparing EPA and NRC regulatory limits to natural background radiation environments (100 rem = 1 sievert; 100 rad = 1 gray)

Fig. 3. Expanded scale comparing EPA and NRC regulatory limits to natural background radiation environments (100 rem = 1 sievert; 100 rad = 1 gray)

From Mark M. Hart, "Disabling the terror of radiological dispersal," *Nuclear News* July 2003

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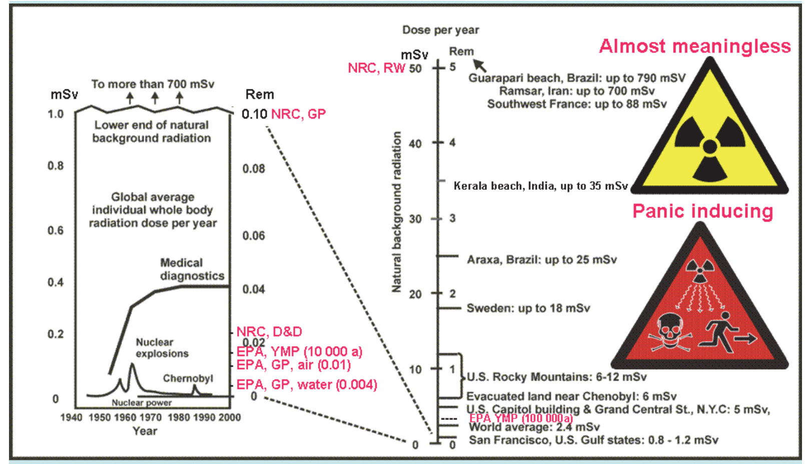


Modified from a Figure prepared by Ted Rockwell from data found in "Radiation Risk and Ethics", Z. Jaworoski, published in Physics Today, American Institute of Physics, September, 1999 and "Ionizing Radiation and Radioactivity in the 20th Century", Z. Jaworoski, presented at the International Conference on Radiation and its Role in Diagnosis and Treatment", Tehran, Iran October, 2000.

http://www.cns-snc.ca/media/uploads/branch_data/branches/Toronto/radiation/natural_and_human_radiation.html
http://hps.org/publicinformation/ate/faqs/regdoselimits.html
http://dspace.mit.edu/bitstream/handle/1721.1/41588/213482682.pdf?sequence=1

ng(o)3

Geology isn't a real science

Sheldon Cooper, Ph.D. (fictional theoretical physicist in TV series "The Big Bang Theory")

ng(o)3

August 25, 2013

Discussion on specific rock salt analogues

Ulrich Noseck, Jens Wolf

German project ISIBEL

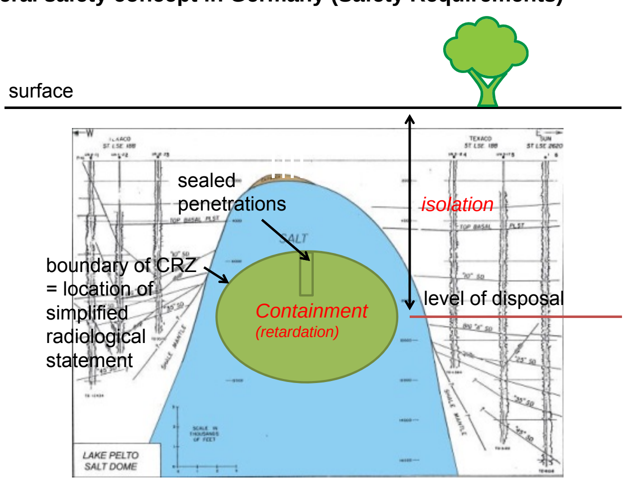
Objectives

- Safety concept and safety demonstration strategy for HLW/SF repository in salt
- Identification of existing deficits
- Specific topic in ISIBEL-2 (start 2010): Applicability of Natural Analogues for a SC
  - Start of a systematic compilation and evaluation of how analogues can be used for the safety case of a HLW/SF repository in salt
  - Focus on the safety concept, i.e. the long-term safe containment by the assessment of the geological and geotechnical barriers

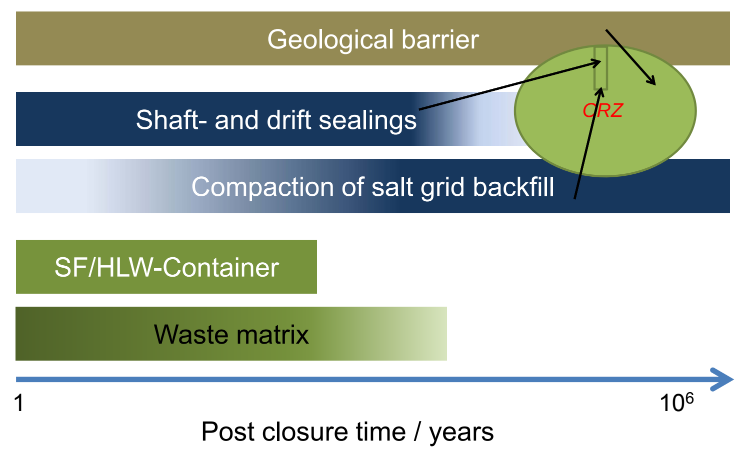
Safety Analysis → Natural Analogues

- Step 1: **Identification of NA**
  For which aspects can analogues contribute to the assessment of safety?
- Step 2: **Assessment of NA**
  What is the status of the identified aspects / analogues?
- Step 3: **Future Work**
  Identification of future work on aspects / analogues

General safety concept in Germany (Safety Requirements)



General safety concept for salt



Analogues for the integrity of the geological barrier

Aspect	Application
Existence of salt domes in Northern Germany	Long-term stability of salt domes
Stability of neotectonic conditions	Occurrence of earthquakes and magmatic events
Thickness and composition of the cap rock	Subrosion rates
Analysis of the salt flow	Uplift rates
Behaviour of competent salt formations in a salt dome	No continuous water pathway e.g. through anhydrite
Br- (and Rb)-distribution in minerals or rocks	Interaction of external solutions with the salt dome
Chemical composition of fluid inclusions in salt formations	Interaction between salt formation and external solutions
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
Basalt intrusions in Fulda-Werra Series of Zechstein	Sealing of fissures (Self sealing)
Basalt intrusions in Fulda-Werra Series of Zechstein	Behaviour of salt at high temperatures
Kryogenic fractures in northern German salt diapirs	Formation and behaviour of fractures formed by salt contraction during cooling

Analogues for the integrity of geotechnical barriers

Aspect	Application
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 Salt grit over long time scales

Analogues for release scenarios

Aspect	Application
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

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

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

Outcomes of the NA workshop Braunschweig 2012

- More NA on (geo)technical barriers required
  - Compaction of crushed salt
- Further topics of high interest for NA
  - Deformation of anhydrite
  - Fluid inclusions
  - Microbial activity in salt
  - Gas storage
- Open discussion of radwaste community with other scientific fields and industry
- Initiation of joint international projects
  - Salt Club
  - US/German Cooperation
- Prioritization → Assessment scheme
- Identification of further analogues
- Workshops focused on single aspect

Compaction behaviour of crushed salt

- Samples compacted under natural conditions with significant reduction of porosity
- Pilot study to determine suitable locations for sampling
- Few objects identified

Example: Compacted rock salt from abandoned salt mine „Riedel" (about 20 years old)

Brenner et al. 1999

Compaction behaviour of crushed salt

- Observations in "nature" rarely directly support safety case
  → to be seen together with lab and field experiments
- Effects of long-term processes in natural system can be investigated (in comparison to short-term lab experiments with artificial boundary conditions)
  - Requirements:
    - Representative material
    - High enough degree of compaction
    - Knowledge about initial state and history (p,T,w, …)
  - Properties / processes to be investigated
    - Permeability, porosity (effective, total), mineralogy, micro-structure
    - Intergranular dislocation, intergranular gliding, grain deformation, pressure-dissolution, re-crystallisation
- Some promising objects are identified / Clarification of boundary condition necessary
- Try to describe compaction state with models used in the safety case (qualification of models, if necessary modification or extension)

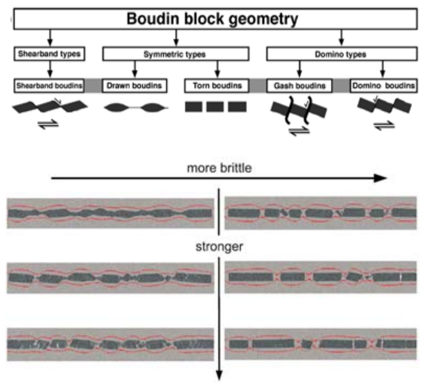
Behaviour of competent formations

Competent layers embedded in incompetent material break under mechanical stress → behave stiff and brittle

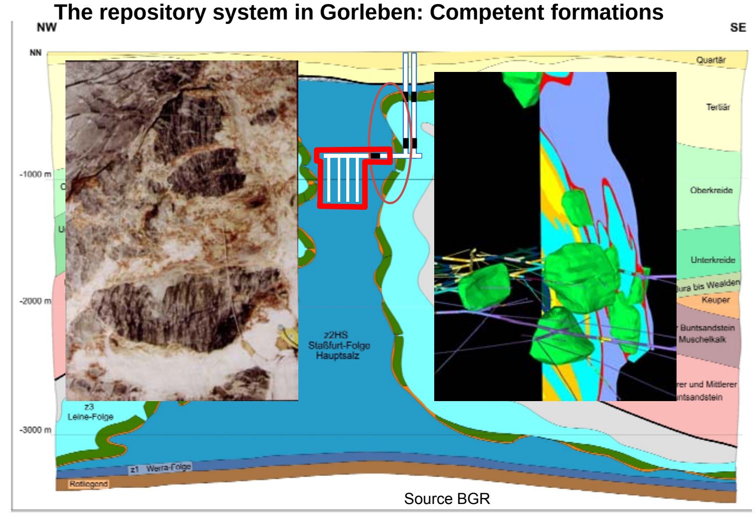
- Several lab investigations
- Results from Gorleben exploration area

Evaluation of literature

Investigation of other sites?



The repository system in Gorleben: Competent formations



Source BGR

Behaviour of competent formations

Competent materials behave stiff and brittle

Competent layers embedded in incompetent material break under mechanical stress

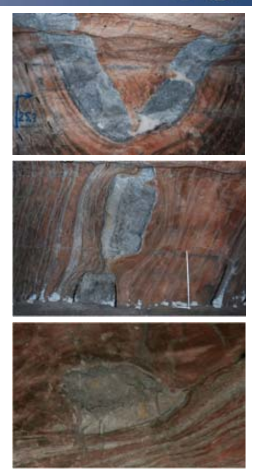
- Several lab investigations
- Results from Gorleben exploration area

(but anhydrite is not always competent material → f(p,T))

Evaluation of literature / Investigation of other sites

- Morsleben (BGR)
- there are more!

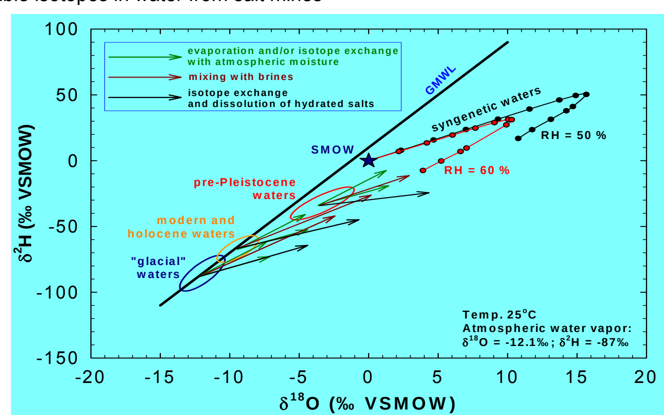
Good example how Natural Analogues support a Safety Case!



Morsleben Salt dome, Anhydritmittelsalz (z3AM), -231m level. Source: BGR

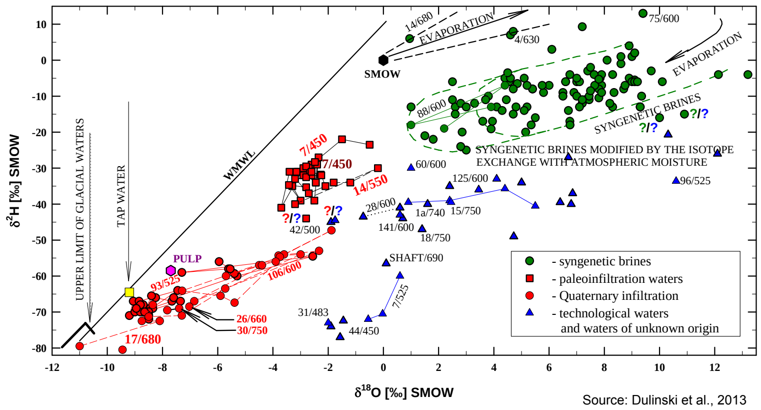
Isotope signatures in salt formations

Stable isotopes in water from salt mines



Isotope signatures in salt formations

Example from Klodawa salt mine, Poland



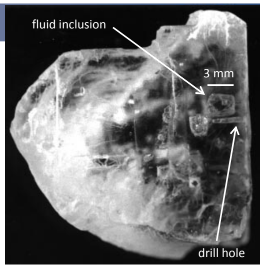
Source: Dulinski et al., 2013

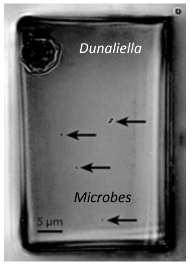
Potential of isotope analyses for demonstrating the integrity of salt formations

Method	Objective
δ¹⁸O and δ²H in brines of Zechstein rock salt	distinguish between meteoric or marine origin of formation waters
δ³⁷Cl in Zechstein rock salt	Amount of evaporation, input of seawater, re-dissolution of salt
δ³⁴S and δ¹⁸O in sulfates of Zechstein rock salt	indicate changes in the inflows, restriction conditions, redox reactions, and biogenic processes
δ¹³C and δ¹⁸O in carbonates	post-sedimentation transformation of carbonates due to a contact with meteoric waters
⁸⁷Sr/⁸⁶Sr in rock salt	modifications of brine chemistry by interaction processes with deep hydrothermal fluids or adjacent rocks
Micro-thermometry of fluid inclusions	Homogenization temperature → temperature during formation of fluid inclusions

Microbes in rock salt

- First literature study by Meleshyn (2013)
- Microbes capable of exerting negative impact on the long-term performance (on the integrity) of a radioactive waste repository are indigenous to rock salt.
- Rock salts can contain electron donors and acceptors in amounts sufficient for microbes to remain active for very long periods of time.
- Additional sources of electron donors and acceptors will inevitably be added to the repository system as a result of repository excavation as well as placement of radioactive waste and other materials.
- A microbiological exploration of repository environments in rock salts, an evaluation of the maximum microbial effect in long-term performance assessments, and – if necessary – an evaluation of possible measures to inhibit or impede microbial activity in a repository in rock salt appear to be necessary.





Microbes in a 12000-year-old inclusion from Death Valley

Role of microbes: Interesting aspects

Microbially induced corrosion of waste container in contact with brine or water vapor and salt grid

Impact of microbially influenced corrosion of container material on gas production and water balance

Formation of biofilms and their impact on microbially influenced corrosion

Methanogenesis and microbial sulfate reduction in fluid inclusions in halite

Microbial sulfate reduction in anhydrite and fluid inclusions in rock salt followed by H_2S diffusion to the container

Microbial reduction of Fe(III) under anaerobic conditions in rock salt

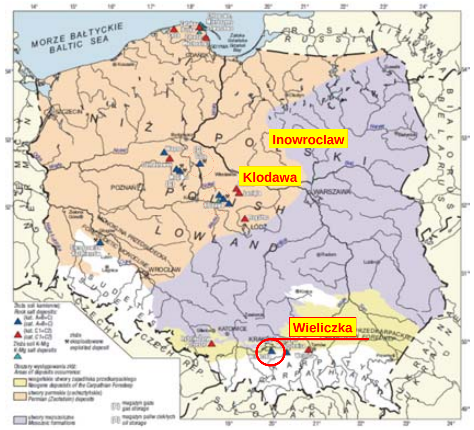
Upper temperature limit for survival of microbes in rock salt

Possible objects for Natural Analogue investigations in Germany

Location	Ressource	Mining from	to	Remarks	Geology	Priority	contact
Bergwerk Heilbronn	Rock salt	1883	aktiv				Südwestdeutsche Salzwerke AG Salzgrund 67 74076 Heilbronn Telefon: +49 7131 959-0 E-Mail: info@salzwerke.de Bereichsleiter: Dr. Gerd Bohnenberger Bereich: Bergbau und Salz
Salzbergwerk Bad Friedrichshall-Kochendorf	Rock salt	1899	1994				Südwestdeutsche Salzwerke AG Bergrat-Bilfinger Str.1 74177 Bad Friedrichshall Telefon: +49 7136 271-3400 E-Mail: info@uev.de
Salzbergwerk Stetten	Rock salt	1854	aktiv				Wacker Chemie AG Salzbergwerk Stetten Salinenstrasse 49 72401 Haigerloch-Stetten Deutschland Tel: +49 74 74694-0 Fax: +49 74 74694-160 E-Mail: info.stetten@wacker.com

In total coordinates from 23 German salt mines have been compiled

Possible objects for Natural Analogue investigations in Poland



Salt mines from Permian
- Kłodawa
- Gorzow
- Inowroclaw

Salt mines from Mesozoic age
- Wielicka

Other objects for for Natural Analogue investigations

USA
- WIPP
- Other sites?

- The Netherlands ?

Operational Safety of a HLW Repository

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

Abstract

The presentation focused on the approach and scope of operational safety for a HLW-repository in Germany. The appropriate regulatory framework comprises the Atomic Energy Act, the Radiation Protection Ordinance, the Federal Mining Act and “Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste” (BMU 2010). The latter one in particular requires for the operating phase of the repository a four level safety concept ("defence-in-depth"):

1.	Normal operation	Measures prevent the occurrence of operational failures
2.	Anomalous operation	Measures prevent the occurrence of design basis accidents
3.	Design basis accidents	Measure control design basis accidents
4.	Beyond design basis accidents /incidents	Measures reduce probability or limit environmental impacts"

It is generally assumed that by applying suitable technical and organizational measures compliance with the safety requirements of the mining and radiation protection regulations, including criticality safety, can be guaranteed in case of undisturbed operation and during operational failures and incidents. The evaluation of operational safety thus concentrated on the identification and analysis of potential weak points and significant incidents. Thus, studies and investigations on the assessment of radiological operational safety were carried out for the delivery and relocation above ground as well as for the shaft transport and for the radiologically controlled area of the final repository mine. Up to now, the assessment of conventional operational safety was carried out for the shaft transport and the radiologically controlled area of the final repository only.

The goal of radiological protection in a repository is the safe confinement of radioactive substances by means of suitable waste packages and emplacement cells. Today there is no regulation which requires a probabilistic safety analysis (PSA) prior to the licencing. Thus, deterministic safety analyses were performed which require a demonstration of completeness (complete list of possible incidents and accidents), a compilation of significant events, and identification of design basis incidents and a demonstration of adequate damage prevention measures.

Conventional operational safety is governed by numerous sectional implementation regulations in the German mining act. The following events were considered to have a possible impact on operating activities that could endanger operational safety: rock mechanical impacts (e.g. cross section reduction, loose material, inclination of floor, etc.), inflow of brine and natural gases, failure of ventilation system, failure of power supply, fire within the facility and derailing of a loaded cart. For the reference disposal concept – HLW and SF-repository in a salt dome - it could be shown that the latter four events are controllable and do not result in a safety risk. Rock mechanical impacts and inflow of brine or gases have to be considered during site selection and exploration.

Two examples of 1:1 scale industrial demonstration test of operational safety were given; the demonstration test on emplacement of unshielded waste canisters into deep vertical boreholes and the demonstration test on safe and reliable shaft transport of POLLUX-casks (hoisting system and arrestor system for a payload of 85 tonnes).

Operational Safety of a HLW Repository

Wilhelm Bollingerfehr

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

Outline

- Regulatory Framework in Germany
- Radiological Operational Safety
  - Deterministic safety analysis
  - Probabilistic safety analysis
- Conventional Operational Safety in a Repository Mine
- Demonstration of Operational Safety (2 Examples)
  - Demonstration Tests on borehole disposal of waste canisters
  - Demonstration tests on shaft transport of POLLUX-casks
- Summary and Conclusions

Regulatory Framework in Germany

- Atomic Energy Act
- Radiation Protection Ordinance
- Federal Mining Act
- Safety Requirements Governing the Final Disposal of Heat-Generating Waste (BMU, 2010)
  - "A **comprehensive safety case** shall be documented for all **operating states of the final repository**, including the surface facilities. In particular, facility-specific safety analyses shall be conducted for emplacement operation and decommissioning…." and
  - "For the safety of the final repository in the operating phase including decommissioning, the reliability and robustness of safety functions within the final repository must be proven….. **For the operating phase**, moreover, **a four-level safety concept** should be planned…"

Defense in Depth Concept

- **four level safety concept:**
  - **level 1: Normal Operation;** measures prevent the occurrence of operational failures
  - **level 2: Anomalous Operation;** measures prevent the occurrence of design basis accidents
  - **level 3: Design Basis Accidents:** measures control design basis accidents
  - **level 4: Beyond Design Basis Accidents/Incidents** measures reduce probability or limit environmental impacts

Radiological Operational Safety

- **Radiological Protection Goal:**
  - safe confinement of radioactive substances
- **Deterministic Safety Analysis**
  - Demonstration of completeness
    - » complete list of all possible incidents and accidents
  - Compilation of significant events
    - » internally and externally initiated
  - Identification of design-basis incidents
    - » analysis of most serious consequences of events/combinations of events on relevant subsystems
  - Demonstration of adequate damage prevention measures
    - » by means of detailed analysis of such incidents

Radiological Operational Safety

- **Radiological Protection Goal:**
  - safe confinement of radioactive substances
- **Probabilistic Safety Analysis**
  - no regulatory provisions to perform a PSA prior to licensing application
  - according to the "Guide Probabilistic Safety Analysis" the results of a PSA are:
    - » supplement to the deterministic safety assessment
    - » form a basis to determine the necessity and urgency of safety improvements
    - » enables a balanced plant concept with regard to safety issues

Conventional Operational Safety in a Repository Mine

- Safety related issues governed by numerous sectional implementation regulations in the German Federal Mining Act
- Events with possible impacts on operating activities that could endanger operational safety:
  - rock mechanical impacts
    - (e.g. cross section reduction, loose material, inclination of floor, etc.)
  - inflow of brine and natural gases
  - failure of ventilation system
  - failure of power supply
  - fire within the facility
  - derailing of a loaded cart

Conventional Operational Safety in a Repository Mine

- Rock mechanical impacts (e.g. cross section reduction, loose material, inclination of floor, etc.)
  - controllable (by means of observation, removal of loose material, etc.)
- Inflow of brine and natural gases
  - both have to be investigated site specific;
  - may be ruled out or
  - volume and potential effects on operational safety to be assessed

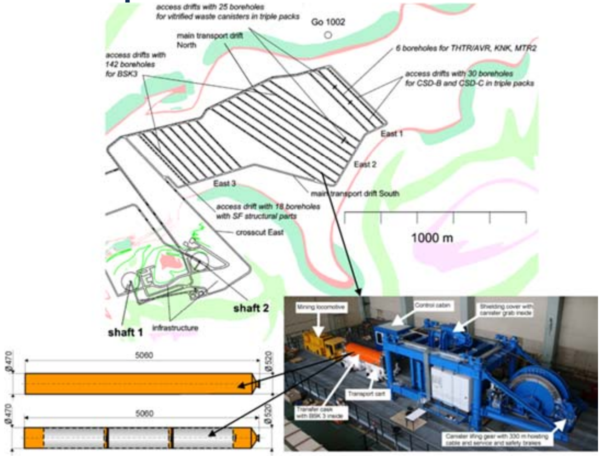
Conventional Operational Safety in a Repository Mine

- failure of ventilation system
- failure of power supply
- fire within the facility
- derailing of a loaded cart

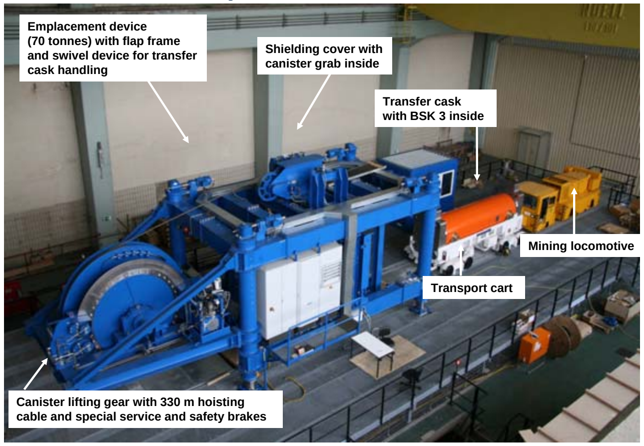
➢ For the Reference Disposal Concept :
(HLW- and SF-Repository in a Salt Dome)

- all these 4 events deem to be controllable,
- thus do not result in safety risks,
- but safe operation has to be demonstrated

Repository Design: Borehole Disposal of waste canisters



Demonstration Test: Waste Canister Emplacement



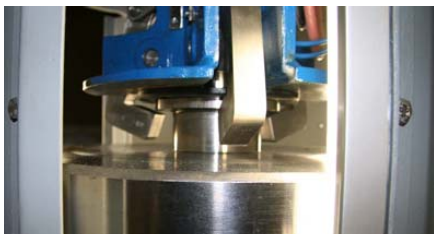
Canister Grab Tests

… functional check prior to test campaign

… in operation

Canister Grab Tests

Maximum slanting positions of BSK 3 (with and without backfill)



Successfully opening of grab

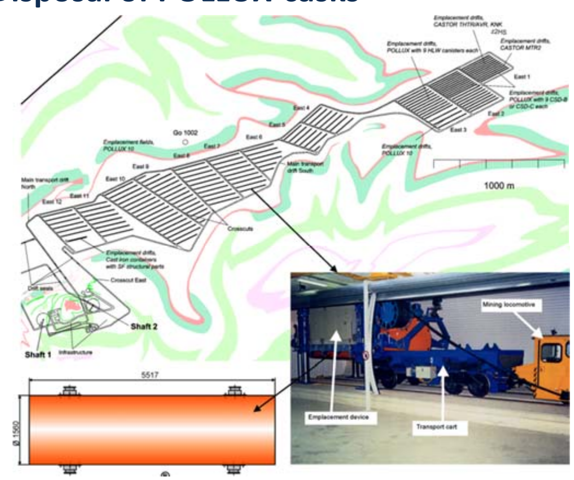
Demonstration Test: Emplacement Device Transportation

Emplacement machine towing with the transport cart and the locomotive

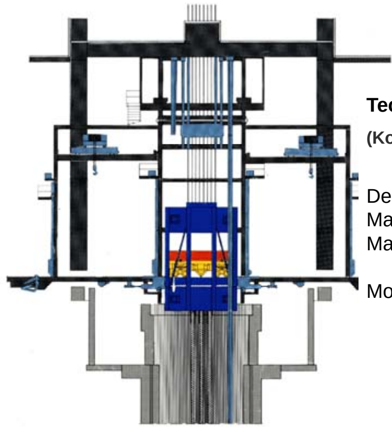
Demonstration Test: Transport Cart Re-railing

Re-railing of transport cart
loaded with transfer cask using standardized equipment (Deutsche Bahn)

Repository Design: Drift Disposal of POLLUX-casks



Shaft Hoisting System



Technical data:

(Koepe-System, one-rope drum)

Depth of shaft:	1,000 m
Max. payload:	85 t
Max. speed:	12 m/s at 30 t
	5 m/s at 85 t
Motor power:	2 x 2,800 kW

Longitudinal section through the shaft hoisting system

Demonstration Test: Shaft Hoisting Arrestor System

Summary and Conclusions

- **Operational Safety is a substantial part of the Safety Case for a HLW/SF-Repository (four-level safety concept)**
- **Events with possible impacts on operating activities that could endanger operational safety have to be systematically analyzed and evaluated**
- **Safety of Technical systems and components has to be demonstrated**
- **Demonstration tests reveal (2 examples)**
  - **reliability and safety of the emplacement device for waste canisters**
  - **the robustness of the shaft hoisting arrestor system (SELDA)**

DBE TECHNOLOGY GmbH

Thank you for your attention.

Exceptional service in the national interest

Sandia National Laboratories

Potential Vertical Movement of Large Heat-Generating Waste Packages in Salt

D.J. Clayton, M.J. Martinez and E.L. Hardin

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

SAND2013-7626P

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Outline

- Problem statement
  - Large, heavy heat-generating packages
- Coupled thermal-mechanical creep
  - Munson-Dawson
- Coupled thermal-viscous flow
  - Equivalent viscosity (temperature dependent)
- Displacement vs. time
- Reduced package density
- No heat generation
- Ideas for further analysis

This presentation is based on: Clayton et al. 2013. *Potential Vertical Movement of Large Heat-Generating Waste Packages in Salt.* SAND2013-3596. Sandia National Laboratories, Albuquerque, NM.

2

Problem Statement (1/2)
Dual-purpose canisters (1,800+) in the U.S.

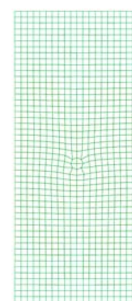
- **Magnastor DPC system**
- **Capacity 37-PWR (equiv.)**
- **Thermal limits: 35.5 kW storage/24 kW transport**
- **Fuel cool time >4 yr OoR**

Pictures and data from NAC International website 31Mar2012

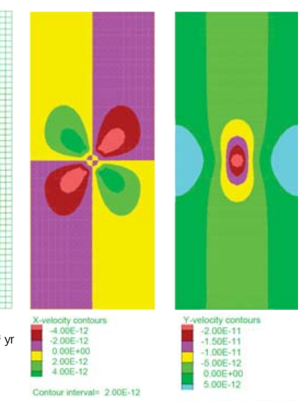
3

Problem Statement (2/2)
Previous analysis of vertical movement

- Large, heavy package
  - 2m D × 5m L
  - Density of steel
- Uniform constant temp.
- **Viscosity 10^{15} Pa-sec** (Dawson & Tillerson 1978)
- **Velocity > 0.6 mm/yr for hundreds to thousands of years?**



FLAC7 Grid
Displacement at 10^3 yr
(Sinking2.prj)
0.5m × 0.5m zones
K=20.7 GPa
G=12.4 GPa



Dawson, P.R. and J.R. Tillerson 1978. Nuclear Waste Canister Thermally Induced Motion. SAND78-0566, Sandia National Laboratories, Albuquerque, NM.

4

Package Vertical Movement
Scoping Studies – Viscoelastic and Other Models
Parameter Study with FLAC7, 2m solid steel package in salt (2D)

Viscoelastic (Maxwell)

1 m grid 20 x 20 m domain

Viscosity (Pa-s)	Velocity (m/s)
1e14	2.03e-10
1e15	2.03e-11
1e18	2.03e-14
1e19	2.03e-15

0.25-m grid 20 x 20 m domain

Viscosity (Pa-s)	Velocity (m/s)
1e12	2.37e-8
1e15	2.37e-11
1e18	2.37e-14
1e20	2.37e-16

0.25-m grid 50 x 100 m domain

Viscosity (Pa-s)	Velocity (m/s)
1e12	3.37e-8
1e15	3.37e-11
1e18	3.37e-14
1e20	3.37e-16

Power law creep $\dot{\epsilon} = A\sigma^{-n}\, e^{\left(\frac{-Q}{RT}\right)}$

A = 5.7e-36
n = 4.9
Q = 50.2 kJ/mole

0.25 m grid 50 x 100 m domain

Temperature	Initial Velocity	Velocity at 10^4 yr
373 K	5e-15 m/s	1.3e-15 m/s
473 K		1.3e-15 m/s

Reference creep model (FLAC7 manual 1.2.3)
0.25 m grid, 50 x 100 m domain
No movement

WIPP viscoplastic model (FLAC7 manual 1.2.5)
0.25 m grid, 50 x 100 m domain
1.3e-22 m/s at 300 yr

5

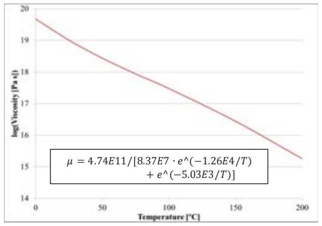
Equivalent Viscosity (Multimechanism Model)

$\tau = \mu \frac{du}{dy}$ where τ is the shear stress, μ is viscosity, and u is the velocity in the x-direction.

Using the M-D creep model stress/strain rate relationship and solving for viscosity gives the following relationship

$$\mu = \frac{\tau}{A_1 e^{\left(\frac{-Q_1}{RT}\right)}\left(\frac{\sigma}{G}\right)^{n_1} + A_2 e^{\left(\frac{-Q_2}{RT}\right)}\left(\frac{\sigma}{G}\right)^{n_2} + H(\sigma-\sigma_0)\left[B_1 e^{\left(\frac{-Q_1}{RT}\right)} + B_2 e^{\left(\frac{-Q_2}{RT}\right)}\right] \times \sinh\left[\frac{q(\sigma-\sigma_0)}{G}\right]}$$

where
- T is the absolute temperature
- R is the universal gas constant
- A_1, A_2, B_1 and B_2 are material constants
- Q_1 and Q_2 are activation energies
- G is the shear modulus
- σ is the generalized stress
- n_1 and n_2 are the stress exponents
- H is the Heaviside step function
- q is the stress constant
- σ_0 is the stress limit for dislocation slip



Effective viscosity versus temperature for intact salt calculated using the M-D creep model (Munson 1997)

Munson, D.E. 1997. "Constitutive Model of Creep in Rock Salt Applied to Underground Room Closure." *Int. J. Rock Mech. Min. Sci*. V.34, N. 2, pp. 233-247.

6

Equivalent Viscosity (Power Law Model)

Power law creep is represented as $\dot{\epsilon} = A\sigma^{-n}\, e^{\left(\frac{-Q}{RT}\right)}$ where $\dot{\epsilon}$ is the strain rate. The shear strain rate is the change in displacement in the x-direction, measured in the y-direction, or $\frac{du}{dy}$. Substituting,

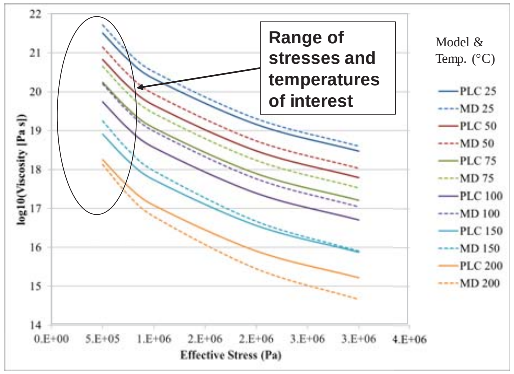
$$\tau = \mu \frac{du}{dy} = \mu \left[A\sigma^{-n}\, e^{\left(\frac{-Q}{RT}\right)}\right] \qquad \mu = \frac{\tau}{\left[A\sigma^{-n}\, e^{\left(\frac{-Q}{RT}\right)}\right]}$$

where
- τ is the shear stress
- μ is viscosity
- u is the velocity in the x-direction
- T is the absolute temperature
- R is the universal gas constant
- A is a material constant
- Q is activation energy
- σ is the generalized stress
- n is the stress exponent

Thus, there is no closed-form solution for equivalent viscosity, for power-law creep.

7

Equivalent Viscosity Calculations

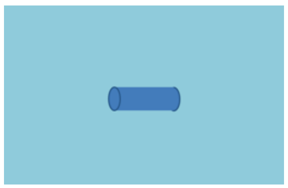


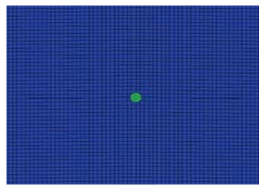
PLC = Power law creep
MD = Multi-mechanism deformation

8

FEM Vertical Movement Simulations

- Sierra codes: Aria (viscous) and Adagio (viscoplastic), Arpeggio (conductor)
- 3D hexagonal elements, 60 × 60 × 100 m domain
- Boundary conditions → Burial depth 600 m
- Package size 2m D × 5m L, density of steel (or salt)
- Package heat generation 13 kW initially, decay as per SNF burnup 40 GW-d/MT emplaced at 50 yr out-of-reactor
- Lateral boundaries: constrained normal displacement, adiabatic
- Top boundary: vertical movement, overburden load, constant temperature
- Bottom boundary: fixed in x and y, constant temperature
- Arrhenius creep-temperature dependence (Q = 40 to 100 kJ/mol parameters in M-D model)





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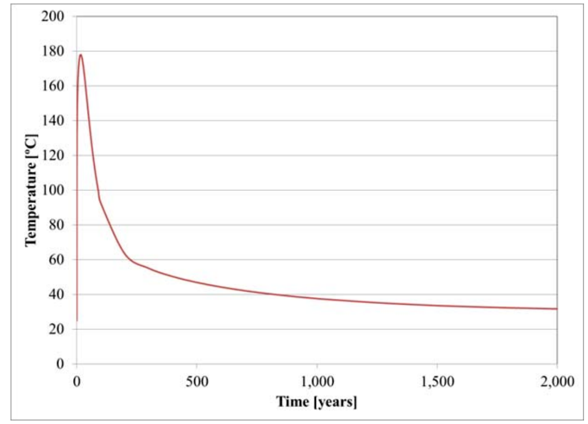
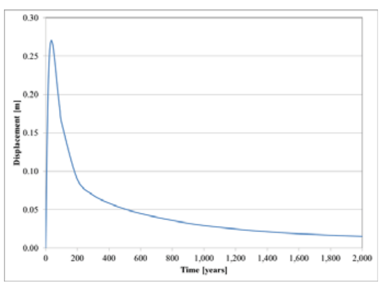
FEM Vertical Movement Results Waste Package Temperature

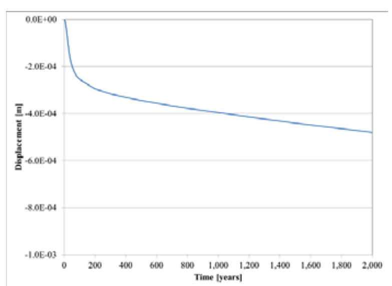


10

FEM Vertical Movement Results Package Vertical Displacement vs. Time



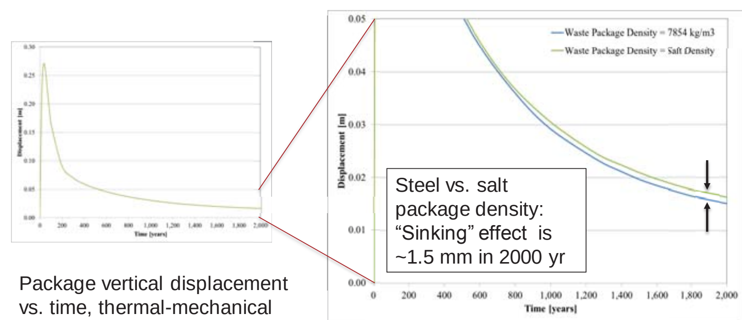
<<< Thermal-mechanical viscoplastic M-D model (Adagio)



Thermal-viscous model (Aria) >>>

11

FEM Vertical Movement Results Movement with Reduced Package Density (= salt)

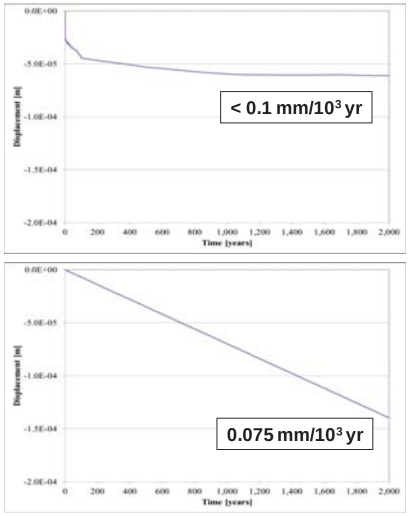


Package vertical displacement vs. time, thermal-mechanical viscoplastic M-D model (Adagio)

12

FEM Vertical Movement Results
Movement with No Heat Generation

Thermal-mechanical visco-plastic M-D model (Adagio) >>>

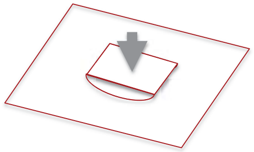


Conclusion: Without thermal expansion ("heave") and thermal creep activation, vertical movement :

- From visco-plastic model is < 0.1 m in 10^6 yr
- From viscous model is < 0.1 m in 10^6 yr

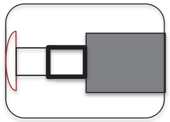
Thermal-viscous model (Aria) >>>

Summary and Possible Further Work

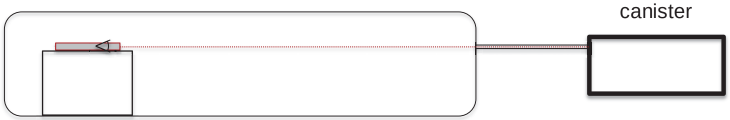


- Summary: << 0.1 m/10^6 yr
- Benchmarking/collaboration
  - Code/model comparison
  - Similarity to DIREGT concept (Graf et al. 2012)
- Multi-year platen jacking validation test concept
- Multi-objective (e.g., heated) *in situ* tests

Heated intact salt



Heated canister



Graf, R., Dr. K.-J. Brammer (GNS), and W. Filbert (DBE Tech GmbH), *Jahrestagung Kerntechnik* 2012, Stuttgart (5/25/12).

Waste Isolation Pilot Plant Status and Planned Salt Research

Abraham Van Luik
Carlsbad Field Office, US Department of Energy

Abstract

The Waste Isolation Pilot Plant (WIPP) has been in operation since 1999. It is currently the only working deep geological repository for radioactive waste in the US, and in the world since the closing of the Morsleben repository in Germany.

Having been in operation for more than 14 years does not mean that all scientific work has stopped. Scientific work continues for three important reasons:

1. To continually improve the scientific/technical basis for periodic regulatory-compliance recertifications.
2. To provide scientific support to optimisation changes proposed for this working repository.
3. To provide scientific support to national waste management decisions.

Scientific work that addresses these three areas of interest includes work on:

- Constitutive modeling of salt mechanical properties
- Actinide chemistry in brines
- Microbiological processes, and
- Salt response to heat-emitting waste (on-floor waste-package configuration).

Preparations are currently being made to conduct a heater test called the “Salt Defense Disposal Investigations” (SDDI). This test will help the Department of Energy make decisions on the disposal of defense-related high-level wastes, and provides the Department, as well as the State of New Mexico, assurance that the current knowledge-base is sufficient to project long-term repository behavior and performance. SDDI is located in a larger excavated area that is called the WIPP Underground Research Laboratory (URL), which is to be used for additional scientific investigations to support technical decision-making related to potential future waste disposal missions in bedded rock salt.

Waste Isolation Pilot Plant (WIPP) Planned Salt Research

Abraham Van Luik
Carlsbad Field Office
US Department of Eenergy

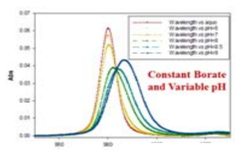
4th US/German Workshop
17-18 September 2013
Berlin, Germany

Active Research in Salt Repository Science

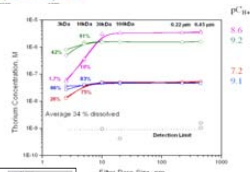
- Studies supporting current and potential future uses of salt for radioactive waste disposal continue
  - To be discussed either in this Salt Club Meeting and/or in the 4th US/German Workshop that follows:
    - Constitutive modeling of salt mechanical properties
    - Actinide chemistry in brines
    - Microbiological processes, and
    - Salt response to heat-emitting waste (on-floor waste-package configuration)
      - ***Currently—Salt Defense Disposal Investigations, SDDI***
        - » Future—Salt Disposal Investigations, SDI

Actinide Chemistry in Brines

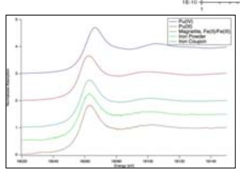
- **What is the Potential for Actinide Release in a Salt Repository?**
  - **Actinide Speciation and Modeling Studies**
    - solubility studies
    - Complexation
    - Colloid formation
  - **Redox and Actinide Oxidation State Distribution**
    - Role of iron chemistry
  - **International Collaboration is key**
    - ABC Salt workshop series (Marcus Altmaier update, and proposed model development activities)
    - INE/Rossendorf Experimental collaborations
    - NEA TDB database development



Complexation of Np(V) with Borate



Thorium intrinsic colloidal size distribution in brine systems



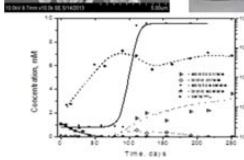
XANES Analysis of Fe-reduced Pu(III) in Brine

Microbiological Processes

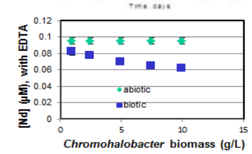
- **What happens if . . .**
  - **microorganisms degrade organic waste components?**
    - gas
    - generation of ligands
  - **microorganisms create a "reduced" environment?**
    - changes in actinide oxidation state/solubility
  - **microorganisms take up radioactive elements?**
    - transport/immobilization

Halophilic Microorganisms

Anaerobic FeS Formation



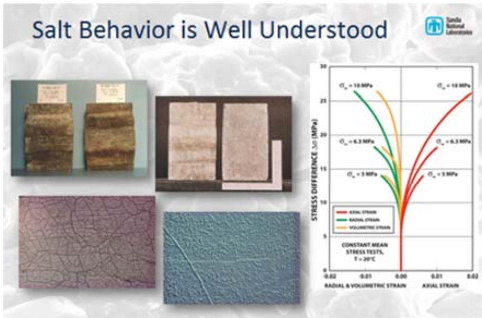
Biodegradation of Organic Chelating Agents



Biosorption of Nd^{3+} as an analog for An(III)

Constitutive Modeling of Salt Mechanical Properties

- Salt behavior is understood
- Refining constitutive models to predict salt behavior continues

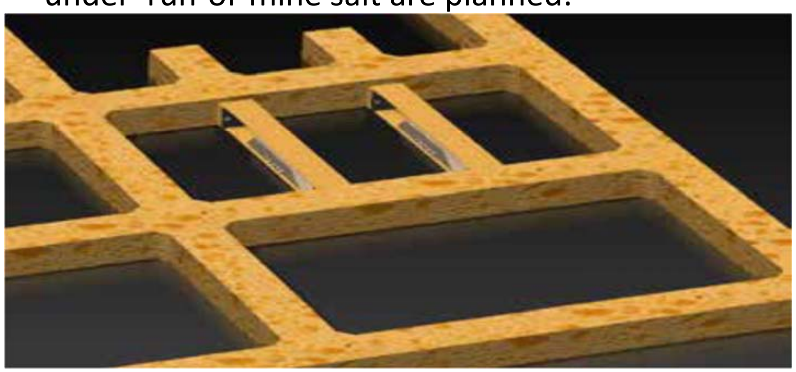


Salt Defense Disposal Investigations (SDDI)

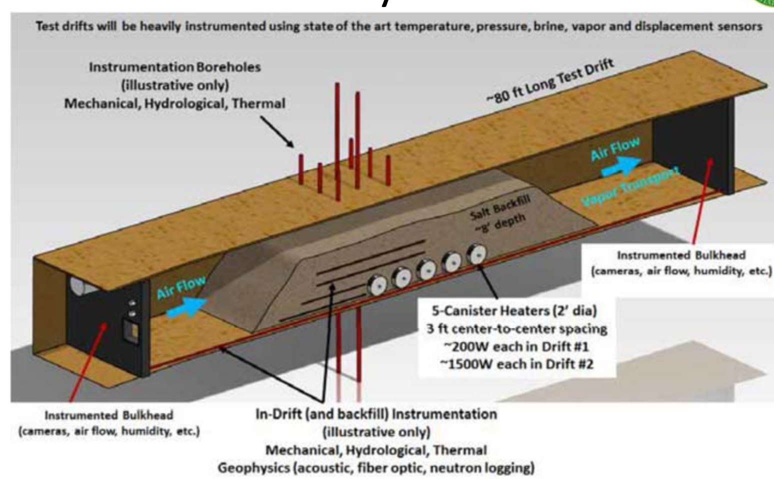
- SDDI is a heater test to simulate direct placement of defense HLW canisters on disposal room floors, covered with run-of-mine salt for radiation shielding
  - Configuration of the test to mimic disposal of defense HLW packages allows early-time evolution studies
    - Evolution of the water within the salt will be investigated
    - Field-scale tests will be conducted in conjunction with selected laboratory-scale studies and computer modeling
- Objective: support future national waste management decisions

SDDI: General Layout

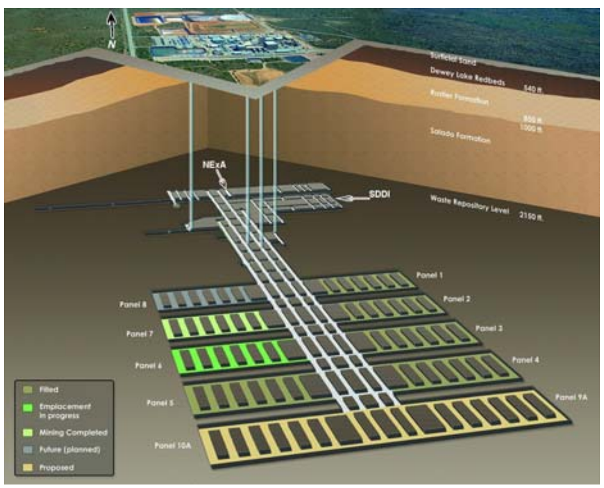
- Two instrumented drifts with heaters shielded under run-of-mine salt are planned:



SDDI: Layout Detail



SDDI: Part of a Larger Future URL Complex



WIPP pilots (shows the way to) safe and environmentally responsible waste management and energy solutions

R&D-Project ELSA (Sealing of Shafts in Salt and Clay Formations)

Wilhelm Bollingerfehr1, Wolfram Kudla[2], D. Freyer[3], M. Gruner[2], M. Jobmann1, N. Müller-Hoeppe1, F. Schreiter[2], T.Wilsnack[3]

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3) IBEWA, Lessingstraße 46, 09599 Freiberg, Germany

Abstract

The Objective of the R&D-Project ELSA is to design and construct functional components of a long-term stable sealing system for a shaft seal (diverse and redundant compiled components) and eventually to demonstrate the constructability and functionality. The project is structured into three phases (phase1: compilation of boundary conditions and design requirements; phase 2: concept development for shaft seals and demonstration of functional elements; phase 3: large scale test and demonstration of developed sealing concept).

Within the scope of the project-phase 1, the shaft seals in salt formations that have been planned or constructed since 1994 were analyzed regarding their applicability in an HLW repository. Furthermore, international developments and designs of shaft seals were studied and analyzed regarding their technical status and their applicability in an HLW repository in Germany.

The methodology of applying partial factors in a safety analysis was summarized and the possibility to apply this method in a safety analysis for a geotechnical sealing structure was confirmed. Due to particularities based in the design, construction, and function of drift and shaft seals, however, it is necessary to make specific adjustments when demonstrating their safety. Based on a draft shaft sealing concept designed within the scope of the preliminary safety analysis of the Gorleben site, two individual assessments were carried out to illustrate the methodology. In due time, this will allow a safety assessment within the scope of – as yet unplanned – large-scale experiments that is based on established methods.

The safety demonstrations as well as the design of engineered barriers are based on site specific boundary conditions (geological, geomechanical and geochemical) which have been compiled based on current knowledge. The general and special requirements pertaining to the design of shaft sealing constructions, especially in salt and clay formations, are described. The requirements are derived from the safety requirements (BMU 2010), the requirements resulting from existing safety assessment concepts developed in the R&D projects ISIBEL (Development of a methodology for a safety and demonstration concept for a HLW-repository in salt), VSG (preliminary safety assessment for the Gorleben site), and AnSichT (Development of a methodology for a safety and demonstration concept for a HLW-repository in clay formations), from functional demonstrations, from site-specific boundary conditions, and from requirements stipulated in other specifications. Potential construction materials were selected for both options ;shaft seals in salt and clay formations.

In claystone, the following additional requirements need to be taken into account: Prevention of advective fluid flow from the repository or from the isolating rock mass, stable geochemical environment, adjustment to the variability in facies, material and technological requirements for the shaft liners, use of materials with a high sorption capacity. All requirements are summarized.

Furthermore, the general information needs for developing shaft sealing systems have been identified.

R&D Project ELSA (Sealing of Shafts in Salt and Clay Formations)

Wilhelm Bollingerfehr, Wolfram Kudla

D. Freyer, M. Gruner, M. Jobmann, N. Müller-Hoeppe, F. Schreiter, T. Wilsnack

(DBE TECHNOLOGY GmbH, TUBAF, IBEWA)

4th US/German Workshop on Salt Repository Research, Design and Operations

Berlin, Germany
September 2013

Outline

- Project structure, objectives, scope of work and fundamentals of the ELSA project
- State of the art of shaft seals (survey)
- Safety concept, approach of safety demonstration
- Boundary conditions for shaft seals in salt and clay formations in Germany
- Requirements for the shaft seal design
- Summary and outlook

Project Structure

Phase 1: Boundary conditions and requirements for saft seals in salt- and clay-formations (April 2011 to January 2013

Phase 2: Concept development for shaft seals and demonstration of functional elements (laboratory tests and medium scale tests) (May 2013 to September 2015)

Phase 3: Large scale test and demonstration of developed sealing concept

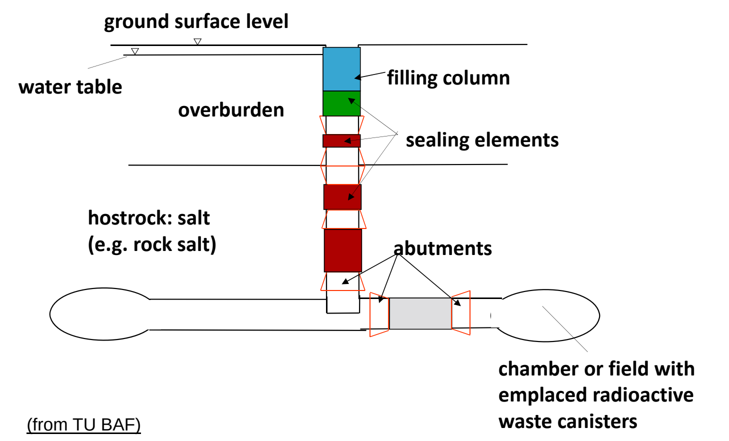
Objectives

- Objective of the ELSA-Project
  - To design and construct functional components of a long-term stable sealing system for a shaft seal (diverse and redundant compiled components) and eventually to demonstrate the constructability and functionality
- Objectives of ELSA Phase 1 :
  - Survey on the state of the art of shaft seals
  - Development of an approach for safety demonstration
  - Compilation of boundary conditions and requirements for shaft seals in salt and clay formations

Fundamentals

- Knowledge and experiences from shaft seals of underground hazardous waste deposites (UTV and UTD) (national und international)
- State of the art of diverse and redundant sealing elements (German research projects: ISIBEL, ANSICHT, CARLA, shaft seal at Salzdetfurth, VSG- preliminary safety analysis Gorleben)
- Potential repository regions (salt and clay formations in Germany (BGR-studies))
- Safety requirements governing the final disposal of heat-generating radioactive waste (BMU 2010)

Sketch of a Repositoy Shaft Seal



(from TU BAF)

Workprogram – Phase 1

- WP 1: state of the art on long-term stable shaft seals
- WP 2: proof of safety – concept of safety demonstration
- WP 3: boundary conditions for host rocks salt and clay
- WP 4: requirements
- WP 5: integration into an international project
- WP 6: report

State of the Art

- Examples of Realized Shaft Seals:
  - tight (against brines) shaft seals in salt mines and at underground natural gas storage facilities (Bernterode I (1978), Immenrode (2011))
  - large scale test „shaft seal Salzdetfurth"
  - shaft seal constructions following the Salzdetfurth concept (by K+S)
  - RESEAL II (Benonit-large scale test in Belgium)
- Planned Shaft Seals:
  - NAGRAs shaft sealing concept
  - ASSE, ERAM, KONRAD
  - WIPP

State of the Art

Proof of Safety – Concept of Safety Demonstration

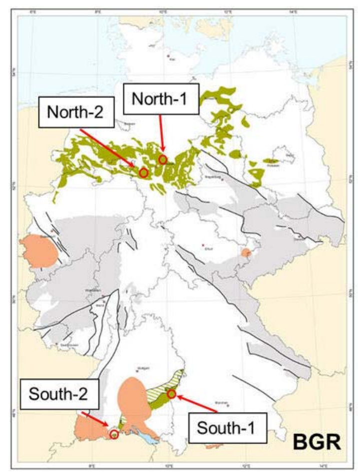
- Adoption of the partial safety factor concept according to Eurocode 7 (DIN EN 1997) as far as applicable
- Proof of:
  - sufficient hydraulic resistance (Dichtigkeitsnachweis)
  - stability
  - durability
  - constructability
- Analogue to the safety demonstration concept applied in the preliminary safety case Gorleben (VSG)
- Proof of sufficient low permeability
  - performed on an example of a sealing element made of salt concrete

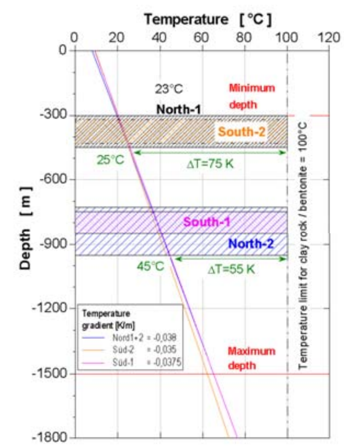
Boundary Conditions

For host rocks salt and clay:

- Geomechanical boundary conditions
- Characterization of EDZ
- Characterization of decisive flow- und transport processes
- Geochemical boundary conditions
- Deduction of knowledge deficits

Potential Repository Regions (Clay)





Parameters Assumed for Potential Sites in Clay

Youngs-Modulus	Boom-Clay, Belgium: 0,2 – 0,4 GPa Opalinusclay, Swizerland: 4 – 12 GPa
Compressive strength	Boom-Clay, Belgien: 2 MPa Opalinuston, Schweiz: 10 – 16 MPa
Cohesion	Boom-Clay, Belgium: 100 kPa Opalinusclay, Swizerland: 2,2 – 5,5 MPa (depending on σ_1)
Creep behaviour	(Visco) elastic – plastic constitutive laws
Thermal conductivity	Boom-Clay, Belgium: approx. 1,5 W/m*K Opalinusclay, Swizerland: approx.. 0,8 – 1,9 W/m*K

Knowledge Deficits on Geomechanical Boundary Conditions

Salt

- Only one single large scale test (Salzdetfurth)
  - RD&D to develop further or new shaft seal components

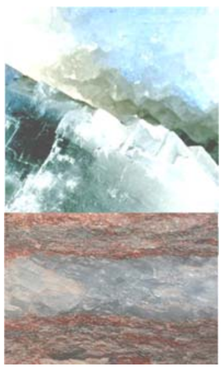
Clay

- Assumtion of geomechanical parameters (lack of data)
- Development and proof of constitutive laws for clay (Benchmark calculations)
- Development of non destructive measurement methodes to measure anisotropic behaviour of clay (in situ).and calibration of data

Salt & Clay

- Determination of geomechanical paramters; necessary for construction locations of the sealing and supporting components of a shaft seal

Geochemical Boundary Conditions



Salt ⇦ **host rocks** ⇨ **Clay**

- **phase composition**
- **solutions**
  (occurence, concentration of access solutions and equilibria solution)
- **material**
  for geotechnical barriers

Chart: Dr. Freyer

Selection of shaft seal material :
Criterion: Natural and thermodynamic equilibrium between host rock and geotechnical barrier material during construction phase achievable

Gorleben Salt Characteristics

- **Pure rock salt layers preferred for a repository in salt !**
  - Rock salt with large extension (height, length) e.g. „Staßfurt-Folge“ (Na 2) and „Leine-Folge“ (Na 3)

Composition of Staßfurt- und Leine-salt-rock at Gorleben /MÜL1985/, /BOR1987/:

layer	subdivision			mineral composition and concentration (% by weight)			
		old symbols	new symbols	Halite	Anhydrite	Polyhalite	Carnallite
Zechstein 3 Leine-Folge Z3	Anhydritmittelsalz	Na 3	z3AM	x	x		x
	Buntes Salz		z3BT	x	x	x	
	Bänder- u. Banksalz		z3BD/BK	97,1	0,4	2,0	0,5
	Orangesalz		z3OS	94,4	5,0	0,5	<0,1
	Liniensalz		z3LS				
	Basissalz		z3BS				
Zechstein 2 Staßfurt-Folge Z2	Hangendensalz	Na 2	z2HG	95,0	4,9	0,1	-
	Hauptsalz		z2HS				
	Basissalz		z2BS				

/BORN1987/ Bornemann, D.; Fischbeck, R.; Exkursionsführer I Zechstein 87, Internationales Symposium Kassel – Hannover, Exkursion K, 08.05.1987, Auszug: Zechstein 2-4 des Salzstocks Gorleben
/MÜLL1985/ Müller-Schmitz, S. (1985): Mineralogisch-petrographische und geochemische Untersuchungen an Salzgesteinen der Staßfurt-, Leine und Aller-Serie im Salzstock Gorleben, Dissertation Universität Heidelberg

Materials for Geotechnical Barriers (Salt)

- Crushed Rock Salt and Rock Salt Bricks ✓
  - are components of the thermodynamic salt-solution-equilibrium.
- Bentonite resp. Clay ✓
  - Bentonite is a mixture of various clay minerals (main phase: Montmorrillonite; minor component: Glimmer (mica), Feldspat (feldspar), Quarz (quartz), Calcit (calcite) und Pyrit (pyrites))
  - In contact with salt solutions Bentonite remains stable if temperatures are less than ~80 C (possible mineral transformations at higher temperatures)
  - Natural bentonite deposits and several papers show that Betonite is formed by transformation of vulcanic sediments in salt enviroment. Bentonite remains stable along geological periods (Lago-Pellegrini deposit in North-Patagonia is an example for a natural analogon)

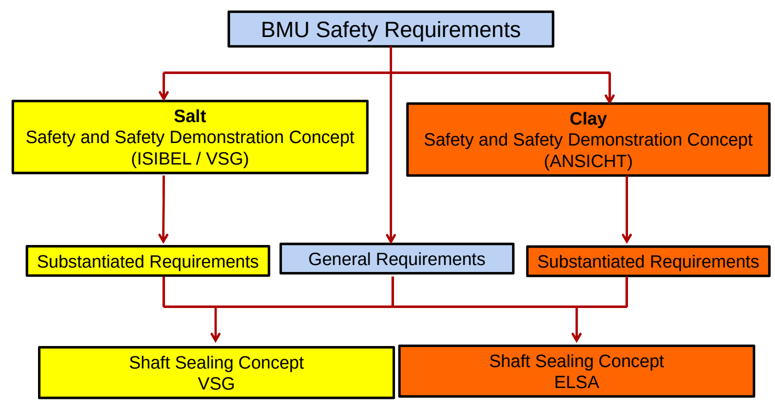
Materials for Geotechnical Barriers (Salt)

- Crushed Basalt Rock ✓
  - Long term stability proved by natural analogon (Basaltintrusions in Werra-Kali-Mining-Region since geological periods without any mutation.)
- Bitumen and Asphalt ✓
  - Artifical and natural mixture of high molecular aliphatic and aromatic hydrocarbon
- Salt Concrete (x) only with temporary stability
  - Binder phases [calcium silicate hydrate (CSH phases)] are not poised in thermodynamic equilibrium with salt host rock and equilibrium solutions
- Salt-Rock-Anhydrite Material ⊗
  - For Salt-rock-anhydrite material (Mischo 2002, Kühn 2004, Langefeld 2005) calcium sulfate dihydrate (gypsum) is the binder phase. Gypsum is not poised in thermodynamic equilibrium with salt host rock and equilibrium solutions of salt host rock.

Phase composition within clay

- Clay Rock show a wide variety of mineralogical compositons
- Clay types with different water contents exist:
  - Boom-Formation, Belgium
  - Callovo-Oxford-Clay, France
  - Oxford-Clay, Great Britain
  - Boda-Clay, Hungary
  - Mizunami-Clay, Japan
- ➢ (see also "Clay Club Catalogue")

Derivation of Requirements



(M. Jobmann, et.al.)

Requirements for shaft seals

- **derived from:**
  - BMU-safety requirements
  - Safety- and safety demonstration concept
  - Proof of technical functionality
  - Site specific boundary conditions
  - Other demands

e.g. from BMU-Safety Requirements

Source	Requirement	Rock salt	Clay
BMU-Safety Requirements (BMU 2010)	• **Process analysis of impacts on shaft seals**	x	x
	• Falls Komponenten des Schachtverschlusses im ewG liegen, so müssen in den Komponenten ablaufende Transportprozesse in ihrer Geschwindigkeit mit diffusiven Transportprozessen vergleichbar sein (ausreichend geringe Durchlässigkeit).	x	x
	• **Quelldrücke von Dichtelementen dürfen die Gebirgsfestigkeit nicht überschreiten.**	x	x
	• Falls für geotechnische Barrieren keine anerkannten Regeln der Technik vorliegen, muss deren Herstellung, Errichtung und Funktion grundsätzlich unter Anwendung von Qualitätssicherung erprobt sein. (Kann entfallen, falls die Robustheit anderweitig nachgewiesen werden kann oder falls ausreichend Sicherheitsreserven bestehen.)	x	x
	• Zum Nachweis der Bauwerksintegrität sind die maßgeblichen Beanspruchungszustände und Eigenschaften der Baustoffe zu untersuchen. Die hinreichende Belastbarkeit und Alterungsbeständigkeit dieser Baustoffe ist für den Zeitraum nachzuweisen, für den die Funktionstüchtigkeit der Bauwerke gegeben sein muss.	x	x
	• Soweit notwendig müssen sofort wirksame Barrieren den Einschluss der Abfälle für den Zeitraum übernehmen, in dem die volle Wirksamkeit der langfristig wirksamen Barrieren noch nicht gegeben ist.	x	x
	• Eventuelle Anforderungen aus einer Analyse von Freisetzungsszenarien sind zu identifizieren und zu berücksichtigen.	x	x
	• **Innerhalb des Schachtverschlusses soll möglichst Redundanz und Diversität berücksichtigt werden z.B. durch Verwendung mehrerer Dichtelemente mit diversitären Materialien.**	x	x
	• Der Schachtverschluss ist in seiner Bedeutung für die Sicherheit des Endlagers im Zusammenspiel mit den anderen Barrieren (z. B. Streckenverschlüsse) zu bewerten (z. B. für die Festlegung des Wirkungszeitraums).	x	x

Folie: Bollingerfehr

e.g. from Safety- and Safety Demonstration Concept

Source	Requirement	Rock salt	Clay
Safety- and Safety Demonstration Concept	• **Maximum period of functioning 50.000 years (next glaciation).** *constraint via sealing concept (salt)*: Der Schachtverschluss muss ***solange hinreichend dicht*** *sein*, bis der ***hydraulische Widerstand des kompaktierenden Salzgrusversatzes groß genug ist. (1000 Jahre nach aktuellen Aschätzungen)***. Daraus resultiert die hydraulische Anforderung, dass der sich einstellende Volumenstrom so gering sein muss, dass die zutretende Lösung den Salzgrusversatz in den Zugangsstrecken erst nach (hier) 1000 Jahren erreicht.	X	-
	• **Maximum period of functioning 50.000 years (next glaciation)** *constraint via sealing concept (clay)*: *open question.*	-	X
	• Vorbemessung des Schachtverschlusses (Dimensionierung, Eigenschaften und Nachweis der prinzipiellen Herstellbarkeit).	x	x
	• Berücksichtigung einer FEP-Liste mit wahrscheinlichen und weniger wahrscheinlichen Prozessen bezüglich einer Konsequenzanalyse. Daraus eventuell resultierende Anforderungen an Funktionselemente des Schachtverschlusses sind zu berücksichtigen (ggf. iterativ optimieren).	x	x
	• **Unterbindung einer advektiven Lösungsbewegung aus dem Endlager bzw. aus dem ewG heraus.**	-	x
	• **Erhaltung eines stabilen geochemischen Milieus**	-	x
	• **Verwendung von Materialien mit hoher Sorptionskapazität.**	-	x

Folie: Bollingerfehr

Summary and Outlook

- ELSA Phase 1 accomplished with a summary report in summer this year comprising:
  - state of the art of shaft seal design and constructions
  - fundamentals
  - boundary conditions for potential repository regions in Germany
  - new approach to derive requirements
- ELSA project became part of the EU RD&D-project DOPAS in February 2012
- ELSA Phase 2 started in spring this year

DBE TECHNOLOGY GmbH

**Thank you
for your attention.**

Perspectives on Plugging and Sealing a Salt Repository

Frank Hansen
Sandia National Laboratories, Albuquerque New Mexico USA

Abstract

Drift and shaft seal systems are vital components of nuclear waste repositories. To obtain a compliance certification from the Environmental Protection Agency an appropriate seal system had to be designed and demonstrated for the Waste Isolation Pilot Plant. Because the salt formation would close disposal rooms and drifts, emphasis for long-term performance was given to shaft seal system design. Shaft seal system functions entail material characteristics, construction, performance, and verification. Functional requirements include low fluid permeability, stable chemistry, robust mechanical properties, and constructability. The WIPP design approach applied redundancy to functional elements and used multiple, common, low-permeability materials to ensure reliable performance. Laboratory and field measurements of component properties and performance provided the basis for the design and related evaluations. Hydrologic, mechanical, thermal, and physical features of the system were evaluated in a series of calculations. The use or adaptation of existing technology for seal construction combined with the use of commonly available materials assure that the shaft seal design can be constructed.

In presenting the scientific basis for granular salt reconsolidation, the case for isolation of nuclear waste in salt is bolstered. The thrust of this work pertains to seal systems constructed of crushed, mine-run, or specially conditioned granular salt; however, the behavior of the less engineered backfill is expected to evolve to the same impermeable end state. Several avenues of substantive evidence for reconsolidation are followed, starting with the microscopic mechanisms and observational techniques. Most laboratory results are determined at ambient conditions, although elevated-temperature consolidation will occur in proximity to heat-generating waste. Micromechanics also help explain field-scale testing results, which can be extended to natural and anthropogenic analogues. Practical application concerned with field-scale performance is the key point of relevance. A well designed salt repository requires minimal engineered barriers. However, if licensing or public assurance requires seals to be placed in drifts or shafts, the capability to seal a salt repository permanently exists.

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DBE TEC DBE TECHNOLOGY GmbH
PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology
U.S. Department of Energy NNSA

Perspectives on Plugging and Sealing a Salt Repository

Frank D. Hansen PhD PE

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany
September 17-18, 2013

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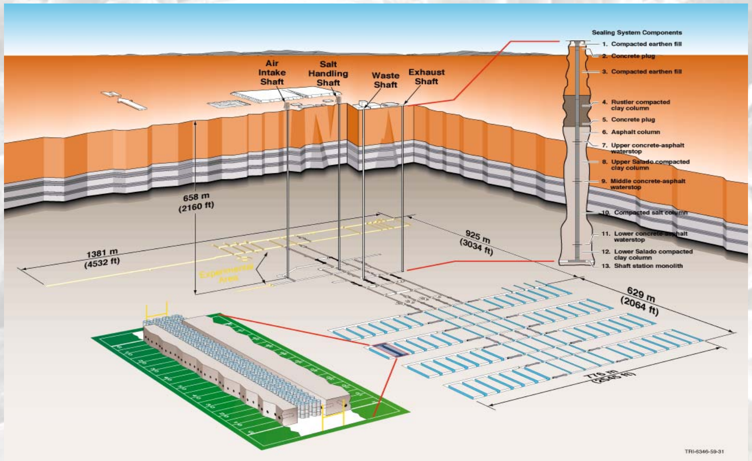
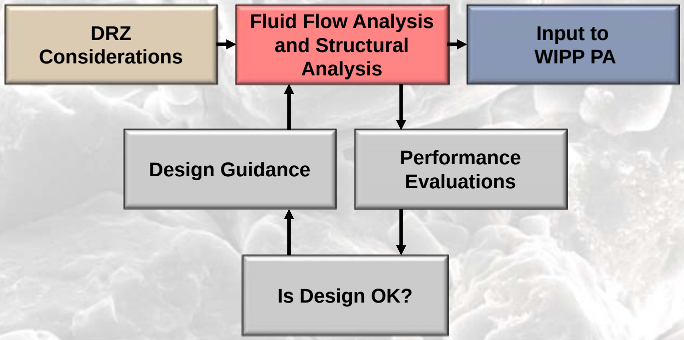
WIPP Facility Layout



2

Shaft Seal Systems Analysis Process



3

Seal Material Specification

- Functions
- Material Characteristics
- Construction
- Performance Requirements
- Verification methods

- *Summary given in Peine 2011--Salt Repository Seal Design and Materials*
- *Waste Isolation Pilot Plant Shaft Sealing System--Compliance Submittal Design Report. SAND96-1326/Two Volumes. Sandia Laboratories, Albuquerque, New Mexico USA.*

4

Modeling the Shaft Seal System

1 – Brine Flow Down

- Predict cumulative brine flow through the seal system down to the salt column and the repository
- Demonstrate the effectiveness seal elements

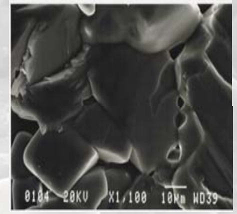
2 – Salt Column Performance

- Predict the intrinsic permeability of the salt column
- Demonstrate effectiveness of the salt column
- Estimate gas migration from the repository horizon

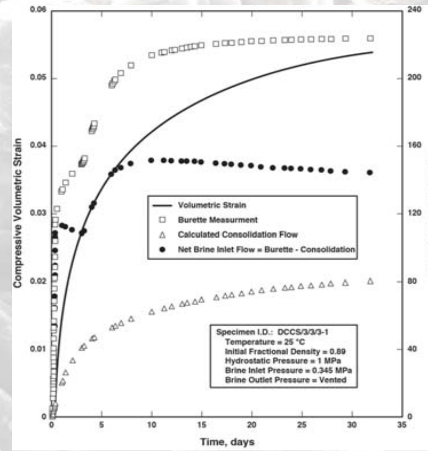
5

Laboratory Results

Compacted



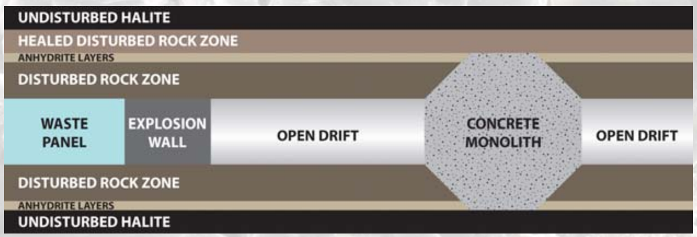
Reconsolidated



Reduction of brine permeability

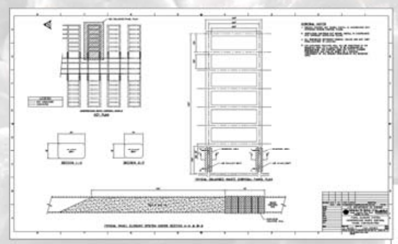
6

Option D Panel Closure System



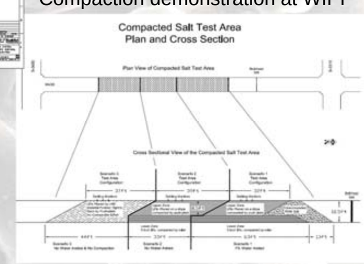
7

Logical Redesign of Panel Closure



Redesign developed in 2002

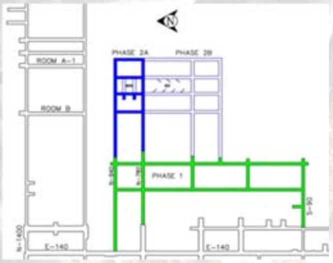
Compaction demonstration at WIPP



8

Use of WIPP URL for Plugging and Sealing

- Salt Defense Disposal Investigations (SDDI)
- Salt Disposal Investigations (SDI)
- Large-Scale Seal Demonstration
- Mining Research
- Wedge Pillar Test
- Mine-By DRZ Measurement
- Single Heater Test
- In Situ Consolidation
- International Test Bed



Finis

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Salt Club: Salt Knowledge Archive

NEA Salt Club Meeting

Berlin, Germany: 16 September, 2013

Kristopher L. Kuhlman

Sandia National Laboratories, Carlsbad New Mexico

U.S. DEPARTMENT OF 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.
This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy.
SAND NO. 2013-7621C

Salt Knowledge Archive

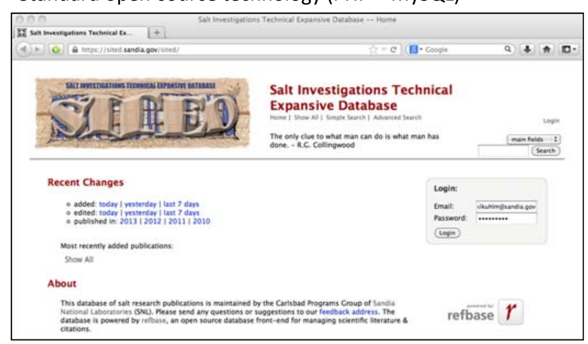
- Extensive reports/studies/papers on salt (50+ years)
- Knowledge archive will contain references to documents on radioactive waste disposal in salt formations
- References include digital copies of documents
- Documents also include metadata:
  - A unique document identifier
  - Document type
  - Document abstract/summary
  - Citation/reference
  - Ranking from a list of keywords
  - Text field for additional short description or notes

Salt Knowledge Archive

- Permitted document types:
  - Reports
  - Journal Articles
  - Conference Proceedings
  - Conference Posters
  - Dissertation or Thesis
  - Project memos and personal communications
  - Archived electronic data (zipped-up)
  - Scans or digital copies of experiment/project photos

SITED: Salt Report Database

- Online (password-protected) digital report archive
  - Sandia-hosted secure server (https://sited.sandia.gov/sited)
- Based on open-source bibliographic database "refbase"
  - Standard open-source technology (PHP + MySQL)



SITED: Salt Report Database

- Developed for US DOE office of Nuclear Energy in 2012
- Database initially populated with pdf copies of reports from:
  - WIPP Project Records Center (WIPP reports)
  - Sandia Technical Library database query (WIPP reports)
  - Oak Ridge National Laboratory library (Salt Vault reports)
  - US Geological Survey library (general salt geology reports)
  - US DOE "OSTI Bridge" online database (all DOE-funded reports)
  - European Union online bookshop database (Asse reports)
- Continually adding to database
  - Scanning old reports
  - Adding new reports

5

SITED as Salt Knowledge Archive?

- SITED is a working database
  - Quickly learned what is important/unimportant
  - Topic-specific archive has different needs/goals from a library
  - Relatively small SQL database (few 100 MB)
  - Large amounts of space for pdf documents (> 100 GB)
  - Full-text document search not currently implemented
- SITED can be used directly as Salt Club database
  - adapted to include additional needs of Salt Club
- Data in SITED can be "cloned" for separate Salt Club database
  - Salt Club database could be based outside US or Sandia
  - Salt Club database could have different access requirements (SNL hosting leads to strict requirements)

6

Thank You.

Discussion?

7

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

Drift seals are to be erected in the repository for radioactive waste Morsleben. These will form a partition between the repository areas in which the radioactive waste is emplaced in 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 migration of radionuclides out of these areas. For the determination of reliable data for the proof of properties used in post-closure safety analysis an situ-test with appropriate test equipment was performed.

Current plans are that 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. Grouting 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 are 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 pressurization tests are 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 minimizing the EDZ. The concreting was performed in 12/2010 and took about 20 hours for around 500 m³ salt concrete. After a waiting time of about 2 month to allow autogeneous shrinkage and thermal contraction to decay the grout injection of the contact zone was carried out.

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, followed by detailed information of measurements (including pneumatic and hydraulic pre-tests) and calculation results on the 3rd US/German Workshop in Albuquerque in October 2012.

From February 2013 up to now the main hydraulic test goes on with an increased fluid pressure of 0.7 MPa. It can be seen that the injectable solution volume is continuously decreasing. Nevertheless there were some unexpected results obtained, which have to be interpreted in future work. This article will show some outstanding results and provide a way how to deal with such results in a verification.

Furthermore there are first findings how to deal with optimization measures necessary for the installation process and quality management concepts. All in all presently available results indicate that the assumed properties of the construction could be validated.

4th US-German Workshop on Salt Repository Research, Design, and Operation - September 17 – 18, 2013, Berlin, Germany

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 presentations at 2nd and 3rd US-German Workshop in Peine and Albuquerque

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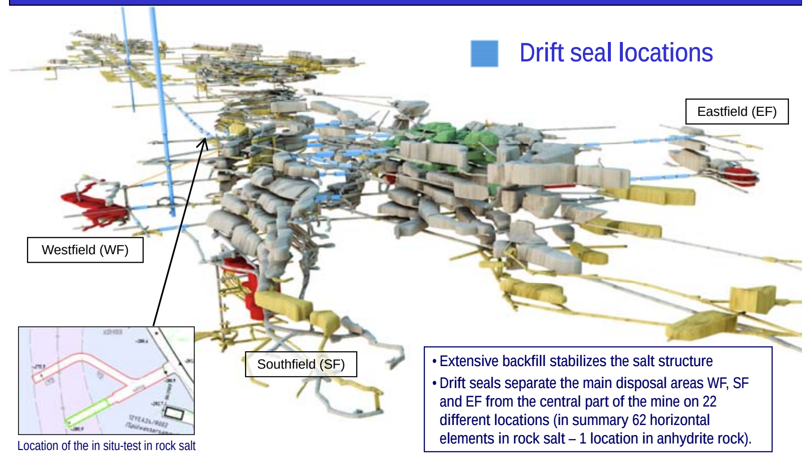
1

Morsleben repository – closure concept and sealing measures



- Extensive backfill stabilizes the salt structure
- Drift seals separate the main disposal areas WF, SF and EF from the central part of the mine on 22 different locations (in summary 62 horizontal elements in rock salt – 1 location in anhydrite rock).

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2

In-Situ Test – Construction Design and Geotechnical Measurements

Measurements on in-situ test

Requirements of concrete technology (e. g. Temperatures, Stresses, Displacements Strength, Young-Modul, Porosity, Permeability)

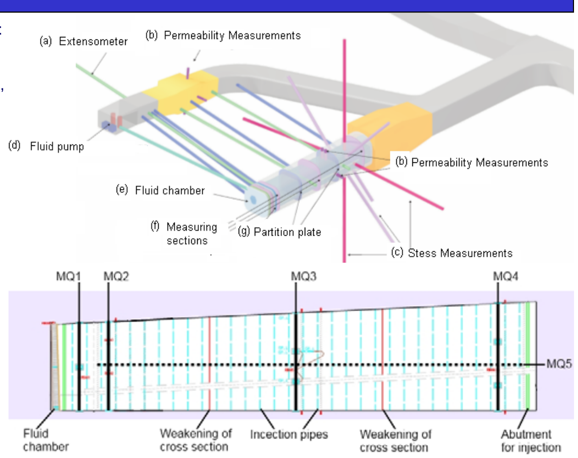
Connection of concrete to the rock salt (e. g. Cores from the contact zone)

Integral permeability (Tests to determine the permeability for gas and solution, loading the fluid chamber with pressure)

Injectability of the contact zone

Mechanical Stability of location

Prediction of stresses and deformations with calibrated numerical analysis



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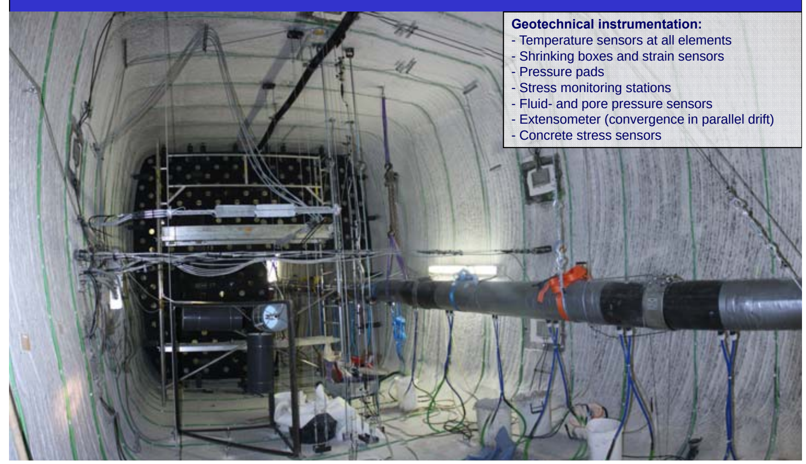
3

In-situ Test - Impression 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



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4

In-Situ Test – View of the Construction

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

Points reported on 3rd US/German workshop in Albuquerque:

- Continuation of the geotechnical measurements
- Over-drilling and sealing of the cladding tube
- Core scanning of the contact zone
- Hydraulic pre- and 1st main test
- Numerical calculations to evaluate the measurements as well as certain problems such as crack propagation
- First micro-section or thin section of core sample

Main statements: Low levels of integral permeability ≤ 1E-16 m² give evidence for assumed functionality. Some technical improvements were identified (e. g. Replacing cladding tube).

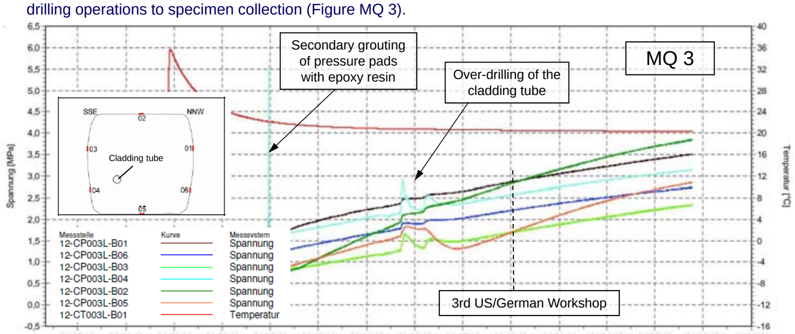
Further Investigation – since last presentation at 3rd Workshop

- **Continuation of the geotechnical measurements** – ongoing
- **Micro-section or thin section of core sample** – completed
- **Investigation program on core sample and in bore holes** – completed (additional investigations are planed)
- **1st Hydraulic main-test (cp 0.3 MPa) (from 21st July to 31st December 2012)** – completed
- **2nd Hydraulic main-test (cp 0.7 MPa) (from 10th March 2013 up to now)** – will continue
- **Numerical calculations to evaluate the overall functional tests** (including successive estimation of the integral permeability over time) – will continue
- **Program to manage technical problems (**such as improving of the injection operation and removal of the cladding tube) **and investigation relating more crack prevention** (modifying the building methods: e. g. block concreting, more separating plates, shotcrete technology or under certain circumstances substitution of the sealing material) – additional investigations are planed

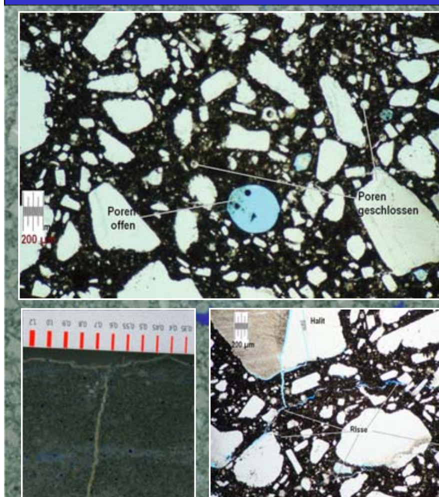
in situ Experiment - Continuation of the Stress Measurement

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

The current increase of the normal stresses in the contact zone are between 0.5 MPa and 3.3 MPa at MQ1 and MQ2 (near the pressure chamber), between 2.4 MPa and 3.8 MPa near the middle of the structure (MQ3) and between 4.1 MPa and 5.8 MPa at MQ4 (MQ4 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).



Micro-Section or Thin Section of Core Sample (Example 1)



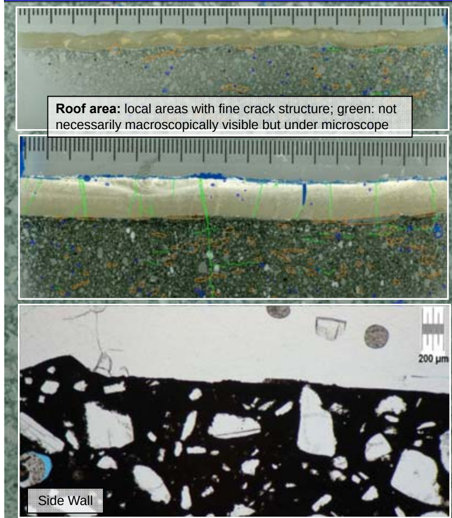
Observations:

1. Salt Concrete:
- Salt concrete is formed homogeneous.
- Salt concrete shows in some core samples fissure systems mostly perpendicular to the rock salt (injected cracks from 0,5 – 1 mm; partially not injected cracks < 0,5 mm)

2. Injection Grout:
- In the roof area the contact joint between salt concrete and rock salt is filled largely with injection grout.
- The other cores from the side walls and bottom area shows significantly less to no injection grout.

3. Rock Salt / EDZ:
- Where salt concrete adhered first cracks occur.
- Cracks between cutting edges from the part-face heading machine partially injected with grout

Micro-Section or Thin Section of Core Sample (Example 2)



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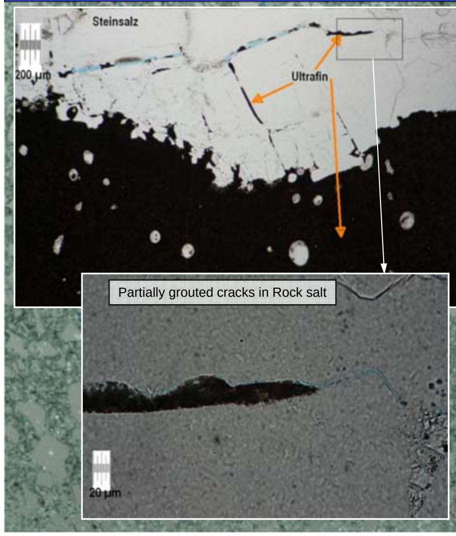
3. Rock Salt / EDZ:
- Where salt concrete adhered first cracks could occur.
- Cracks between cutting edges from the part-face heading machine partially injected with grout

Micro-Section or Thin Section of Core Sample (Example 3)



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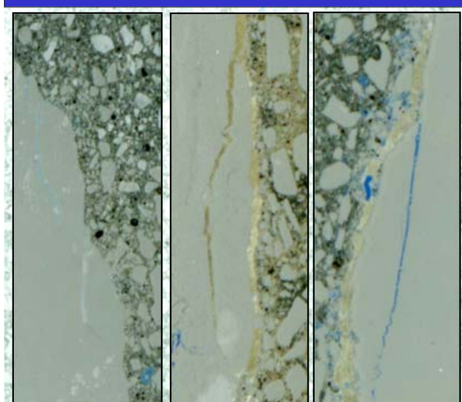
- Where salt concrete adhered first cracks could occur.
- Cracks between cutting edges from the part-face heading machine partially injected with grout

Micro-Section or Thin Section of Core Sample (Example 4)



Conclusions: The micro and thin sections show local cracks that are partially injected. How far these cracks mostly of limited extension are hydraulically relevant, is planed to be investigated.

Observations:

1. Salt Concrete:
- Salt concrete is formed homogeneous.
- Salt concrete shows in some core samples fissure systems mostly perpendicular to the rock salt (injected cracks from 0,5 – 1 mm; partially not injected cracks < 0,5 mm)

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- Where salt concrete adhered first cracks could occur.
- Cracks between cutting edges from the part-face heading machine partially injected with grout

Investigation program on core sample – permeability (gas / fluid)

Bohrung 12YEA25/... (Lage)	Material	Probe	Probenahme-bereich [m]	Mantel-druck)[1] [MPa]	Prüf-druck)[1] [MPa]	Einspann-dauer [h]	effektive Gas-permeabilität [m²]	Lösungspermeabilität für NaCl-Lösung [m²]
RA328 (SSE-Stoß, oben)	Salzbeton M2	P206-74/1	0,02–0,12	1,02	0,48	44	1,5E-18	---
		P206-74/3	2,09–2,19	1,01	0,51	95	6,5E-19	
				1,07	0,60	407		2,0E-21
		P206-74/5	4,10–4,20	1,00	0,51	167	4,2E-19	
				0,80	0,11	817		2,0E-22
		P206-74/7	5,96–6,06	0,98	0,50	163	7,0E-19	
				1,08	0,56	168		3,0E-21
		P206-74/9	8,12–8,22	0,96	0,47	163	7,0E-19	---
		P206-74/11	9,10–9,20	1,00	0,47	144	2,0E-19	
				1,04	0,54	141		2,0E-21
RA532 (NNW-Stoß oben)	Steinsalz / Salzbeton M2	P206-75/10	4,41–4,46	0,70	0,12	27	1,5E-14	
				0,61	0,14	330		9,0E-17
		P206-75/3	7,16–7,21	0,78	0,12	2	8,0E-16	
				0,73	0,13	309		5,0E-19
RA515 (Sohle)	Steinsalz / Salzbeton M2	P206-77/1	0,89–0,94	0,79	0,12	2	1,9E-15	
								)[2]
		P206-77/3	5,70–5,75	0,73	0,14	2	3,5E-15	
				0,85	0,21	359		2,0E-18
RA510 (SSE-Stoß Mitte)	Steinsalz / Salzbeton M2	P206-78/1	1,23–1,28	0,72	0,13	70	2,7E-17	
				0,80	0,14	378		1,0E-21
		P206-78/3	3,08–3,13	0,70	0,12	43	8,5E-18	
				0,73	0,11	865		1,0E-20
RA516	Salzbeton M2 / Salzbeton M2.H1	P206-79/1	0,47–0,57	1,02	0,53	144	1,8E-15	
				0,88	0,12	600		7,0E-20
		P206-79/3	8,17–8,27	0,72	0,16	188	1,1E-15	
				0,74	0,15	216		2,0E-19

)[1] Relativdruck)[2] Messwiederholung nicht möglich, Probe zerstört

Observations:

On specimens in the lab **effective gas permeabilities** of **salt concrete** of **1.5 E-18 m² to 2E-19 m²** and of the **contact zone** of **1.5 E-14 m² to 8,5E-18 m²** were measured.

Due to the **lower fluid permeability** of **3.0E-21 m² to 2.0E-22 m²** for the **salt concrete** and **9.0 E-17 m² to 1.0E-21 m²** for the **contact zone** it is expected that the fluid permeability in the structure is much lower than the measured effective gas permeability.

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Investigation program in bore holes – permeability (previously only gas)

Bohrung 12YEA25/...	Material	Durch-messer [mm]	Mess-punkt	Test-methodik)[1]	Teufe (Beginn Prüfraum) [m]	Intervall-länge [m]	Prüf-druck [MPa]	Niveau der effektiven Gas-permeabilität (integral) [m²]
RA328 (SSE-Stoß, oben)	Salzbeton M2	133	MP1	CP	8,90)²	1,10)²	0,04	> 1,0E-14
			MP2	IT	9,84	0,16	0,32	8,0E-21
			MP3	CP	7,50)²	2,50)²	0,10	> 1,0E-14
			MP4	IT	2,87	0,16	0,53	5,5E-16
			MP5	IT	3,41	0,16	0,55	4,0E-21
RA532 (NNW-Stoß, oben)	Steinsalz / Salzbeton M2	70	MP1	IT	2,00	0,18	0,15	4,0E-16
			MP2	CP	5,04	0,18	0,14	4,0E-15
			MP3	CP	3,50	0,18	0,13	> 1,0E-14
			MP4	IT	7,19	0,18	0,17	7,0E-16
			MP5	IT	8,77)²	0,18)²	0,15	1,0E-21
RA515 (Sohle)	Steinsalz / Salzbeton M2	70	MP1	IT	0,87	0,18	0,10	1,0E-15
			MP2	IT	3,70	0,18	0,18	8,5E-16
			MP3	IT	5,72	0,18	0,16	9,6E-17
			MP4	IT	6,75	0,18	0,16	1,0E-15
			MP5	IT	2,50	0,18	0,13	5,0E-16
RA510 (SSE-Stoß, Mitte)	Steinsalz / Salzbeton M2	70	MP1	IT	1,21	0,18	0,14	3,0E-16
			MP2	IT	1,97	0,18	0,14	1,0E-15
			MP3	IT	3,06	0,18	0,15	7,0E-15
			MP4	IT	3,73	0,18	0,17	1,4E-16
			MP5	CP	2,50	0,18	0,13	> 1,0E-14
RA516 (neben Hüll-rohrbohrung)	Salzbeton M2 / Salzbeton M2.H1	133	MP1	CP	0,42	0,16	0,10	> 1,0E-14
			MP2	IT	4,00	0,16	0,01	> 1,0E-14
			MP3	IT	6,00	0,16	0,13	> 1,0E-14
			MP4	IT	8,30	0,16	0,13	> 1,0E-14
			MP5	CP	0,45	0,16	0,01	> 1,0E-14

)[1] IT: Impulstest; CP:Test mit konst. Druck)² Prüfraum bis Endteufe Bohrung

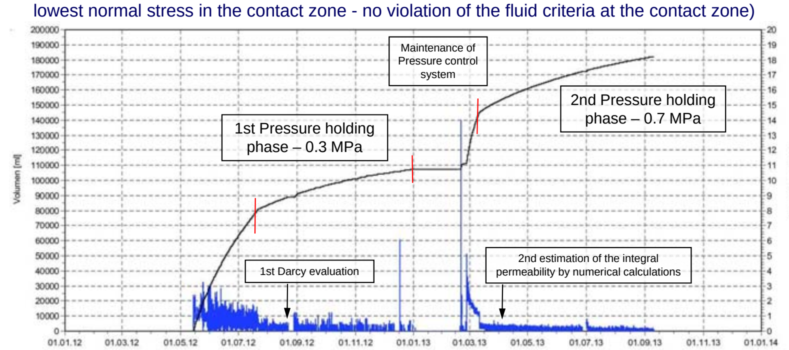
Observations:

The measurements of the **gas permeabilities** in bore holes showed **some high permeabilities** of **greater than 1E-14 m²**, but **also very low permeabilities** of the order of **1E-21 m²**.

Additional investigations are planed to investigate the fluid permeability at the measuring points of the gas permeabilities.

in situ Experiment - Hydraulic Main-Test (1st and 2nd 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)



Observation: Continuous decreasing of the flow rate recently **below 0.2 ml/min** (Recalculations using the values of individual pore pressure sensors results **integral "Darcy" permeabilities between 2E-16 m² and 6E-18 m²** (State: 22.08.2012; 8 of 15 sensors in the cross-section MQ2 showed no reaction. Considering all the sensors a lower permeability would result.)

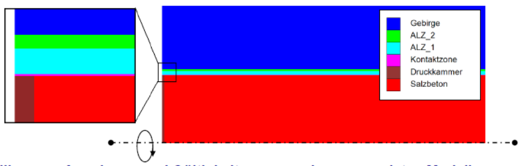
Numerical Calculations to Estimate the Intregral Permeability

Background:

The pore pressure sensors show very different reactions. In the area near the pressure chamber it is assumed that cracks could form hydraulic pathways of limited extension and / or incomplete injection of the contact zone (both comparable to the air side).

The planned evaluation of the pressurization tests using a fit to the measured profiles of the pore pressure sensors (Darcy Recalculation) is assumed to be not appropriate.

To estimate the integral permeability, calculations are carried out with a model that considers homogeneous material model regions and simplifies the inhomogeneous conditions. For this purpose, the permeability and extent of the contact zone is varied, any cracks in the salt concrete are not considered. This mean that the results can be used for integral reflections only. The permeability of the contact zone is just a calculated value!



- Applying the in situ measured fluid pressure as function of time as model boundary condition (so called inflow-condition)
- Adjusting the calculated and measured flow rates during the pressure holding phase for different assumptions of a contact zone (thickness, permeability)

Results of Estimation:

Under the chosen model assumptions (hydraulic model, single-phase flow, Darcy model, rotational symmetry with chosen geometrical dimensions and permeabilities of the model ranges) an **integral permeability of the sealing structure in the range between 3E-18 m² and 8E-18 m².** can be estimate. (State: April 2013 - will updated)

Conclusion

- **Successful production of the in-situ test structure proofs its principal technical feasibility. Technical improvements are necessary during the injection process (also in terms of the removal of the cladding tube)** (see presentation at 2nd and 3rd Workshop).

- **The results of permeability and pressure tests show that an integral permeability of 1.0E-18 m² is accessible by the intended building design. To confirm this, the test will be continued** (the previously pressurized test area near the pressure chamber can possibly not be considered as representative, because the injection procedure was not fully implemented – no influence on the experimental procedure - and the normal stresses are lower than in the other building areas).

- **There are local pathways (cracks) observed, although the in the in situ-test plan assumed requirements for the salt concrete technology have been fulfilled. The aim is to clarify the causes of these cracks clearly and to limit them later by technical measures.**

- **Regarding the local permeabilities, which may have a decisive influence on the corrosion behavior, further investigations must be carried out by in situ and laboratory measurements to obtain a better description of "Permeability distribution". In this case, the influence of restraint pressure and restraint duration on the permeability of the EDZ and if possible of the salt concrete has to be considered.**

Outlook (1)

New findings from the ongoing detailed planning phase:

- At some of the 22 sealing locations the rock characteristics deviated from the original assumptions of the conceptual planning phase (regarding stress and deformation).
- The pore-diffusion-coefficient of the salt concrete might be lower than expected. This leads to changes in corrosion properties (Geochemnical calculations show significantly shorter corrosion times).
- Until now, there is no reliable method to determine the saturation of salt concrete.

Resulting questions:

- What effects lead to cracking-pressures within the material, although the calculations just expected them at the contour and in the area of the separating plates?
- Is it possible to develop measures or materials to exclude such cracks?
- What influences (chemical and geomechanical) have to be considered with regard to the long-term functioning of the overall sealing structure?
- What quality can or must have chemical and geomechanical prediction models?
- Is the realized measurement system still suitabale to demonstrate the relevant building characteristics?

Outlook (2)

Possible solutions:

- **Modifying the installation methods** (e. g. concrete cooling, concreting smaller blocks, more separating plates, shotcrete technology)
- **Modification of the sealing material** (possibly redefinition of all properties necessary)
- **Replication of the in situ experiment with less or no measuring instruments**
- **Improvement of the calculation prediction models** (THMC)
- If necessary, **re-run of the long term safety assessments** (with the real reachable hydraulically and geochemical properties of the drift seals)

About this issues please notice the announced presentation **"Morsleben Repository – Interdependence of Technical Feasibility and Functionality of Geotechnical Barriers and Safety Case Development"** *(J. Wollrath et. al., 2nd International Safety Case Symposium, 7-9 October, 2013, Paris, France).*

Thank You for Your Attention !!!

and Welcome to the Technical Tour at the Asse and Morsleben Site on September 19, 2013

ABC-Salt - a workshop series focusing on Actinide Brine Chemistry

M. Altmaier, Karlsruhe Institute of Technology, Institute for Nuclear Waste Disposal, Germany
D. Reed, Los Alamos National Laboratories, Carlsbad Office, USA

A reliable understanding of actinide geochemical processes and their quantification are required as building blocks of the nuclear waste disposal safety case. As a consequence of many dedicated research activities, a detailed scientific understanding of fundamental processes controlling the behavior of radionuclides in aqueous systems has been established for all relevant host-rock formations including rock salt. The performance and safety of a repository based on analysis of pertinent scenarios can thus be assessed based upon scientific evidence and laws of nature.

ABC-Salt is a series of workshops that is centered on actinide and brine chemistry pertaining to the permanent disposal of nuclear waste in a deep underground salt repository. Topics generally relevant for the description of aqueous chemistry at intermediate to high ionic-strength conditions are covered. Workshop topics include

- Brine evolution
- Brine chemistry
- Actinide chemistry
- Assessment of temperature effects
- Microbial effects
- Radiolysis
- Modeling studies
- Thermodynamic data and databases

ABC-Salt Workshops were very productive and resulted in several research cooperations and exchange, e.g. on Sorel phase stability, microbial effects in salt brine systems, actinide redox transformations (i.e. Pu chemistry), actinide-borate interactions and Pitzer modeling and related thermodynamic databases.

Three ABC-Salt Workshops were organized since 2010 on annual basis in Carlsbad (USA), Karlsruhe (Germany) and Santa Fe (USA). Since 2013, ABC-Salt Workshops are integrated as NEA Salt Club activities. ABC-Salt workshops are co-organized by KIT-INE and LANL-CO and have received sponsorship from US-DOE, WIPP, and BMWi. From 2013 the ABC-Salt Workshop Series change to a bi-annual mode with ABC-Salt (IV) being scheduled for May-April 2015 in Heidelberg, Germany.

Institut für Nukleare Entsorgung

ABC-SALT Workshop Series

Marcus Altmaier (KIT-INE), Don Reed (LANL-CO)

Institute for Nuclear Waste Disposal (INE)

- ABC-Salt concept
- ABC-Salt (I-IV)
- Main topics covered
- Impact of ABC-Salt - Pitzer TDB

ABC-Salt Workshop Series

- RN chemistry in salt brine solutions required for assessing repository safety in rock salt formation (USA, Germany).
- Although water intrusion is clearly a less probably scenario in salt rock repository concepts, robust prediction of RN-brine interactions are essential part of PA. (WIPP, VSG, Asse?)
- Activities on RN and brine chemistry research mainly related to US and German initiatives over last 30 years.

ABC-Salt Workshop Series

- Idea for an International Workshop on **A**ctinide and **B**rine **C**hemistry relevant for nuclear waste disposal in rock **salt** was born in 2009.
- ABC-Salt workshops: (co-org. KIT-INE and LANL-CO) International forum for research on actinide and brine chemistry.
- Three ABC-Salt Workshops organised since 2010 on annual basis. Sponsored by US-DOE, WIPP, BMWi, …
- From 2013, ABC-Salt Workshops integrated in NEA Salt Club activities.

Bundesministerium für Wirtschaft und Technologie

Waste Isolation Pilot Plant www.wipp.energy.gov

ABC-Salt Workshop Series

Main focus of ABC-Salt:

- Centered on actinide and brine chemistry research pertaining to the permanent disposal of nuclear waste in a salt repository.
- Topics generally relevant for the description of aqueous chemistry at intermediate to high ionic-strength conditions.
- Regular update of ongoing high ionic-strength research activities.

- "Non-radioactive" chemistry and brine evolution.
- Actinide and fission/activation product chemistry in brines.
- Microbial effects.
- Special focus on Pitzer-based geochemical modeling, TDB and the further development of modeling and TDB in this context.

ABC-Salt (I)

15-16 September 2010, Carlsbad, NM, USA

40 participants from 4 countries

ABC-Salt (II)

7-8 November 2011 Karlsruhe, Germany

80 participants from 8 countries, proceedings published via KIT

ABC-Salt (II) held in connection with HITAC workshop

ABC-Salt (III)

15-17 April 2013, Santa Fe, NM, USA

60 participants from 8 countries

ABC-Salt (IV)

- Consensus to change ABC-Salt Workshop Series to bi-annual mode.
- ABC-Salt (IV) scheduled for *May-April 2015* in Heidelberg, Germany.
- ABC-Salt (IV) organized in connection to HiTAC workshop on High Temperature Aqueous Chemistry.

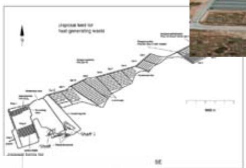
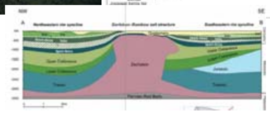
Topics

- Overview talks on current repository projects
- Brine chemistry
- Microbial effects in brines
- Actinide chemistry in brines
- Experimental techniques
- Thermodynamic databases and modeling
- ~ 30-40 oral talks + ~20-30 posters presented at each workshop !!!

Topics

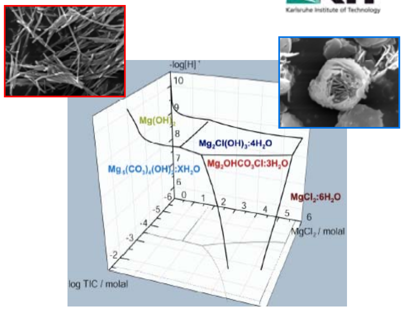
- **Overview talks on current repository projects**
  - **USA (WIPP project, …)**
  - **Germany (VSG, …)**
  - Canada NWMO
  - European Commission
  - OECD-NEA

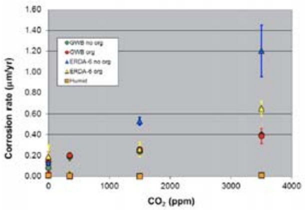


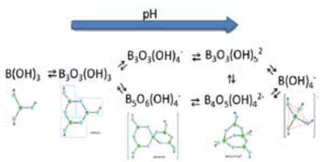




Topics

- **Brine chemistry**
  - Iron chemistry
  - Sorel phases
  - Heavy metals
  - Organics speciation
  - Ra chemistry
  - …

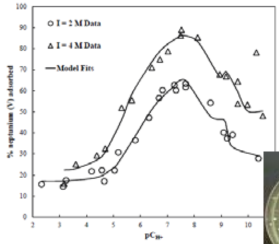


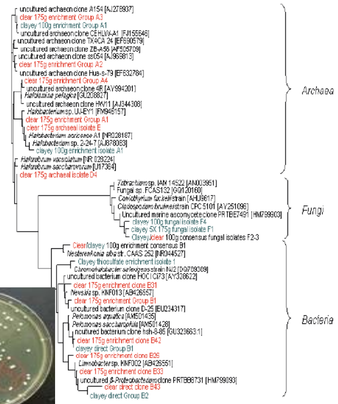




Topics

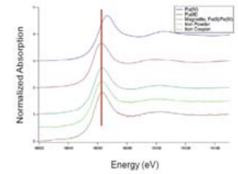
- **Microbial effects in brines**
  - Microbial research - WIPP
  - Microbial research - Germany



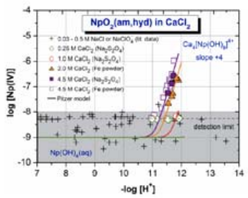



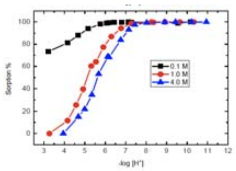
Topics

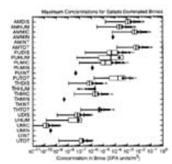
- **Actinide chemistry in brines**
  - Speciation and solublity
  - Actinide redox reactions
  - Actinide organic interactions
  - Sorption at high I conditions
  - Plutonium chemistry
  - Colloids
  - …



Am-Ox	0°C	25°C	45°C	60°C
$\log \beta_{101}$	5.18±0.08	5.37±0.09	5.65±0.08	5.85±0.09
$\log \beta_{102}$	8.52±0.08	9.04±0.09	9.21±0.0.11	9.41±0.11
Cm-Ox				
$\log \beta_{101}$	5.09±0.08	5.34±0.08	5.58±0.09	5.82±0.10
$\log \beta_{102}$	8.49±0.09	8.61±0.08	8.98±0.10	9.44±0.10
Eu-Ox				
$\log \beta_{101}$	4.72±0.07	5.03±0.08	5.33±0.09	5.49±0.08
$\log \beta_{102}$	8.54±0.01	8.93±0.09	9.30±0.11	9.50±0.11

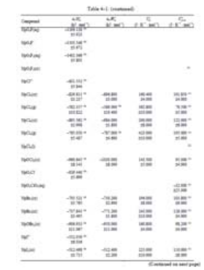


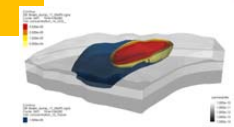


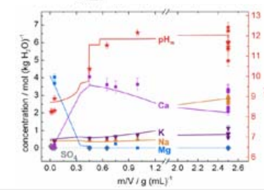


Topics

- **Thermodynamic databases and modeling**
  - WIPP model
  - THEREDA database
  - ASCEM
  - Benchmarking/validation
  - …







ABC-Salt related activities

- ABC-Salt Workshop resulted in several research cooperations:
  - Ongoing discussion on sorel phase stability
  - Microbial effects
  - Actinide redox transformations (Pu chemistry)
  - Actinide-borate interactions
  - Pitzer modeling and TDB
  - …
- Exchange of students and training of young researchers evolving around ABC-Salt Workshop topics.
(→ provide funding for supporting student exchange…)

Aquatic chemistry and TDB

Thermodynamic database

Equilibrium constants at I = 0 →

Solubility products
$An(OH)_x(s) \Leftrightarrow An^{x+} + x\,OH^-$
$K°_{sp} = (An^{x+})\ (OH^-)^x$

Complex formation constants
e.g. Hydrolysis
$x\,An^{z+} + y\,OH^- \Leftrightarrow An_x(OH)_y^{xz-y}$
$\beta°_{xy} = (An_x(OH)_y^{(xz-y)})\ (An^{z+})^{-x}\ (OH^-)^{-}$
→ other complexing ligands…

Ion interaction parameter → **Activity coefficients** (SIT, Pitzer)

- *Need for transparent, traceable and consistent thermodynamic databases.*

OECD-NEA TDB Project

OECD-NEA Thermochemical Database Project (http://www.oecd-nea.org/dbtdb) established international standard for aqueous actinide thermodynamics and solution chemistry.

- Thermodynamic data for solid compounds, aqueous complexes and gas phases
- Use of transparent, traceable and well documented guidelines. Standards, conventions, symbols, nomenclature strictly defined and applied.
- → NEA-TDB is highly consistent.
- SIT used to account for ion-interaction processes and to derive standard-state thermodynamic data.
- No activities by NEA-TDB so far to consider Pitzer consistent thermodynamic data required to assess radionuclide and brine chemistry in rock salt repositories

Title	Vol., Year
Chem. Thermodyn. of Uranium	Vol. 1 (1992)
Chem. Thermodyn. of Americium	Vol. 2 (1995)
Chem. Thermodyn. of Technetium	Vol. 3 (1999)
Chem. Thermodyn. of Np and Pu	Vol. 4 (2001)
Update on the Chem. Thermodyn. of U, Np, Pu, Am and Tc	Vol. 5 (2003)
Chem. Thermodyn. of Ni	Vol. 6 (2005)
Chem. Thermodyn. of Se	Vol. 7 (2005)
Chem. Thermodyn. of Zr	Vol. 8 (2005)
Chem. Thermodyn. of Compounds and Complexes of U, Np, Pu, Am, Tc, Se, Ni, Zr with Sel. Organic Ligands	Vol. 9 (2005)
Chem. Thermodyn. of Solid Solutions	Vol. 10 (2007)
Chem. Thermodyn. of Thorium	Vol. 11 (2009)
Chem. Thermodyn. of Tin	Vol. 12 (2012)
Chem. Thermodyn. of Iron	coming soon

ABC-Salt, NEA-TDB, NEA-Salt Club

- Strong motivation to better coordinate efforts of (small) international community working on chemistry in salt brines (oceanic salt system, radionuclides, …).
- ABC-Salt workshops: (co-org. KIT-INE and LANL-CO) Int. forum for research on actinide and brine chemistry.

- OECD-NEA: well established frame to integrate joint activities on an international scale.
- Proposal (KIT-INE, LANL-CO) to NEA-TDB: State-of-Art-Report on Pitzer consistent thermodyn. data currently under preparation.
- Proposal (KIT-INE, LANL-CO) to NEA-Salt Club: Establish technical/scientific working group to develop joint international Pitzer TDB.

Summary

- ABC-Salt Workshops Series (co-organized KIT-INE and LANL-CO) established as int. forum for research on actinide and brine chemistry.
- Three successful workshops organized in 2010, 2011 and 2013.
- ABC-Salt Workshop resulted in several joint research activities.
- ABC-Salt (II) proceedings published via KIT scientific publishing; ABC-Salt (III) proceedings pending so far.
- ABC-Salt integrated NEA-Salt Club activity since 2013.
- ABC-Salt (IV) planned for May-April 2015 in Heidelberg, Germany.
- SOAR on Pitzer initiated within NEA-TDB frame.
- TSWG set up within NEA Salt Club to discuss joint int. Pitzer-TDB.

MICROBIAL EFFECTS ON SALT-BASED NUCLEAR WASTE REPOSITORY PERFORMANCE

Actinide Chemistry & Repository Science Program—
Los Alamos National Laboratory

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 17, 2013

LA-UR-13-27064

SUMMARY of YESTERDAY'S TALK

- Assumptions are made regarding microbial activity in salt-based repositories
- Assumptions do not always reflect reality, but reality must be established by site-specific research
- Even if the reality is that microbial influence is minimal, one can never say "never" to regulators or public; therefore, models must be appropriately conservative

MICROBIAL PROCESSES MOST IMPORTANT TO WIPP REPOSITORY PERFORMANCE (LLW)

- Gas generation from the consumption of organic waste components (cellulose, plastic, rubber) leading to pressure elevation and possible fracture
- Biocolloidal transport of actinides (dependent upon brine type, oxidation state, and element)

WHAT WILL THE GAS GENERATION RATES BE?

Long Answer:

To measure gas generation rates, we need to have actively growing organisms

If we get nothing to grow in the lab under repository relevant conditions, can we truly say that gas will not be generated?

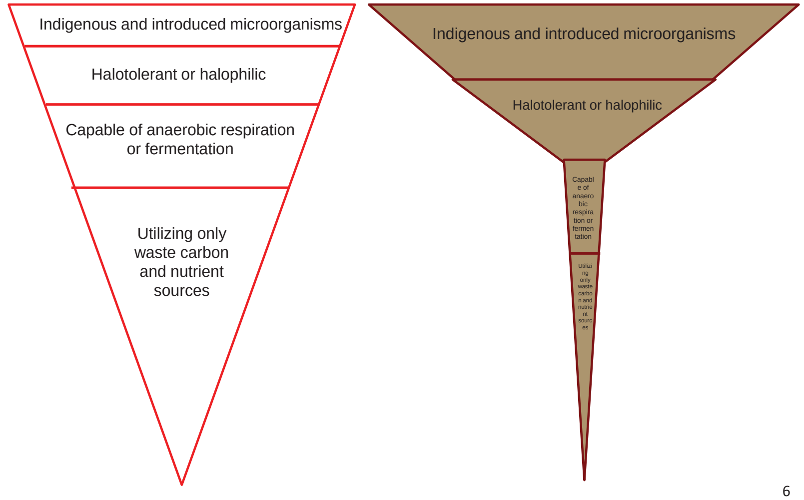
In the absence of gas generation data, microbial ecology studies are the best tool to infer likelihood of survival and activity

Rates will probably be a lot less than models predict

MICROBIAL GAS GENERATION

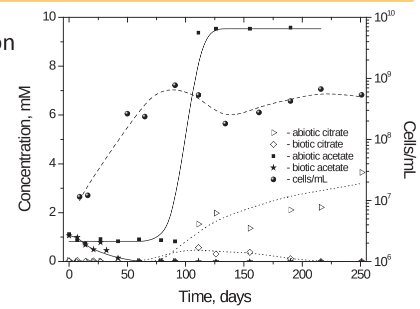
- Microbial gas generation results from microbial activity. Activity is dependent upon survival. Ability to survive in hypersaline systems narrows playing field to halophilic microorganisms.
- Activity of halophilic microorganisms depends upon suitable and available substrates, nutrients, and electron acceptors
- Known WIPP repository conditions are not optimal for extreme halophiles; research needed at other sites

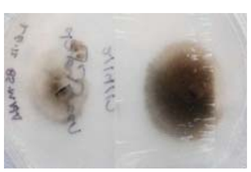
"NARROWING THE PLAYING FIELD"



BIODEGRADATION of ORGANIC WASTE COMPONENTS

- Degradability dependent upon availability of components
- Availability dependent upon solubility
  - Solubility-limited organics include rubber, plastic, cellulose, oxalate





No Kimwipe Kimwipe

- Degradability also dependent upon suitability as substrate
- Only one halophilic, anaerobic, cellulolytic organism detected thus far

BIOCOLLOID TRANSPORT

- "Uptake" = internalization or surface adsorption
- Model assumptions:
  - All cells associate with actinides
  - All cells are mobile
  - All cells are viable and growing optimally
- Reality:
  - Not all cells associate with actinides
  - Not all cells are motile
  - Repository conditions not optimal for growth
  - Extreme halophiles will lyse upon reaching lower ionic strength matrices

LINKING BIOSORPTION TO BIOMASS CONCENTRATION IN PERFORMANCE MODEL

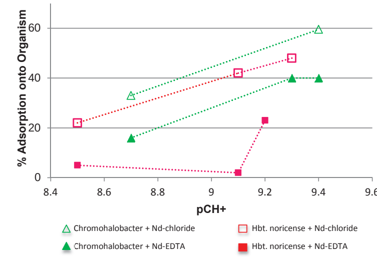
- Increased biomass → increased surface area → increased surface sorption

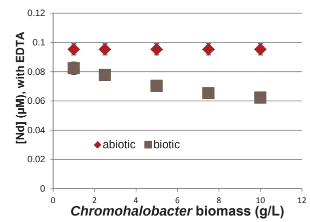
BUT

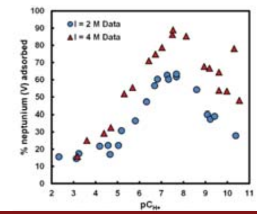
- Biomass concentrations level off
- High biomass CANNOT be maintained indefinitely
  - Substrate, nutrient, terminal electron acceptor depletion
  - Formation of toxic by-products, metabolites
- What is a reasonable biomass concentration to assume for the repository environment?

BIOCOLLOID TRANSPORT SUMMARY

- Sorption is dependent upon:
  - Organism type
  - Biomass concentration
  - pH
  - Matrix ionic strength
  - Actinide, oxidation state
  - Presence of complexing agents







MICROBIAL ISSUES IN HIGH-LEVEL WASTE REPOSITORIES

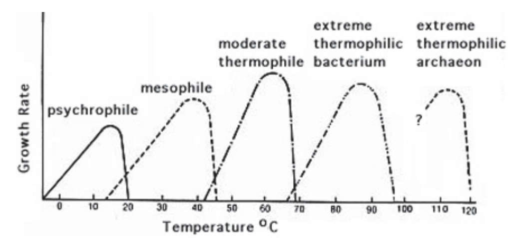
ARE THERE ANY?

Are microorganisms viable at the temperatures reached in high-level waste repositories?

Are microorganisms viable after exposure to the level of radioactivity in high-level waste repositories?

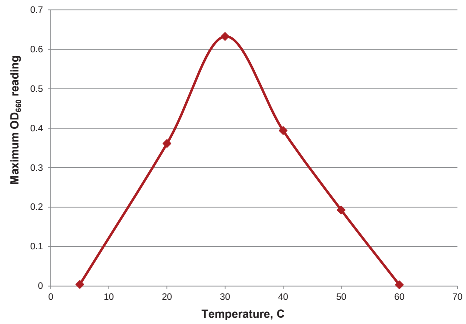
TEMPERATURE RESISTANCE

- Some studies have shown haloarchaeal adaptability to high temperatures over successive generations; maximum reported in literature is 61°C; DNA degrades at ~94° C
- Upper limit of life: 110°C (organism found in geothermal vent at sea bed)
- Indigenous haloarchaea not likely to survive at T > 60°C, but can they recover?



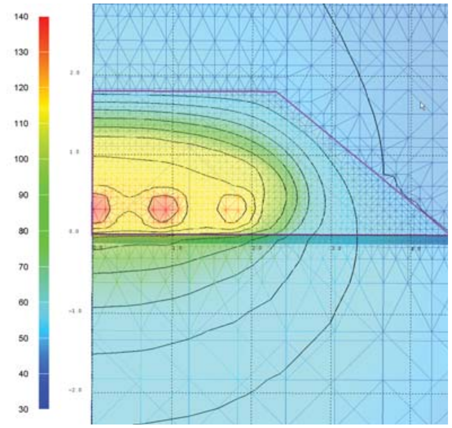
WIPP Isolate: *Halobacterium noricense*

- Enriched at ambient temperature; therefore, lower optimum expected
- Did not recover viability after incubation at 60°C



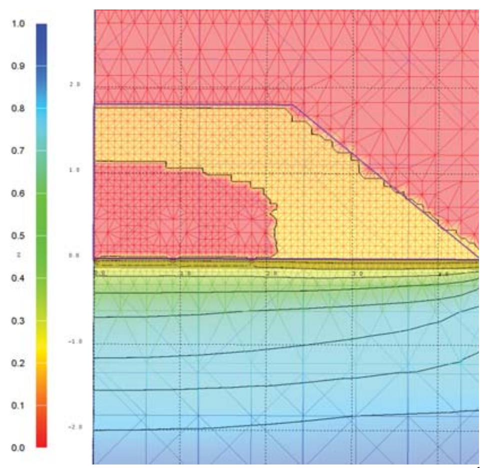
EXPECTED TEMPERATURE PROFILE

- In preparation for Salt Defense Disposal Investigations in-drift test at WIPP
- Numerical simulation of HLW in salt; 750W heaters
- Organisms not viable within 1 m of containers, due to T, but may be viable beyond that



EXPECTED SATURATION PROFILE

- Migration of organism-containing fluid and dissolution of organism-containing halite toward heat source
- May extend boundary of non-viable organisms to 2 m



RADIATION RESISTANCE

- Haloarchaea possess many resistance mechanisms:
  - Carotenoid pigmentation
  - Bias against amino acids prone to ROS
  - High Mn/Fe ratios inside cells
  - Redundancy of genes encoding antioxidants
  - Polyploidy (more than 10 copies of the genome)
  - Ability to differentially regulate genes needed for ROS repair functions
- Salt/brine halides confer resistance by acting as scavengers of free radicals
- *Halobacterium salinarum* is resistant to 5 kGy; mutant exists that is resistant to 7.5 kGy (most resistant organism on earth)

MICROBIAL RESISTANCE TO RADIATION

- What will levels of radiation and ROS be?
- Haloarchaea may be better equipped to adapt to increased radiation than heat
- Further research is needed

ACKNOWLEDGMENTS

- Microbial work is sponsored by the US Department of Energy—Carlsbad Field Office
- HLW simulations provided by Phil Stauffer of Los Alamos National Laboratory Earth & Environmental Sciences Division/ Computational Earth Sciences Group as part of the Salt Defense Disposal Investigations, funded by US DOE's Office of Environmental Management

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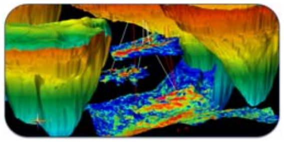

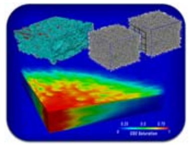

Implications of Microbiology for the WIPP

Christi D. Leigh, Ph.D.
Sandia National Laboratories

Presentation at Salt Club Meeting
Berlin Germany
September 16, 2013

U.S. DEPARTMENT OF ENERGY NNSA

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Gas Generation in the WIPP

Anoxic corrosion of Fe- and Al-base metals
- Steel waste containers and steels and other Fe-base metals in the waste
- Will produce H_2; could consume H_2O initially and release it later

Possible microbial consumption of cellulosic, plastic, and rubber (CPR) materials
- Could produce CO_2, H_2S, N_2, and CH_4; effect on H_2O budget is unclear

Alpha radiolysis of H_2O in brine, and of CPR materials
- Will produce H_2, O_2, other gases; and consume H_2O

Relative importance of these processes from the standpoint of gas generation:
- Corrosion ≅ microbial activity >> radiolysis

Requirements for Microbial Activity in WIPP

Halophilic or halotolerant microbes present when repository filled and sealed

Halophilic or halotolerant microbes survive for a significant fraction of the 10,000-year regulatory period

Sufficient H_2O present in brine in the repository and available to microbes

Sufficient electron acceptors present and available

Sufficient nutrients present and available

Microbes in the WIPP?

Halophiles present in the WIPP

Possible sources of these microbes
- Salt lakes in Nash Draw
  - Transport to the excavated areas via wind, the Air Intake Shaft, and the mine ventilation system
- Soils near the WIPP Site
  - Same transport mechanisms
- Salado Formation (Permian microbes)?
  - Viable Permian microbes reported by Vreeland et al. (2000). See also Parkes (2000)
  - Permian microbes still controversial (e.g., Hazen and Roedder, 2001; Vreeland et al., 2000)
  - Permian microbes (if present) not an issue for PA

Probability of Microbial Activity in WIPP

Probability of microbial gas generation implemented by the U.S. DOE's WIPP Project

- Significant microbial activity possible, but by no means certain
- Used in the 1996 CCA PA, 1997 PAVT, and CRA-2004 PA
- Certified by the U.S. EPA in 1998

Probability specified by the U.S. EPA for the CRA-2004 PABC and subsequent PAs

- Microbial activity is certain, but may not be significant because of the use of a sampled "effectiveness factor" (and lower gas-production rates) in PA

5

Implementation in WIPP PA

Conceptual model

- Sequential use of electron acceptors
- Potentially significant respiratory pathways
  - Denitrification
  - SO_4^{2-} reduction
  - Methanogenesis
- Insignificant respiratory pathways
  - Aerobic
  - Fe(III) reduction
  - Mn(IV) reduction

Rates

- Microbial activity produces gas at rates measured in long-term lab studies

6

Implementation in WIPP PA (cont.)

Reactions for potentially significant microbial respiratory pathways

- Denitrification
  - $C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2$
  - CO_2 yield = 1 mol per mol of organic C consumed
- SO_4^{2-} reduction
  - $C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S$
  - CO_2 yield = 1 mol per mol of organic C consumed
- Methanogenesis
  - $C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$
  - CO_2 yield = 0.5 mol per mol of C consumed

7

Laboratory Studies

Mid-late 1970s

- M. A. Molecke, SNL, Principal Investigator (PI)
- Carried out by investigators at the University of New Mexico
- Supported the development of the WIPP Waste Acceptance Criteria

1988-2003

- L. H. Brush and Y. Wang, both SNL, PIs
- Carried out by investigators at Stanford University and Brookhaven National Laboratory
- Used short-term experiments (a few years long) to establish parameters for the WIPP CCA PA and long-term experiments (≈10 years long) to establish less conservative parameters

8

Laboratory Studies (cont.)

Current

- Julie Swanson, LANL – CO, PI
- Experiments underway in Carlsbad, NM, to reduce conservatism

9

Use of MgO in the WIPP

Functions as the WIPP engineered barrier by consuming essentially all CO_2 that could be produced by microbial activity, thereby decreasing actinide solubilities

- Will prevent acidification of brine that would result if microbes consumed significant quantities of cellulosic, plastic, and rubber materials during the 10,000-year regulatory period
- Will limit the extent of complexation of actinide elements by CO_3^{2-}
- Will buffer the pH at mildly basic values

Consumption of significant quantities of H_2O by MgO (and other materials) could also affect long-term performance

10

Geochemical Role of MgO in the WIPP

Reaction that will buffer f_{CO_2} initially

- $5Mg(OH)_2 + 4CO_2(aq\ or\ gas) \rightleftharpoons Mg_5(CO_3)_4(OH)_2 \bullet 4H_2O$
  - Hydromagnesite (5424) is metastable with respect to magnesite, but could persist for hundreds to thousands of years
  - The EPA has specified that the brucite-hydromagnesite carbonations reaction be used to calculate f_{CO_2} for actinide solubility calculations

Possible long-term f_{CO_2} buffer reaction

- $Mg(OH)_2 + CO_2(aq\ or\ gas) \rightleftharpoons MgCO_3 + H_2O(aq\ or\ gas)$
  - Magnesite is stable with respect to hydromagnesite (5424), and is present in the Salado

Reaction that will buffer pH

- $Mg(OH)_2 \rightleftharpoons Mg^{2+} + 2OH^-$

11

Predictions of Near-Field Conditions[A]

$f_{CO_2} \cong 3.14 \times 10^{-6}$ atm (for both GWB and ERDA-6)

- TIC $\cong 3.79 \times 10^{-4}$ M (GWB) or 4.55×10^{-4} M (ERDA-6)

Very low f_{O_2} (at or even below the lower stability limit of H_2O on an Eh-pH diagram)

- H_2O unstable in the WIPP (reduced to H_2 by steels and other Fe-base metals, Al, and Pb

A. Predicted for the minimum volume of brine required for a release from the repository to the surface. Compositions for larger volumes not shown

12

Predictions of Near-Field Conditions (cont.)[A]

Brine pH

- Pitzer pH = 8.82 (GWB) or 8.99 (ERDA-6)
  - The Pitzer scale is an unofficial pH scale consistent with pH values calculated using single-ion activity coefficients based on the Pitzer activity-coefficient model and the Harvie-Møller-Weare (HMW) database (DB) for brines and evaporite minerals, extended to include Nd(III), Am(III), Cm(III), Th(IV), and Np(V).
  - T. J. Wolery of Lawrence Livermore National Laboratory in Livermore, CA, proposed the term "Pitzer scale" unofficially.

Brine pcH

- pcH = 9.54 (GWB) or 9.69 (ERDA-6)

A. Predicted for the minimum volume of brine required for a release from the repository to the surface. Compositions for larger volumes not shown

13

Effects of Microbial Activity on WIPP PA

H_2 from anoxic corrosion of Fe- and Al-base metals

- Will pressurize the repository to ≥ 8 MPa (hydrostatic pressure) in many PA vectors, which will result in direct brine releases (DBRs) of radionuclides to the surface
- Will pressurize the repository to ≈ 15 MPa (lithostatic pressure in some vectors
  - Fracturing in the near field will limit pressurization to 15 MPa
  - Fracturing will be limited in extent and does not affect PA

Microbially generated gases will not affect repository pressure

- CO_2 will be consumed by MgO
- H_2S will be consumed by reactions with steel waste containers and steels and other Fe-base metals in the waste

14

Effects of Microbial Activity on PA (cont.)

Microbially generated gases will not increase actinide solubilities

- MgO will consume essentially all CO_2 and establish conditions favorable for actinide solubilities
- Microbial colloids could enhance actinide concentrations to some extent

Microbes will reductively immobilize actinides

Microbial activity will not affect the near-field region of a repository for spent fuel or HLW

- Microbes could reductively immobilize actinides in the far-field of a repository for spent fuel or HLW

15

Status of the US-German Joint Project Comparison of Current Constitutive Models for Rock Salt – Part 2 –

Andreas Hampel
Scientific Consultant, Grünberger Str. 56, 55129 Mainz, Germany

Abstract

Joint Project III on the Comparison of Constitutive Models for Rock Salt started in October 2010 as a collaboration of the following partners:

- Dr. Andreas Hampel (AH), 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 (LUH-IUB), Germany
- Technische Universität Braunschweig (TUBS), Germany
- Sandia National Laboratories (SNL), Albuquerque, New Mexico, USA.

This project focuses on comparisons of the modeling of the temperature influence on deformation and of the sealing and healing of damaged and dilatant rock salt. The latter work is currently in progress and subject of this part 2 of the status report.

The benchmarking study on sealing and healing comprises all phenomena that result from the elastic closure of open microcracks up to the re-establishment of the chemical bonding along microcrack surfaces, i.e. the reduction of damage, dilatancy and permeability, the re-establishment of tightness and the restoration of mechanical strength. In the constitutive models of the partners, the modeling of these effects is based on a description of the healing rate as function of the current dilatancy and the stress state. Differences occur in the assumption of a healing boundary. Two laboratory tests of the TUC on healing with high-precision dilatancy measurements show that even above the dilatancy boundary the volumetric strain starts to decrease as soon as the deviatoric stress is reduced. This indicates that the reduction of damage and dilatancy can take place at all stress states – contrary to their generation and growth.

Like the benchmarking effort on the temperature influence, this second project phase again comprises the performance and back-calculation of specific laboratory tests as well as simulations of a selected in-situ structure. Back-calculations of many different lab tests with one unique salt-type dependent set of parameter values are an important and crucial test of the constitutive models, since in the laboratory the various deformation phenomena and their dependencies on different influences are investigated under well-defined and controlled boundary conditions. Therefore, back-calculations of the healing tests have to be performed with the same parameter values like various creep and strength tests with the same salt type.

The modeling of sealing and healing in a real underground situation 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 partners are currently performing different simulations: 1) open drift, 2) drift with bulkhead: 2a) no healing assumed, 2b) healing assumed. First results demonstrate that the considered models are able to describe the sealing and healing of damaged and dilatant rock salt in the disturbed rock zone (DRZ). This is essential for calculations of the plugging and sealing of underground chambers, drifts, and shafts.

4[th] US-German Workshop
on Salt Repository Research, Design and Operation

Berlin, Germany – September 17-18, 2013

Status of the US-German Joint Project on the "Comparison of Current Constitutive Models for Rock Salt" - Part 2 -

Dr. Andreas Hampel

Sponsored by Federal Ministry of Economics and Technology (BMWI)

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

Dr. Andreas Hampel · Sandia National Laboratories · IfG Institut für Gebirgsmechanik GmbH Leipzig · Leibniz Universität Hannover · KIT · TU Clausthal · Technische Universität Braunschweig

Managed by PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology

Benchmark II (work in progress): Comparison of the Modeling of "Healing"

"Healing" of damaged rock salt around underground openings (DRZ)

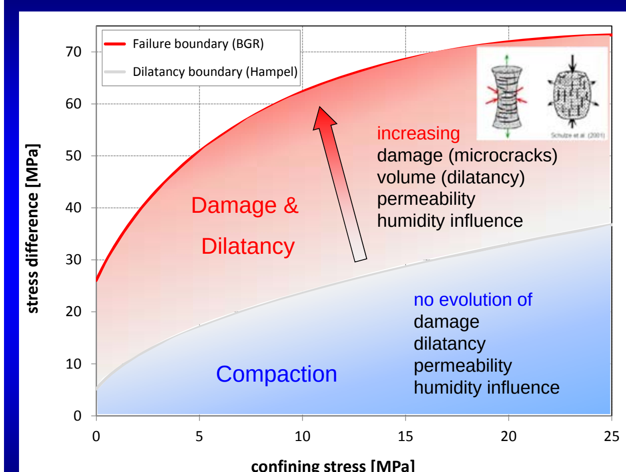
Physical phenomena:

- (elastic) closure of open microcracks
- re-establishment of chemical bonding

=> to be modeled:

- reduction of damage & dilatancy (volumetric strains)
- reduction of permeability, re-establishment of tightness
- restoration of mechanical strength

Dilatancy Boundary Concept → Healing?



Modeling:

$\dot{\varepsilon}_{hl} = f(\varepsilon_{vol}, \Delta\sigma, \sigma_{min})$

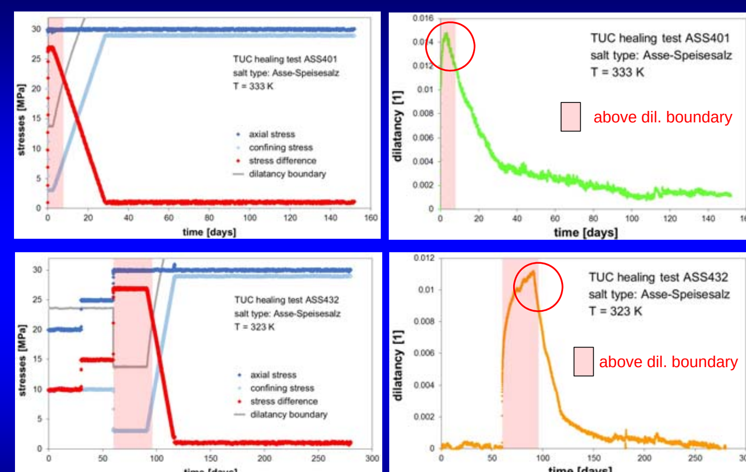
healing boundary?

increasing healing
⇓
decreasing damage dilatancy permeability humidity influence

High-Precision Laboratory Healing Tests (TU Clausthal)

1)

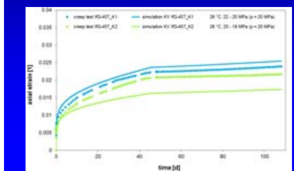
2)



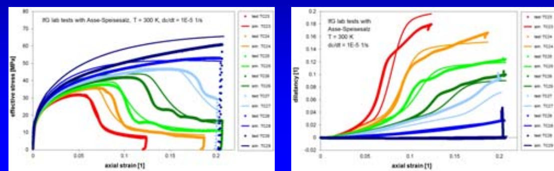
Δσ↓ => dilatancy reduction starts above the dilatancy boundary !

Model Adjustments to Laboratory Creep & Strength Test Data with one Salt Type

1. Check the ability of the models to describe the relevant deformation phenomena & dependencies.
2. Determine a unique salt-type-specific set of parameter values for a constitutive model.

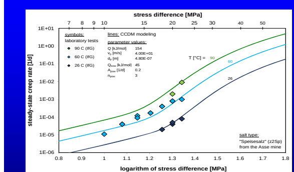


transient creep



evolution of damage, dilatancy, failure, post-failure behavior, residual strength

for 3 different temperatures !

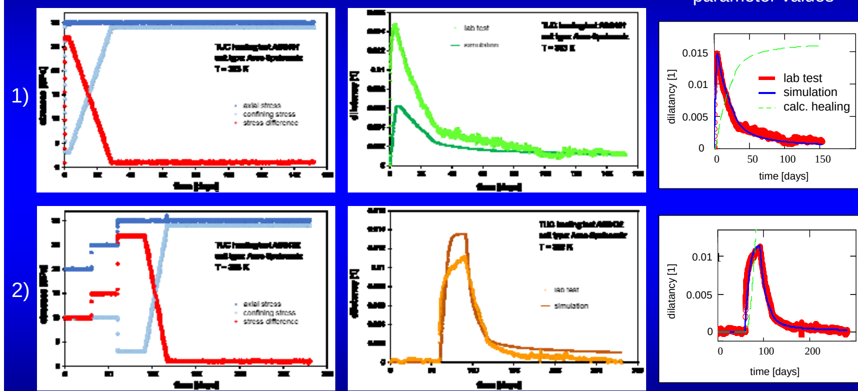


steady-state creep

Back-calculations of Hampel (model: CCDM, salt type: Asse-Speisesalz)

Back-Calculation of Laboratory Healing Tests

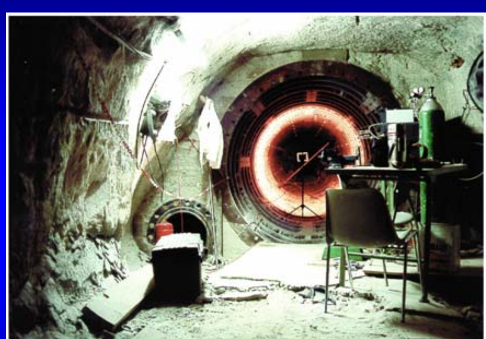
applied stresses | dilatancy calculated with unique set of parameter values | dilatancy calculated with individual parameter values

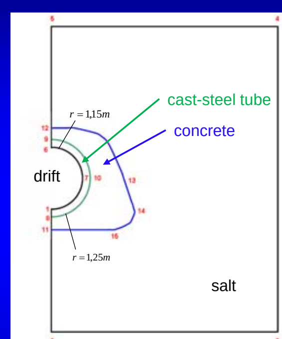


Back-calculations of Hampel (model: CCDM, salt type: Asse-Speisesalz)

"Dammjoch" (bulkhead) in a drift at 700 m depth in the Asse Mine

1911: drift excavated, 1914: 25 m long section lined





drift size: h_{max} = 2.75 m, w_{max} = 3.80 m

cast-steel tube: $Ø_{in}$ = 2.30 m, wall thickness = 10 cm

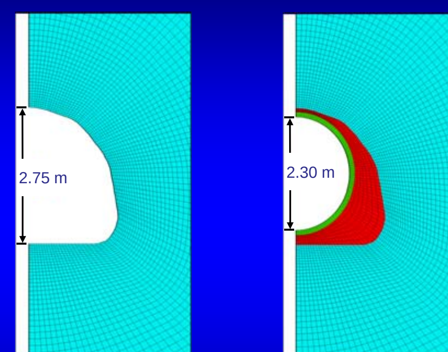
residual gap: concrete

total model size (h x w x d)
100 m x 50 m x 0.05 m

Simulations of the "Dammjoch" (Bulkhead) Model

depth: 700 m

initial stress: 15 MPa



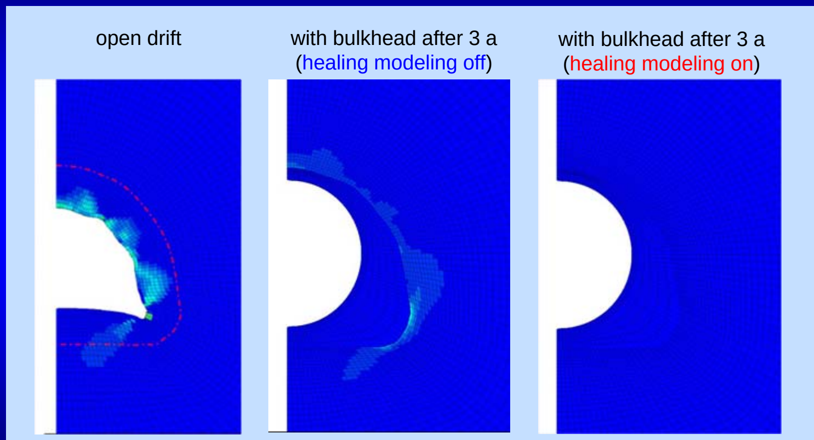
rock salt
concrete
cast-steel tube

Simulation 1:
0 ... 88 a: open drift

Simulation 2:
0 ... 3 a: open drift
3 ... 88 a: drift with bulkhead

Calculation of Dilatancy (LUH-IUB)

88 years after drift excavation



Summary

Current US-German Joint Project on the Comparison of Constitutive Models for Rock Salt

Part 2: Modeling of healing of damaged & dilatant rock salt

Investigation: High-precision laboratory healing tests (TU Clausthal)

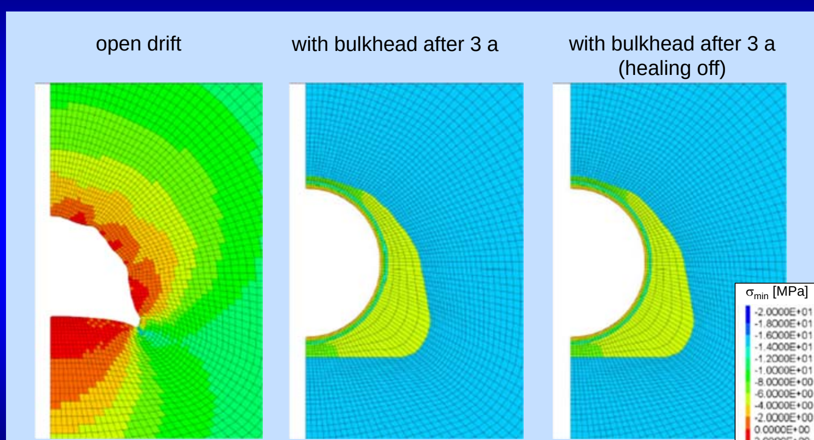
Benchmarking:

1. Back-calculations of laboratory healing tests with a unique set of parameter values
2. Simulations of the "Dammjoch" (bulkhead) in the Asse Mine 1) open drift, 2) drift with bulkhead after 3 years

→ Considered constitutive models are appropriate to model reliably the temperature influence on the deformation and healing of rock salt.

Calculation of Minimum Principal Stress (LUH-IUB)

88 years after drift excavation



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

Exceptional service in the national interest

Sandia National Laboratories

Status of the US-German Joint Project on "The Comparison of Current Constitutive Models . . ."

J. Guadalupe Argüello

4th US/German Workshop on Salt Repository Research, Design and Operations

Berlin, Germany September 2013

Sandia National Laboratories

DBE TEC DBE TECHNOLOGY GmbH

PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology

U.S. DEPARTMENT OF ENERGY NNSA

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US-German Joint Project III Partners

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)	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

Review of Scope & Objectives

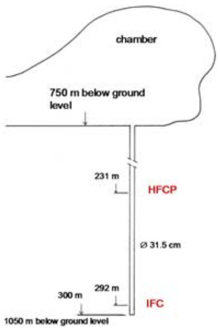
- To provide a basis for scientific collaboration in the documentation, check, and comparison of the advanced geomechanical constitutive models of the partners and of their procedures for the determination of salt-type-specific parameter values and for the performance of numerical simulations.
- The general aim of the project is to check the ability of the models to describe correctly the relevant deformation phenomena in rock salt under various influences, and thus to increase confidence in the results of numerical simulations and enhance the acceptance of the results.
- Another aim is to demonstrate possibilities for the further development and improvement of the models.

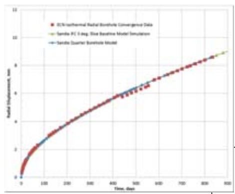
Efforts to date

- This US-German Joint Project III on the 3D benchmarking of advanced rock salt models is in its third year
- First benchmark problem related to the modeling of the temperature influence on the deformation of salt has been completed
  - Back-calculations of various lab tests at different temperatures
  - Simulations of two in-situ borehole tests conducted at the Asse Mine, (Germany)
    - the Isothermal Free Converge (IFC) test
    - the Heated Free Convergence Probe (HFCP) test
- Work is currently underway on a second benchmarking problem which is related to the modeling of healing of damaged rock salt
  - Back-calculations of lab tests on healing
  - Simulation of the in-situ "Dammjoch" (bulkhead) structure, also at the Asse Mine

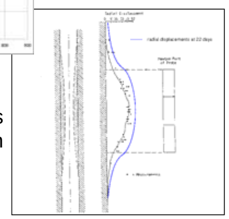
Initial Results from JPIII Presented

- Results from IFC and HFCP Joint Project efforts presented to a wider audience at the ARMA 47th U.S. Rock Mechanics / Geomechanics Symposium, June 2013 (at 3rd US-German Workshop to this group)





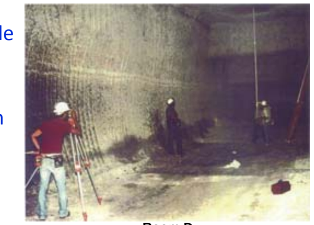
Sandia Results for IFC Problem



Sandia Results for HFCP Problem

Future Efforts for JPIII

- “Joint Project” recently extended to include two additional benchmarking problems based on in-situ full-scale tests conducted in the early 1980’s at the Waste Isolation Pilot Plant (WIPP), located in Southeastern New Mexico, USA
  - The isothermal Mining Development Test – WIPP Room D
  - The heated Overtest for Simulated Defense High-Level Waste – WIPP Room B
- Work on WIPP salt (lab tests and Rooms D & B) is again related to temperature dependence and is thus an extension of the first benchmarking problem
  - Larger rooms
  - Quadrilateral cross-section
  - More importance of damage (at least at corners and possibly roof)
  - At different temperatures than in IFC & HFCP tests

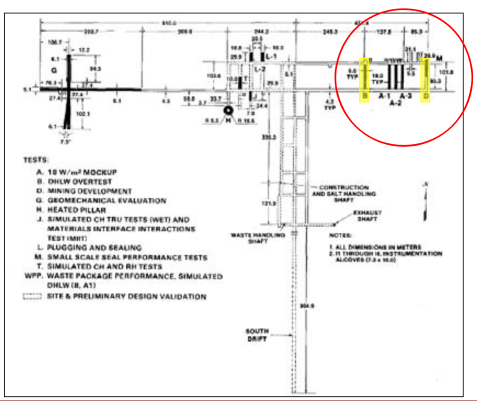


Room D

Room B

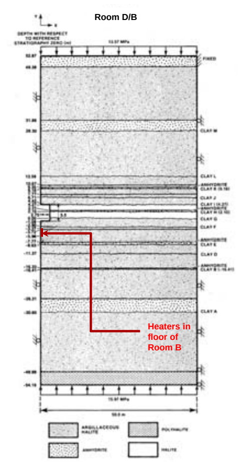
WIPP Experiments of Early 80’s

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



Experimental WIPP Rooms D & B are of special interest & well-suited for benchmarking

Why are WIPP Rooms D & B Well-Suited 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 for benchmarking efforts

Supplementary Laboratory Testing of WIPP Salt

- During the 3rd US-German workshop, German participants indicated their need for laboratory tests of WIPP salt to
  - Perform back-calculations of the various lab tests with different boundary conditions, to demonstrate the ability of the models to describe the different phenomena and their dependencies under different and well-controlled conditions
  - help parameterize their constitutive models to support the WIPP Rooms D & B benchmarking effort
- At that time three participants made requests for WIPP salt core for laboratory testing
- In late 2012, a first shipment of 4” WIPP salt core (both clean and argillaceous), from existing inventory, was sent to TUC, TUBS, and BGR
- A second large shipment of 12” clean salt core was sent to IfG in March 2013 (along with seven 5-gallon buckets of unsieved, run-of-mine crushed salt that went to BGR)
- Another shipment of 12” argillaceous salt core was sent to IfG in June 2013
- A final shipment of 4” core acquired through MB 139 to go to BGR

WIPP Salt Shipment

March 2013 Salt Shipment
(CCW from top-left)

- Packed core samples on pallet
- 12” clean salt core
- Run-of-mine crushed salt (this photo shows a sieved sample – material sent was unsieved)

Status of Thermo-mechanical Laboratory Tests on WIPP-salt

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Abstract

In the frame work of the Joint Project on the Comparison of Constitutive Models for the Thermo-Mechanical Behaviour of Rock Salt (Part 3) benchmark calculations are planned for the WIPP-site, simulating the in situ-tests performed in room D and B. Although a comprehensive mechanical data base for WIPP-salt already exists from investigations in the 80 - 90's, due to the development of existing and new material laws tailored test series facilitating the derivation of specific material parameters are missing. Thus a comprehensive laboratory test plan for WIPP-salt has been developed, which is described below. In the scope of work the tests are not only designed to derive material-law specific parameters but also to act itself as a base to perform benchmark calculations.

As a bedded salt repository, the idealized stratigraphy for the WIPP underground is composed of mainly argillaceous salt with a clean salt layer above the disposal room between Clay G and Clay I, anhydrite MB 139, and a thin anhydrite layer located in the clean salt layer, identified as anhydrite A. Thus, the main focus was on argillaceous salt and, subsequent, clean salt. As a representative material suite 60 12''-diameter cores (□ □ 30.48 cm, length: 0.6 m; weight: 90 kg) were sampled at the WIPP site, i.e. 5.5 t, and delivered to IfG in three shipments. The preparation of the cylindrical samples (□ = 100 mm x l = 200 mm respectively 40 mm x 80 mm) is a special task of IfG.

Laboratory studies allow generic or site-specific salt properties (mechanical, thermal and transport) to be measured in a controlled environment of loading and material conditions. A specific request, therefore, is to conduct a suite of triaxial strength tests on intact salt comprising a triplet of triaxial strength test series (at □3 = 0.2, 0.5, 1.0, 2.0, 3.0, 5.0 and 20 MPa) with a standard deformation rate of 10-5 1/s at each of three temperatures: 27°C, 60°C, 100°C) and, in addition, with two different deformation rates (10-4 1/s, 10-6 1/s) at 27°C, all with simultaneous measurements of dilatancy. In addition, a series of creep tests will be performed at loading conditions in the non-dilatant stress zone for a wide range of differential stresses.

The investigation program consists, at least, of 109 strength and 37 creep tests, which are under execution in close cooperation between the rock mechanical labs of IfG and TUC:

- The material represents excellent test conditions, i.e. undisturbed / intact salt.
- Strength testing on „Clean salt" is nearly finished.
- Creeps tests are started (preliminary test results are available).
- In the clean salt the humidity content (ca. 0.15 wt.-%) is only slightly higher than in domal salt.

The remaining test-time for strength and creep tests (without special healing tests) is estimated to be 6 to 9 month. Data sets from Asse salt are available for comparison.

Status of Laboratory Tests on WIPP-salt

In the Joint Project III: Comparison of Constitutive Models

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Outline

- Motivation / Background
  - Objectives of the tests
  - Test program / matrix
  - Sampling / Sample preparation
- Lab investigations - approach / results
  - Creep test results
  - Triaxial strength testing
  - Humidity content
- Summary

Sandia National Laboratories

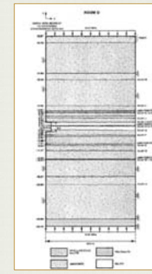
Objective

- Benchmark calculations of Room B and Room D
- ☺ A comprehensive data base for WIPP-salt exists from investigations in the 80 - 90's , but
- ☹ due to the development of existing and new material laws tailored test series facilitating specific material parameters are missing

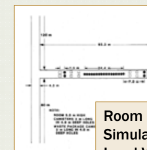
e.g. Günther-Salzer :

General Creep Parameters			
• Stess Exponent			
for undamaged rock salt:		np0	= 19.6
parameter for stress dependency		np1	= 0.8
		np2	= -0.22
parameter for damage dependency		np4	= 0.3
• Creep Factor		A_DVA	= 2.5E-14 [d⁻¹]
Creep Factor for σ_eff=0		A_DVA0	= 1.25E-21 [d⁻¹]
Parameter for stress dependency		mAp	=0,7
Activision Enegry		act_Ap	= 140 [kJ/mol]
• Hardening Parameter		mu	= 5.25
Steady State Cpeep Parameters			
• Term 1 - hardening driven recovery:	Recovery Time	t0	= 2,8 [d]
	Activision Enegry	act_t0	= 10 [kJ/mol]
• Term 2 - stress driven recovery :	Creep Factor	As_1	= 2E-4 [d⁻¹]
	Stress Exponent	ms_1	= 6,9
	Activision Enegry	act_1	= 54 [kJ/mol]
• Term 3 - high temperature creep	Creep Factor	As_2	= 1e5 [d⁻¹]
	Stress Exponent	ms_2	= 7,42
	Activision Enegry	act_2	= 120 [kJ/mol]

Dilatancy Boundary	md1 = 21	md2 = 2	md3 = 1.7
Dilatancy Damage Parameters	b1 = -0,03	b2 = 0,049	b3 = -0,058
	b4 = 3E-5	b5 = 5E-4	b6 = -15
	b7 = 0,3	b8 = 4,5	b9 = -0,27



Room D – Mining Development Test

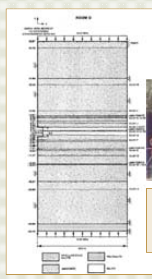


Room B – Overtest for Simulated Defense High-Level Waste

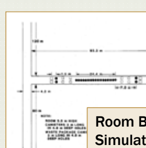
Objective

- Benchmark calculations of Room B and Room D
- ☺ A comprehensive data base for WIPP-salt exists from investigations in the 80 - 90's , but
- ☹ due to the development of existing and new material laws tailored test series facilitating specific material parameters are missing

- Geomechanical characterization of the WIPP-rock salt :
  - "clean salt" or "Halite"
  - "argillaceous salt"
  - Temperature effect
- ➔ Strength testing
- ➔ Creep tests

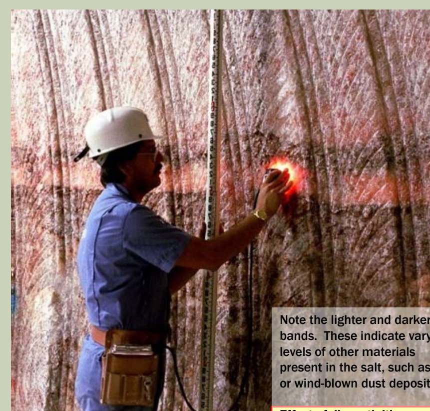


Room D – Mining Development Test



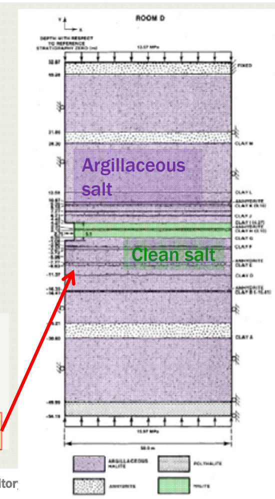
Room B – Overtest for Simulated Defense High-Level Waste

Lithology: „Clean salt" – „Argillaceous salt"



Note the lighter and darker bands. These indicate varying levels of other materials present in the salt, such as clay or wind-blown dust deposited

Effect of discontiuities, not considered up to now!



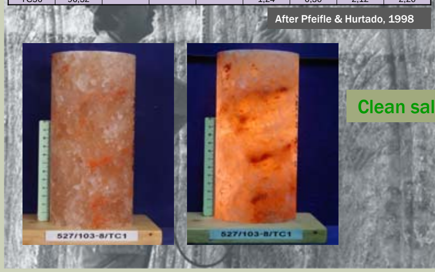
Argillaceous salt

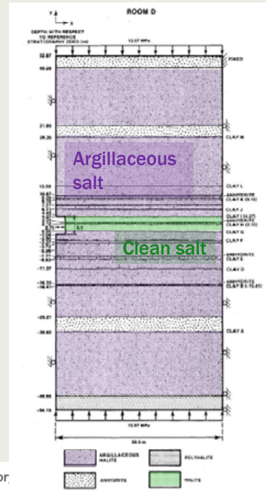
Clean salt

Lithology: „Clean salt“ – „Argillaceous salt“

Sample	Compound (Weight Percent)							Porosity ∅ (percent)
	Halite	Polyhalite	Kaolinite Clay	Illite Clay	Anhydrite	Quartz	Magnesite	
TC49	92,24	5,73	2,02	-	-	-	-	0,93
TC50	96,98	3,01	-	-	-	-	-	0,37
TC51	95,57	4,42	-	-	-	-	-	0,62
TC52	92,04	5,22	2,15	-	0,56	-	-	1,44
TC53	99,34	-	-	-	0,65	-	-	1,15
TC54	93,37	-	-	2,89	0,57	0,17	2,98	2,93
TC55	92,80	-	-	3,68	0,52	-	2,98	3,22
TC56	96,32	-	-	-	1,24	0,30	2,12	2,20

After Pfeifle & Hurtado, 1998





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Investigation program

Strength testing

T	Eps-rate	σ3 (MPa)							Σ CS - IfG	Σ AS - TUC
27°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7	14
60°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7	14
100°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7	14
27°C	10^{-4} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7	14
27°C	10^{-6} 1/s	0,2	-	1,0	2,0	-	5,0	20,0	5	5
Σ Standard tests									33	61
Optional tests										
?°C	? 1/s	?	?	?	?	?	?	?	7	8
Σ all									40	69

- 109 strength tests
  - ➔ ca. 150 test days (30 weeks)
- 37 creep tests
  - ➔ ca. 5000 test days

☺ Close cooperation between TUC and IfG (division of tasks)

☹ At least 6 to 9 month are required for complete testing

Creep testing

σ_3 MPa	σ_{eq} MPa	T °C	load level -	duration d	loading / unloading	above/below dilation strength	quantity pure salt	quantity clay salt	lab -
20	>10	27	2	60/60	L/U	b/b	2	3	IfG
20	>10	60	2	60/60	L/U	b/b	5	5	IfG
20	>10	80	2	60/60	L/U	b/b	1	2	IfG
20	<10	60	1	120	L	b	2	2	IfG
20		27/60/80	3	60/60/60	L/L/L	b	1	2	TUC
5	>35	27	1		L	a	1	0	TUC
different	different	27	4	60/60/30/30	L/L/L/L	b/b/a/a	2	3	TUC
?	?	?	?	?	?	?	3	3	IfG / TUC
							Σ = 17	Σ = 20	

L/U Load/unloading
L/L/L Multi-step testing
L Single step

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Drilling and wrapping of cores at WIPP - site

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Shipment – 3 Deliveries

March 2013	⇒ 18. April 2013	- clean salt	(~ 12,2 m)
June 2013	⇒ 09. June 2013	- arg. salt	(~ 12,3 m)
August 2013	⇒ 22. August 2013	- arg. salt	(~ 12,1 m)

60x 12” WIPP salt cores

∅ ≈ 30,48 cm
L ≈ 0,60 m
W ≈ 90 kg

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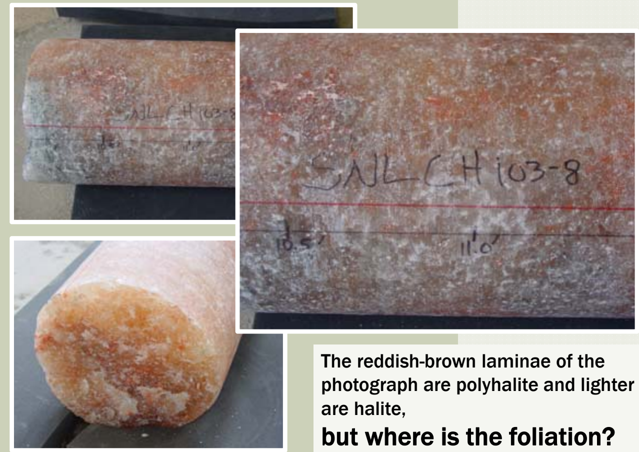
opened package of cardboard tubes

Core piece SNL CH 103-8 – clean salt



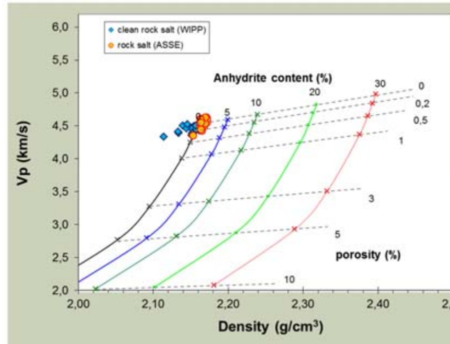
The reddish-brown laminae of the photograph are polyhalite and lighter beds are halite,

but where is the foliation?

Preparation of a test specimen on a lathe

Ca. 150 cylindrical samples will be prepared at IfG

Petro-physical characterization



VELOCITY-POROSITY RELATIONSHIP

after Wyllie et al., 1956

$$\frac{1}{v_p} = \frac{\phi}{v_f} + \frac{1-\phi}{v_m}$$

Pore space: air

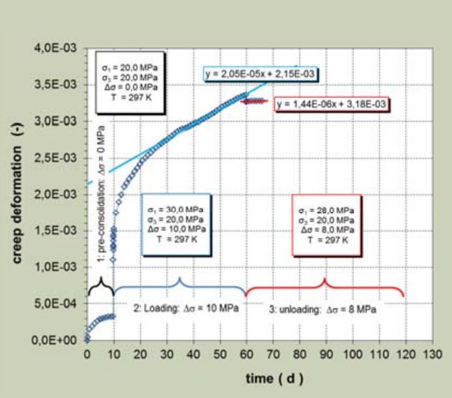
Matrix: halite (2,16 g/cm³) + Anhydrite (2,96 g/cm³)

v_p- air (km/s) =	0,33
v_p- anydrite (km/s) =	6,05
v_p- halite (km/s) =	4,52

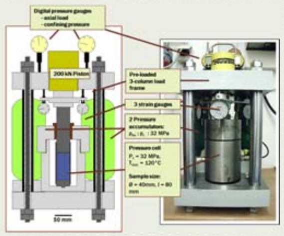
- Very pure salt, both CS and Asse salt:
  - $\rho_{WIPP-CS} \leq \rho_{Asse\ salt}$
  - The amount of impurities is very low
  - Initial porosity is low, i.e. undisturbed salt

Excellent material!

Multi-stage - Creep testing: T = 27°C

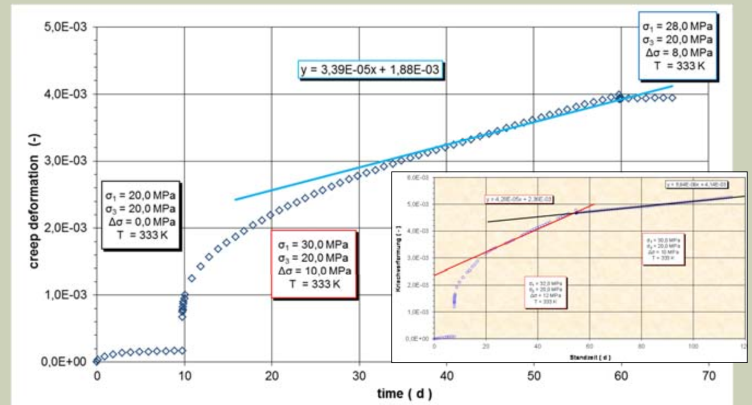


New IfG creep test rig



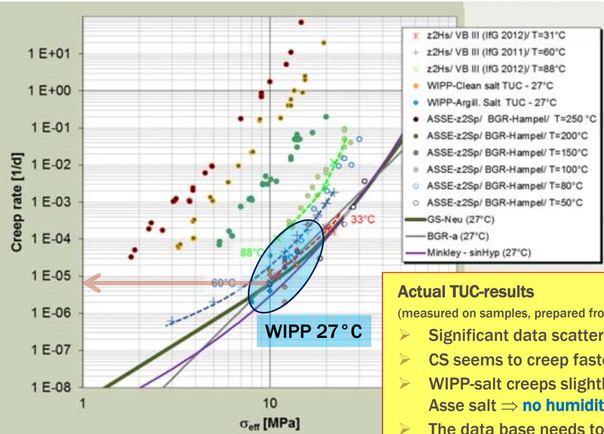
- Hydraulic stress control
  - No electrical power supply
  - Long term stability due to pressure accumulators
  - More flexibility during stress changes

Preliminary comparison WIPP-CS vs. Asse salt: T = 60°C



- The creep of WIPP CS seems to be slightly higher than Asse salt ....

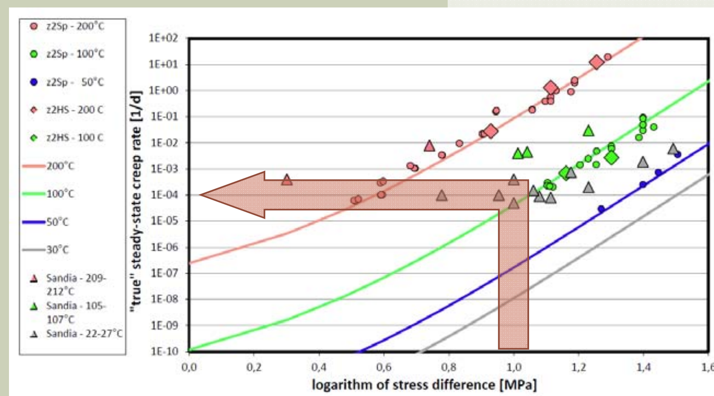
Creep properties: WIPP-Salt vs. Asse salt



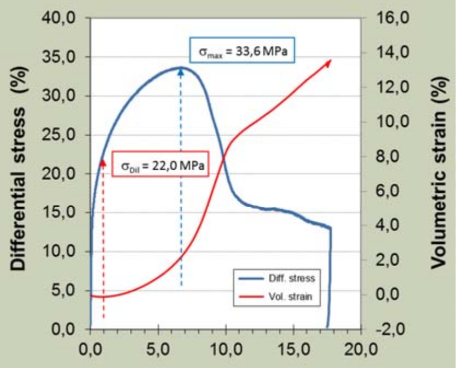
Actual TUC-results
(measured on samples, prepared from small cores)

- Significant data scattering
- CS seems to creep faster than AS
- WIPP-salt creeps slightly faster than Asse salt ⇒ **no humidity effect?**
- The data base needs to be extended

Comparison SANDIA Creep Tests vs. Asse Creep Tests



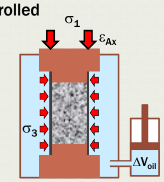
Standard strength testing



$\dot{\varepsilon}$ = $1 \cdot 10^{-5}$ 1/s
σ_3 = 1 MPa
T = 27°C

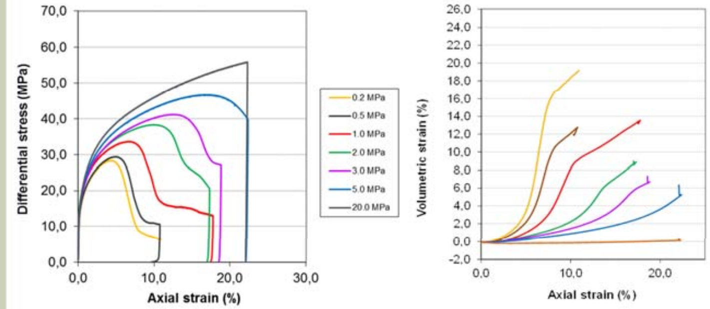
Axial strain (%)

Strain-rate-controlled deviatoric Deformation in a triaxial Kármán-cell



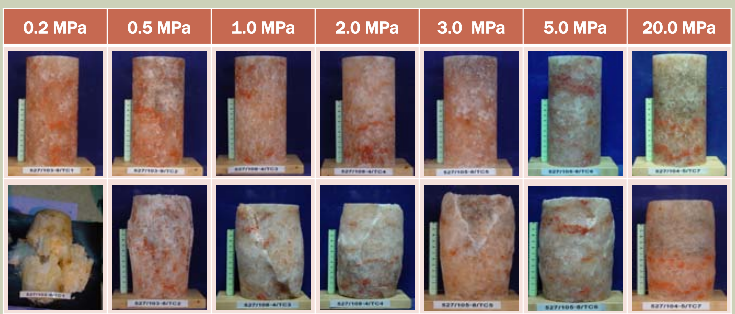
$\sigma_1 > \sigma_3$
$\Delta\sigma = f(\varepsilon_1)$
$\Delta V/V = f(\varepsilon_1)$

triaxial strength tests ($1{\cdot}10^{-5}s^{-1}$, 25°C)



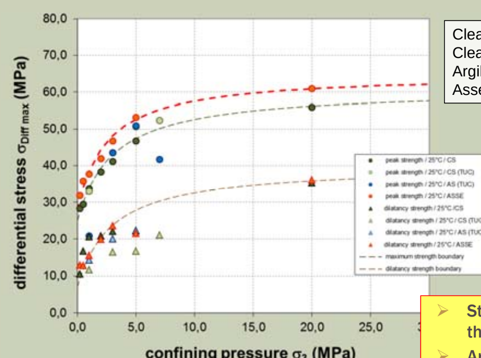
➢ The strength- / dilatancy behaviour ⇒ change in deformation style

triaxial strength tests ($1{\cdot}10^{-5}s^{-1}$, 25°C)



brittle ⇔ semi-brittle ⇔ ductile

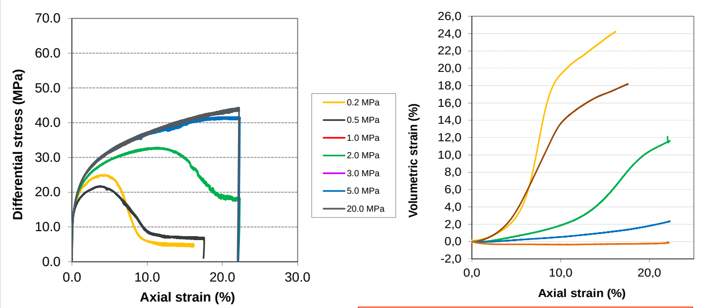
triaxial strength tests ($1{\cdot}10^{-5}s^{-1}$, 25°C) - Asse



Clean salt	- large cores (IfG)
Clean salt	- small cores (TUC)
Argillaceous salt	- small cores (TUC)
Asse salt	(Joint Project II)

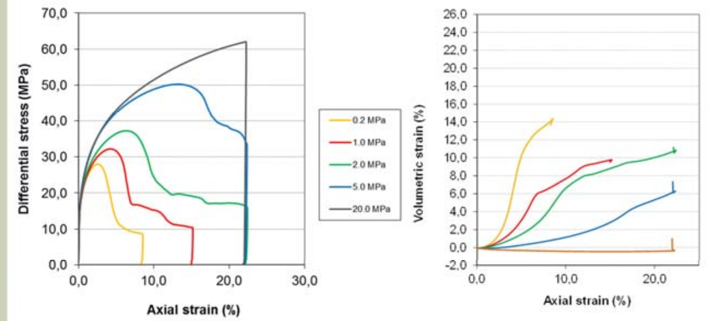
- ➢ Strength: significantly lower than for Asse salt
- ➢ Argillaceous salt higher scattering but comparable to CS
- ➢ Dilatancyboundary similar

triaxial strength tests ($1{\cdot}10^{-6}s^{-1}$, 25 °C)



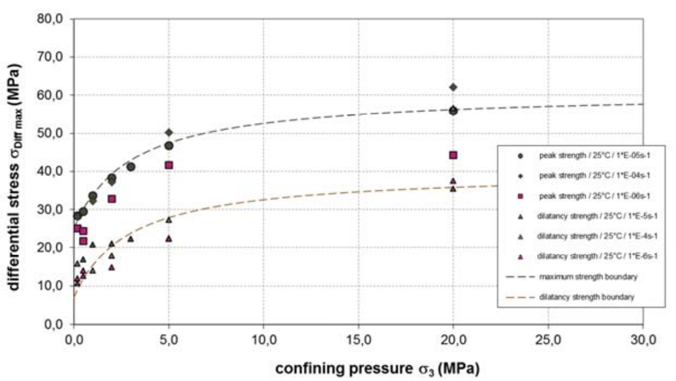
At lower strain rate (1/10x)
- Strength: significantly lower
- Failure strain becomes higher

triaxial strength tests ($1{\cdot}10^{-4}s^{-1}$, 25 °C)

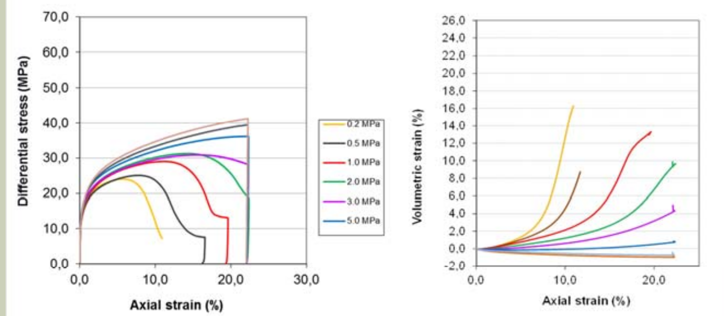


At higher strain rate (10x)
- Strength: significantly higher
- Failure strain becomes lower

triaxial strength tests (25 °C) – deformation rate dependence

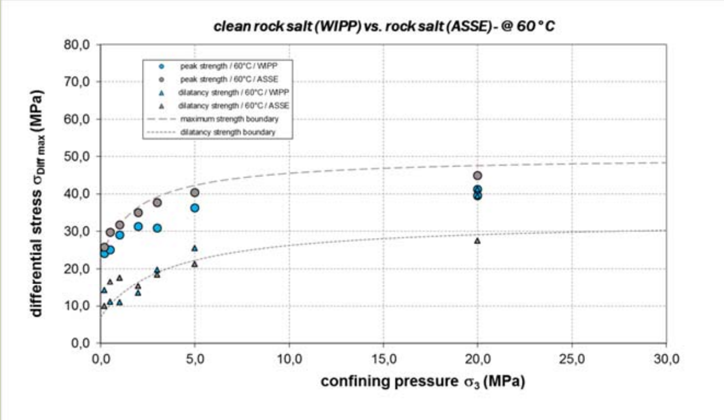


triaxial strength tests ($1{\cdot}10^{-5}s^{-1}$, 60 °C)

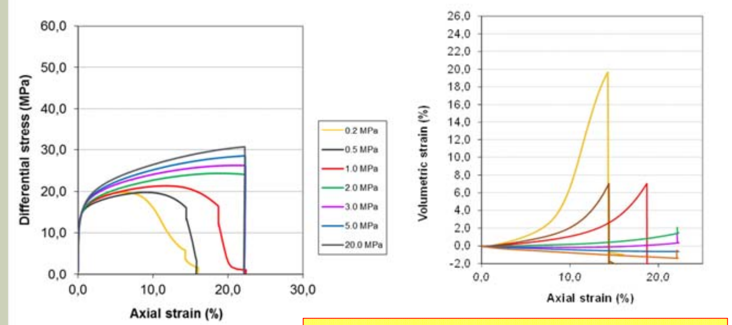


At higher temperatures
- Strength decreases
- Change from brittle to more ductile deformation

triaxial strength tests ($1\cdot10^{-5}s^{-1}$, 60 °C)

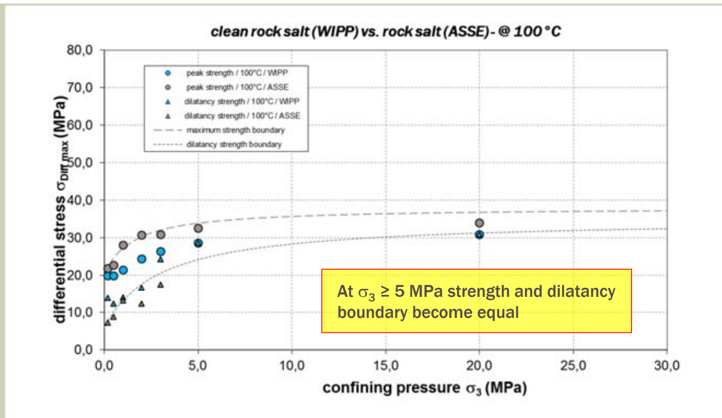


triaxial strength tests ($1\cdot10^{-5}s^{-1}$, 100 °C)



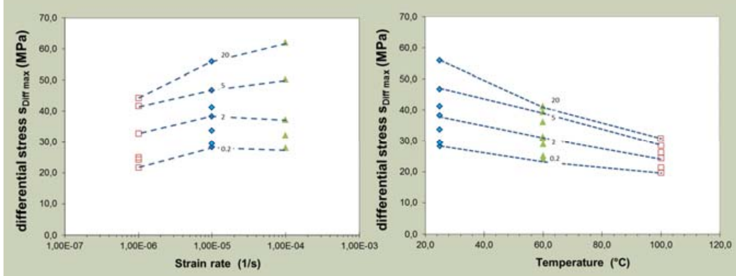
Increase of temperature
- Further strength decrease
- Change from brittle to more ductile deformation

triaxial strength tests ($1\cdot10^{-5}s^{-1}$, 100 °C)



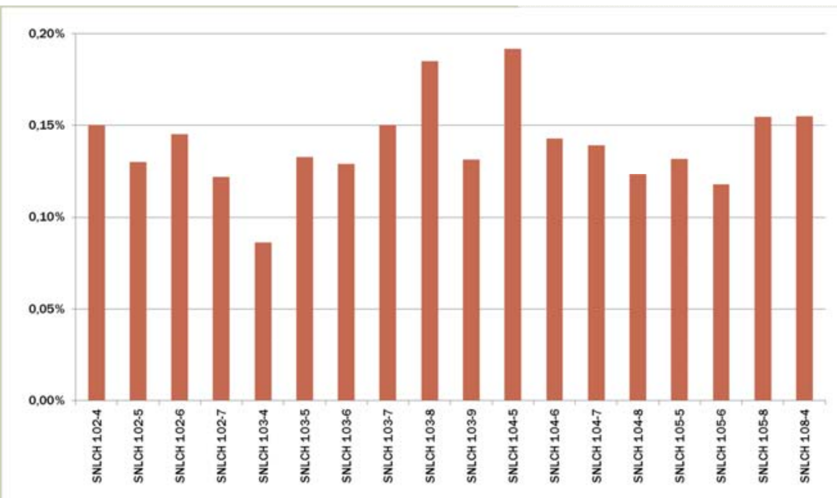
At $\sigma_3 \geq 5$ MPa strength and dilatancy boundary become equal

Strength: Strain rate – Temperature effects



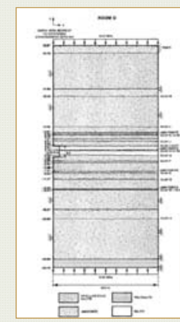
Extrapolation of strength data to in situ requires sufficient data sets to describe temperatur and strain rate effects

Humidity (after flue-curing 24 h 100 °C)

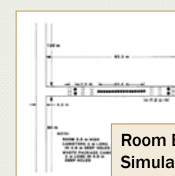


Summary – actual state

- ca. 6t WIPP salt was delivered until 08/2013:
  - ☺ The material represents excellent test conditions: undisturbed / intact salt – **Homogenous?**
  - ☺ The preparation (150 samples) is underway
  - ☺ Close collaboration between IfG and TUC
- ☺ Strength testing on „Clean salt" nearly finished
  - ☺ Data sets for describing the temperature and deformation rate-effects are available
  - ☺ Creeps tests are started (preliminary test results are available).
  - ☹ Remaining test-time (6 to 9 month)
- ☺ Argillaceous salt some preliminary stress test results are available – significant data scattering
- ☺ Asse data sets are available for comparison.
- 😐 **In the clean salt the humidity content is increased compared to domal salt.**
- 😐 **Argillaceous salt?**




Room D – Mining Development Test




Room B – Overtest for Simulated Defense High-Level Waste

High Temperature Characterization of Bedded Permian Salt

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Abstract

Generic salt research and development sponsored by the Department of Energy includes uniaxial testing of bedded salt to 300°C. A suite of such testing was put forward as one of the prerequisite efforts for advancing the studies of heat-generating waste in salt, such as a proposed high-temperature field test. An axial strain rate of 10–4 s–1 was applied while each specimen was very accurately heated inside an environmental chamber. These reconnaissance tests extend the considerable database available for Permian-bedded salt, most of which was developed during site characterization for the Waste Isolation Pilot Plant. As expected, tests of natural salt at 200°C and 250°C exhibited extensive crystal plasticity. Tests at 300°C were not subjected to load because the bedded salt specimen decrepitated at 280°C.

These laboratory studies examine temperature effects on elastic properties, time-dependent creep behavior, and ultimate strength. Posttest microstructural observations allow for the assessment of deformational processes. Petrographic work also provides the basis for the vast difference between bedded and domal salt; the bedded salt exhibited violent decrepitation at temperatures near 280°C and the domal salt remained stable to 300°C. Test data developed here provides the foundation for an initial evaluation of how well the existing constitutive model extrapolates to temperatures outside of the substantial database at much lower temperatures and provides an indication of the model validity in the high temperature regimes when used for the design and evaluation of salt disposal options for heat-generating waste.

Sandia National Laboratories is a multi-program laboratory 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. SAND2013-4040J.

SEPTEMBER 2013
4TH INTERNATIONAL
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Salt Repository Research, Design, & Operation
BERLIN, GERMANY

Elevated Temperature Unconfined Compression Uniaxial Stress Tests on Salt Specimens From the Waste Isolation Pilot Plant

Kirby Mellegard, RESPEC

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

Uniaxial Test System

2

Decrepitation Summary

Specimen I.D.	Temperature Target (°C)	Status/Comment
WIPP/QGU38-43-2/1	175	Successful
WIPP/QGU37-20/1	200	Successful
WIPP/QGU37-48/1	200	Successful
WIPP/QGU38-43/1	200	Successful
WIPP/QGU37-15/1	250	Successful
WIPP/QGU36-28/1	250	Successful
WIPP/QGU38-71/1	250	Successful
WIPP/QGU36-17/1	250	Heater system failed
WIPP/QGU36-27-2/1	270	Successful
WIPP/QGU36-18/1	270	Violent decrepitation at approximately 270°C (no data)
WIPP/QGU36-48/2	270	Violent decrepitation at approximately 270°C (no data)
WIPP/QGU37-20/2	300	Violent decrepitation at approximately 275°C (no data)
WIPP/QGU37-45/1	300	Violent decrepitation at approximately 285°C (no data)

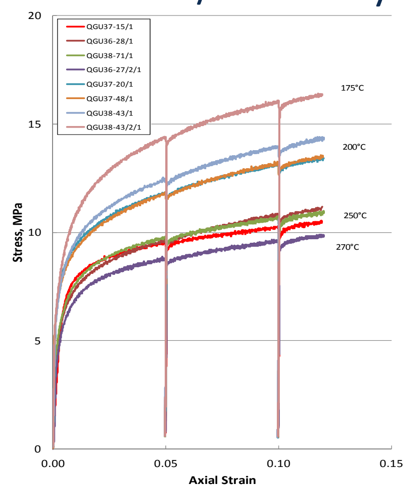
3

Three Stages of a Test

1. Apply constant strain rate of $10^{-4}s^{-1}$ to a strain level of 12%. Perform unload/reload cycles at strains of 5% and 10%. Use stress-strain data during reloading to estimate Young's Modulus. This first stage takes less than ½ hour.
2. Set strain rate to zero to perform a stress relaxation creep test. Monitor stress drop while strain is held constant at 12%. This second stage lasts about a day and sometimes several days.
3. Resume strain rate controlled loading to determine ultimate strength. This third and final stage takes less than an hour.

4

Stage 1. Unload/Reload Cycles



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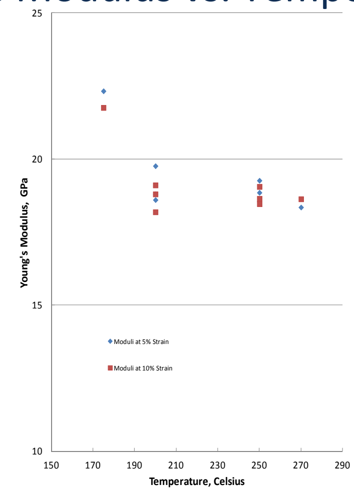
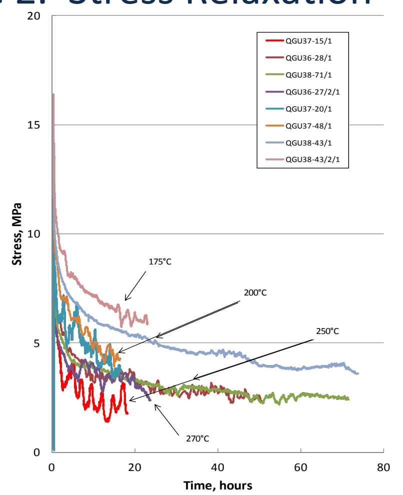
Young's Modulus vs. Temperature



6

Stage 2. Stress Relaxation



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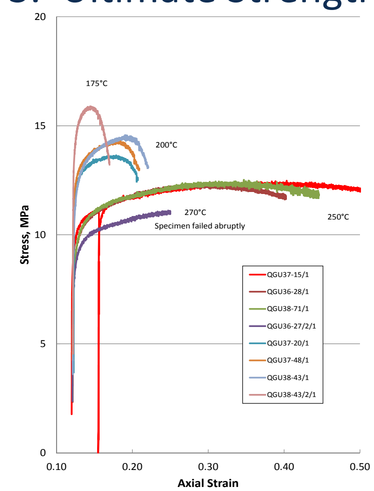
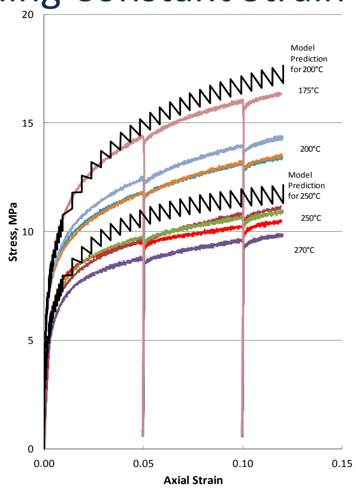
Stage 3. Ultimate Strength



8

Modeling Constant Strain Rate

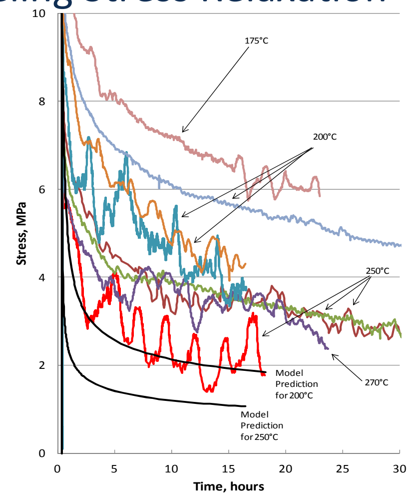
RESPEC



9

Modeling Stress Relaxation

RESPEC



10

Posttest Specimens

RESPEC

11

Improved crushed salt/clay backfill – Experiences from the seal concept shaft “Saale” Teutschenthal mine –

T. Popp, D. Weise, K. Salzer & W. Minkley

Crushed salt is the preferred backfill material for engineered barrier systems in salt environments. In the past most experimental work has been done on compacting crushed salt with respect to a use as buffer/backfill material around the casks and canisters in a geologic repository for HLW in rock salt. In addition, a crushed salt column installed in the shaft represents the characteristic long-term sealing element in the level of salt formations due to its compatibility with the surrounding host rock.

However, for confidence reasons a realistic proof of the efficiency and correct operation of the technical sealing concept is essential but large scale experiments are expensive and thus rare. Experiences from conventional shaft sealing projects (e.g. during decomissioning of former used salt mines) may give valuable input for optimization of sealing concepts in nuclear waste repositories. Recently, a shaft sealing concept has been developed for the shaft “Saale” as part of the closure measures of the former potash mine Teutschenthal. Due to the risk of rock bursts backfilling measures with hazardous waste are being performed in the mined carnallite areas requiring a long-lasting and aftercare insolation of the stored harmful substances. Thus their safe long-term containment has to be ensured and demonstrated.

Because the local shaft situation represents an engineering challenge, i.e. the flooded lower shaft part is not accessible, a complex technical closure concept is developed. The shaft plug consists of a self-carrying lower abutment (MgO-concrete) and a series of complementary shaft sealing elements (e.g. Bitumen, bentonite), separated by MgO-concrete layers. With respect to a redundant and diverse shaft concept also a crushed salt section is foreseen.

To avoid inflow of water to the waste emplacement areas, respectively to exclude an escape of toxic components into the biosphere, the hydro-mechanical integrity of the seal has to be ensured, but again, as a challenge, in the special case of Teutschenthal after only some few decades. Despite it is always stated that crushed salt will finally reach a similar mechanical stability and hydraulic resistance like the surrounding rock salt, an investigation program has been performed to improve the crushed salt compaction using additives like humidity or clay. A preferred crushed salt/clay mixture was selected in close cooperation with the BA Freiberg. With respect to the decisive backfill material properties to quantify hydraulic processes measurements of permeability and porosity were the main objective of the tests.

Our laboratory results confirm earlier results from Stührenberg (2007), that a mixture of 85% crushed and 15% clay, respectively bentonite is optimal for backfill measures in shafts:

- The backfill resistance is low □ easy in situ-compaction for shaft sealing;
- Low initial permeability: 10-15 - 10-16 m2 (pre-compacted: ca. 15% porosity):
- Compacted wet material (□ = some few %) has a permeability in the order of 10-20 m2.

Using the new material parameters the hydro-mechanical integrity and the effectiveness of the technical sealing concept has been demonstrated by HM-modeling. Fortunately it came out that already one sealing element is sufficient to ensure the required long-term-tightness.

Improved crushed salt/clay backfill

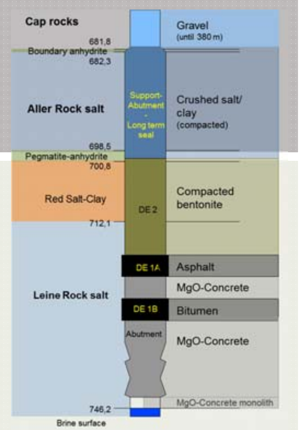
Experiences from the seal concept shaft "Saale" – Teutschenthal mine

T. Popp, D. Weise, K. Salzer & W. Minkley
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

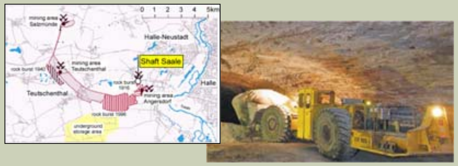
In collaboration with W. Kudla, M. Gruner (BA Freiberg)

Outline

- Background
  - Teutschenthal mine (hazardeous waste repository)
  - Long term sealing doncept of the shaft "Saale"
  - Crushed salt / clay mixture
- Lab investigations - approach / results
  - Compaction behavior
  - Permeability of compacted salt/clay backfill
- Summary

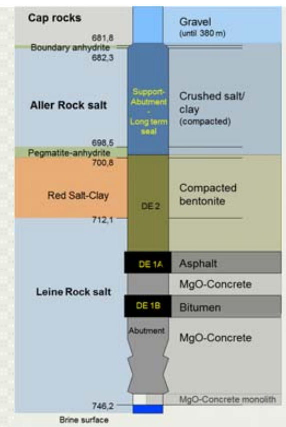


An unusual shaft seal project - „Shaft Saale"



Due to the risk of rock-bursts backfill measures with hazardeous waste are performed, but, therefore, a long-term safe closure of the mine is required.

- Current situation of the „Shaft Saale"
  - ☹ Allready sealed by a clay plug in the overburden in 1983 ➔ not a long-term tight seal
  - ☹ No access to the lower shaft end
  - ☹ Brine surface at around 746 m in the shaft,
  - ➔ brine pressure in the mine
  - ➔ water bearing layers in the overburden (the sealing will not discussed here)

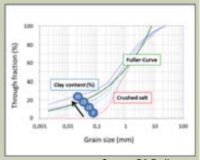


Constructed 1910 – 1912
Depth 826 m

Crushed salt consolidation: material and testing

- Use of additives : humidity/clay
  - ☺ Improvement of the compaction
  - ☺ Reduction of permeability

- 85 % crushed salt:
  - maximum grain size: 32 (4) mm
- 15 % Friedländer clay
- Water content: 4,5 %
- ➢ Pre-compaction to a specific porosity of around 15% = in situ-consolidation state



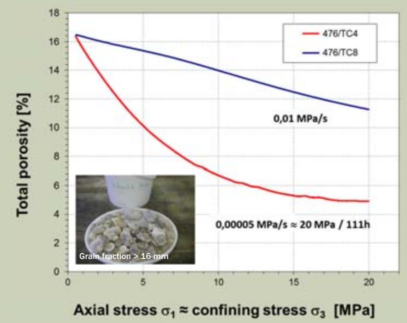
Source: BA Freiberg

Investigation program

- Stress-controlled isostatic compaction tests
- Triaxial strength testing
- Gas permeability at isostatic compaction
- Brine permeability during isostatic creep test
- Shear tests on backfill / rock salt interfaces

Sample	Density$_{dry}$ r_{tr} [g/cm^3]	Density$_{wet}$ r_f [g/cm^3]	Water cont. w [%]	Porosity n [%]	Saturat. s [%]
476/SV1	1,97	2,06	4,5	13,5	54,2
476/SV2	1,94	2,03	4,5	14,8	49,0
476/SV3	1,93	2,02	4,5	15,1	47,8
476/SV4	1,93	2,01	4,5	15,3	46,9
476/SV5	1,94	2,02	4,5	14,9	48,6
476/SV6	1,93	2,02	4,5	15,2	47,3
476/SV7	1,96	2,05	4,5	13,9	52,7
476/SV8	1,93	2,02	4,5	15,0	48,1

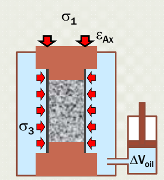
Compaction of crushed salt / clay aggregates



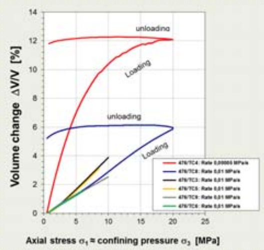
Isostatic compaction in a triaxial Kármán-cell

$\sigma_1 = \sigma_3$

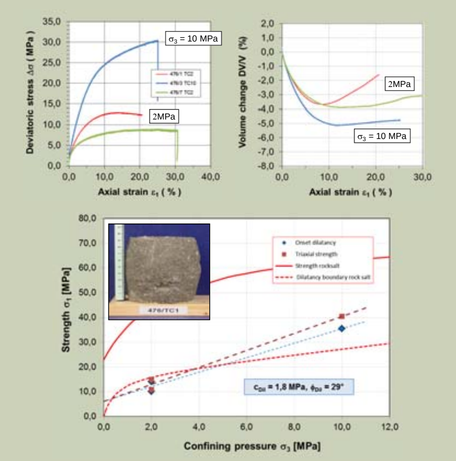
$\Delta V/V = f(\sigma)$



- ☺ Fast and efficient, time dependent compaction until the end of the fluid filled pore space



Deformation behaviour of crushed salt / clay aggregates

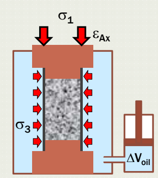


Deviatoric deformation in a triaxial Kármán-cell

$\sigma_1 > \sigma_3$

$\Delta\sigma = f(\varepsilon_1)$

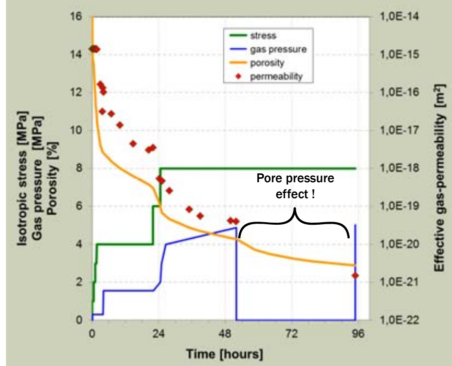
$\Delta V/V = f(\varepsilon_1)$



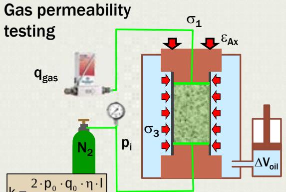
☺ **The overall deformation is dominated by compaction:**

- At low pressures onset of dilatancy corresponds to the rock strength but the general strength is low
- At higher pressures (compacted state) strength increases and more or less plastic behaviour dominates

Gas-permeability of crushed salt / clay aggregates – Short term test



Gas permeability testing



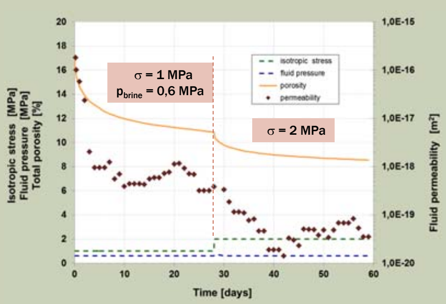
$k = \frac{2 \cdot p_0 \cdot q_0 \cdot \eta \cdot l}{A(p_i^2 - p_2^2)}$

☺ Compaction of the sample results in a significant permeability reduction, but

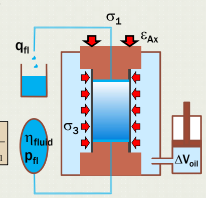
☹ 2-phase flow effects, i.e. a capillary pressure threshold, can not be excluded.

➔ **Gas flow measurements are not representative to describe the hydraulic behaviour**

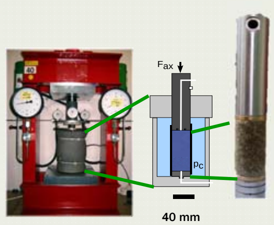
Brine-permeability of crushed salt / clay aggregates – Creep test



Stationary Darcian Fluid flow



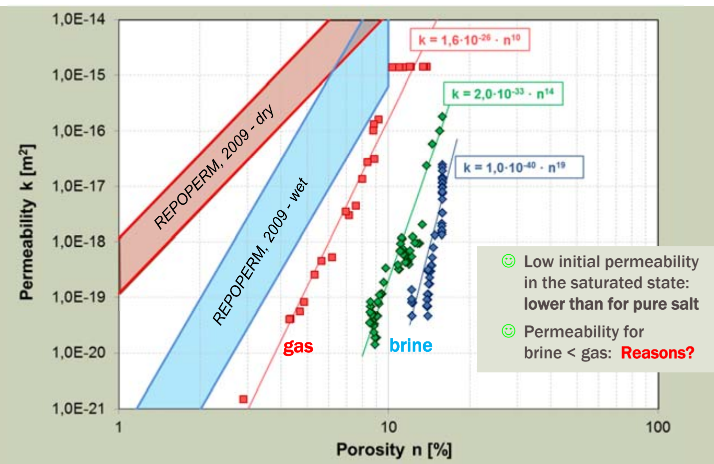
$k = q_{fl} \cdot \frac{\eta \cdot \Delta l}{A \cdot \Delta p_{fl}}$



☺ Saturation of the sample results in **enhanced compaction** at low pressures

☺ Compaction creep is accompanied with a drastic permeability decrease **until the order of 10^{-20} m²**, despite a remaining porosity of 8%

Crushed salt / clay mixture: Hydraulic properties

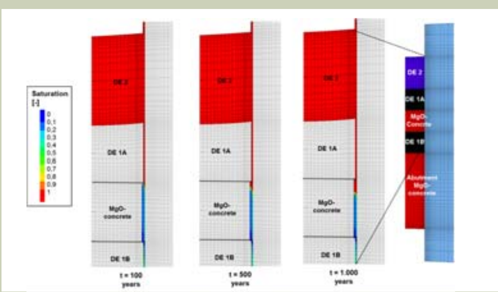


☺ Low initial permeability in the saturated state: **lower than for pure salt**

☺ Permeability for brine < gas: **Reasons?**

Proof of the long term safety – hydro-mechanical calculations

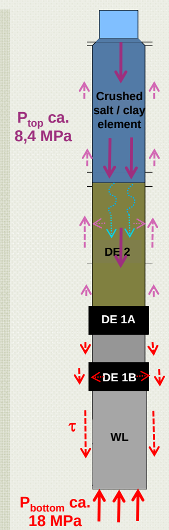
- **Usability of the design concept**
  - Prevention of water inflow to the mine
  - Prevention of outflow of contaminated fluids from the waste
- **Stability against hydro-mechanical loading, i.e. no collapse or loss of integrity**



Considered processes

- Convergence-induced ompaction of the sealing elements
- Water saturation of the bentonite sealing element DE2 → Development of swelling pressure
- In the crushed salt / clay element decrease of the permeability due to to associated compaction and healing processes

➢ Change of the load support from the lower abutment to the upper sealing (abutment) elements



Lessons learned

- ➢ Experiences from conventional shaft sealing concepts (during decomissioning projects) give valuable input for sealing concepts in nuclear waste repositories
- ➢ Complementary sealing elements (e.g. Bitumen, crushed salt) ⇒ effficient long term seal of shafts
- ➢ Wetted crushed salt / clay mixtures (85:15) have favored backfill properties:
  - ☺ The backfill resistance is low ⇒ easy in situ-consolidation
  - ☺ Low initial permeability: 10^{-15} - 10^{-16} m² (pre-compacted: ca. 15% porosity).
  - ☺ Compacted wet material (∅ = some few %) has a permeability in the order of 10^{-20} m².
- ☺ Earlier investigations from Stührenberg (2007) with salt/bent. mixtures (85:15) are confirmed.
- 😐 What happens in the long-term with the remaining brine (ca. 4.5 %) in the sealing plug?

Shaft condition 20.05.2004 © Lars Baumgarten

07/2013 Pre-studies (i.e. safety proof) finished

in 2013/14 Technical execution planning
Next step: Re-opening of the shaft

Salt Reconsolidation: Principles and Applications

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 accessible moisture is well understood mechanistically as buttressed by large-scale tests, laboratory consolidation measurements, and microscopic documentation of deformational processes. Permeability/density functions developed from the Waste Isolation Pilot Plant shaft seal experience provide a foundation for granular salt consolidation that informs design, analysis, or experimentation in drift sealing and backfill placement where variables are less constrained. And, in contrast to significant testing and observational evidence under ambient conditions with application to shaft seal systems, large-scale salt reconsolidation under thermally-elevated or potentially dry conditions is less well described and documented. Our collective state of knowledge points directly to the important implications with respect construction, evolution, and performance of lateral closure systems in a salt repository. This research examines reconsolidation of granular salt with particular emphasis on seals or backfill placed in a horizontal configuration.

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Exceptional service in the national interest

Sandia National Laboratories

Salt Reconsolidation: Principles and Applications

Frank D. Hansen PhD PE

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany
September 17-18, 2013

Sandia National Laboratories · DBE TEC · PTKA · U.S. Department of 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. 2013-7010P

A Joint Report on Principles and Application

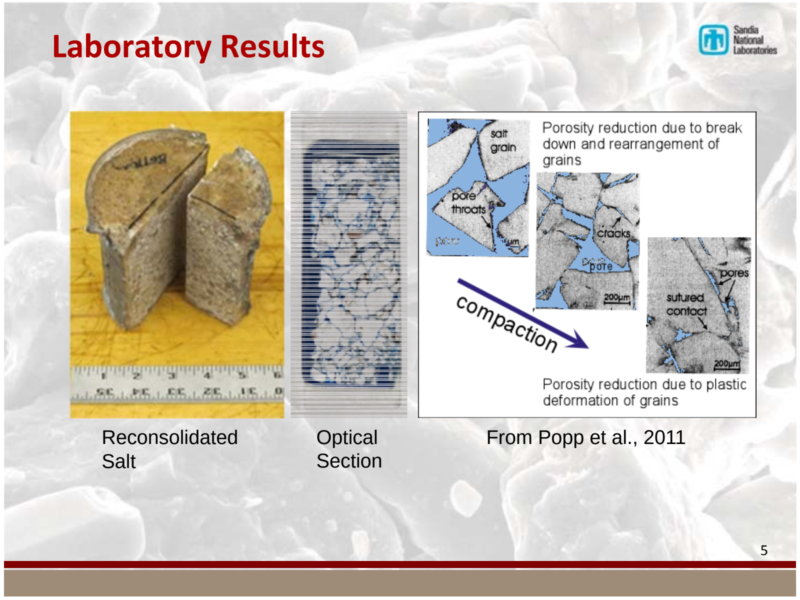
- Why?
  - Establish the scientific basis for granular salt evolution in repository applications
  - Summarize state of knowledge for preservation, reference and research
  - Demonstrate progress on US/German collaborations
- What can we add today?
  - Analogues
  - Industry experience
  - Updates from ongoing R&D
- Recommendation for additional testing
  - Large-scale short-duration consolidation in situ
  - Single heater test
  - Use of the WIPP URL

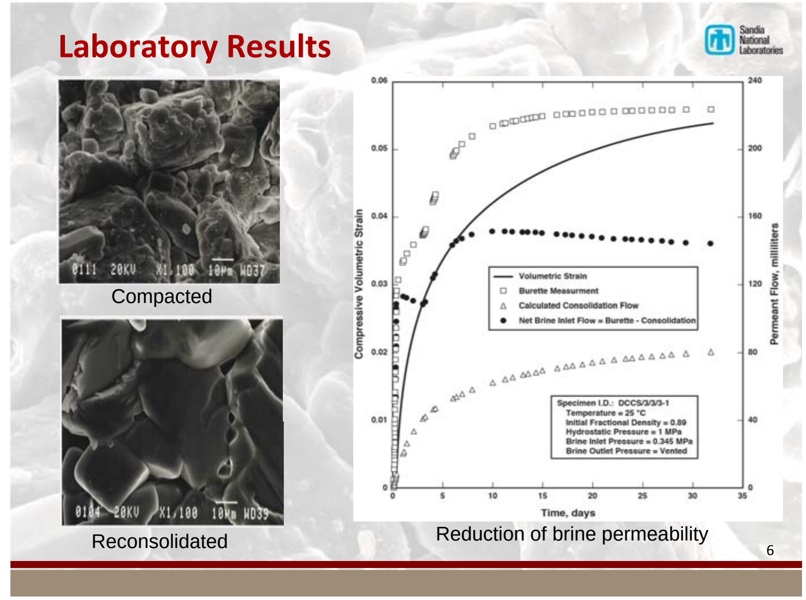
Joint Report Content

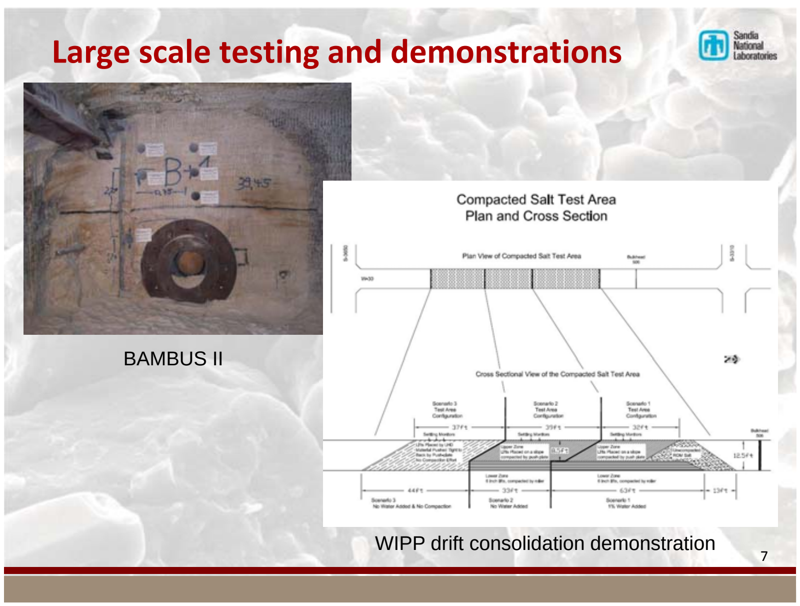
- Overview of subject matter
- Principles
  - Micromechanical processes
  - Laboratory testing summary
  - Results
    - Room temperature
    - Elevated temperature
- Applications
  - WIPP shaft seal RD&D
  - BAMBUS II
  - Operating mines
  - Drift closures at WIPP
  - Vorläufige Sicherheitsanalyse Gorleben
- Suggestions?

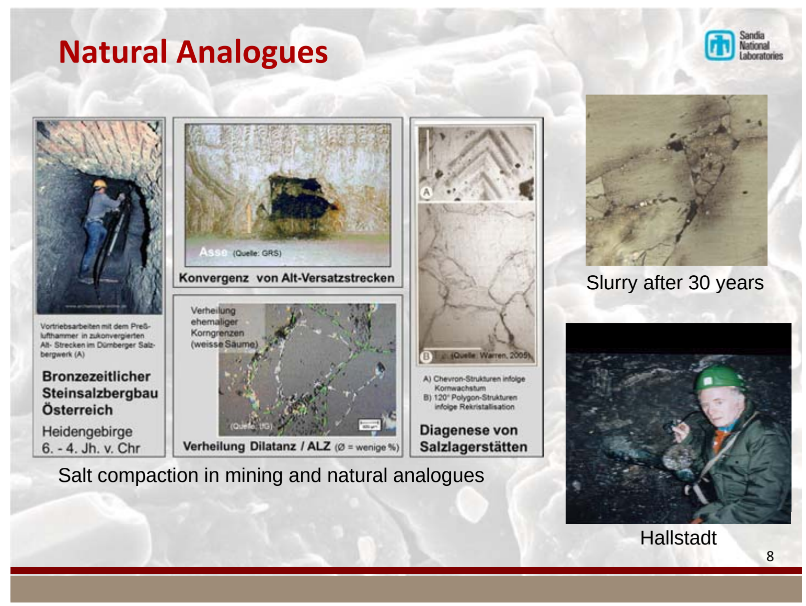
Laboratory Testing

- Overview of subject matter
- Theory and microstructural observations of densification processes (Spiers and coworkers, 1988, 1990, 1993…)
- REPOPERM Phase 2 (Czaikowski et al., 2012)
- Vorläufige Sicherheitsanalyse Gorleben (Popp et al., 2011)
- 3rd US/German workshop on salt repository research, design and operations (Hansen, et al., 2012)
- Temporal evolution of granular salt compaction


Laboratory Results
Sandia National Laboratories
salt grain
pore throats
cracks
pore
sutured contact
pores
compaction
Porosity reduction due to break down and rearrangement of grains
Porosity reduction due to plastic deformation of grains
Reconsolidated Salt
Optical Section
From Popp et al., 2011
5


Laboratory Results
Sandia National Laboratories
Compacted
Reconsolidated
Compressive Volumetric Strain
Permeant Flow, milliliters
Time, days
Volumetric Strain
Burette Measurment
Calculated Consolidation Flow
Net Brine Inlet Flow = Burette - Consolidation
Specimen I.D.: DCCS/3/3/3-1
Temperature = 25 °C
Initial Fractional Density = 0.89
Hydrostatic Pressure = 1 MPa
Brine Inlet Pressure = 0.345 MPa
Brine Outlet Pressure = Vented
Reduction of brine permeability
6


Large scale testing and demonstrations
Sandia National Laboratories
BAMBUS II
Compacted Salt Test Area
Plan and Cross Section
Plan View of Compacted Salt Test Area
Cross Sectional View of the Compacted Salt Test Area
WIPP drift consolidation demonstration
7


Natural Analogues
Sandia National Laboratories
Bronzezeitlicher Steinsalzbergbau Österreich
Heidengebirge
6. - 4. Jh. v. Chr
Konvergenz von Alt-Versatzstrecken
Verheilung ehemaliger Korngrenzen (weisse Säume)
Verheilung Dilatanz / ALZ
Diagenese von Salzlagerstätten
Salt compaction in mining and natural analogues
Slurry after 30 years
Hallstadt
8

Recapitulation

Sandia National Laboratories

- Create the state-of-the-art report
  - Establish the scientific basis for granular salt reconsolidation
  - Emphasize repository applications
  - Preserve knowledge and references
  - Identify and recommend research
  - Demonstrate progress on US/German collaborations
  - Deliverable product for Salt Club
- Additional content
  - Analogues
  - Mining experience
  - Large-scale short-duration consolidation in situ
  - Use of the WIPP URL

Finis

Sandia National Laboratories DBE TEC PTKA

Compaction of Crushed Salt in Consideration of the Moisture Content

D. Stührenberg
Federal Institute for Geosciences and Natural Resources
4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

Reconsolidation of crushed salt

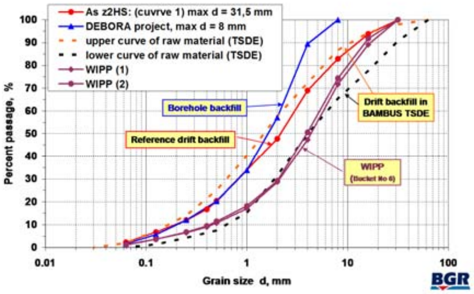
Contents:

Recent BGR laboratory investigations and results on backfill

- Material and grain size distribution
- Strain controlled oedometer test Oedo-106
  Influence of compaction rate, temperature, moisture
- Triaxial compaction test TK-031 (stress controlled)
  Compaction rate vs. void ratio, creep compaction
  comparison with results of oedometer tests
- Initial investgation on WIPP run-of-mine material
  Moisture content, grain size curve,
  planed oedometer test

Reconsolidation of crushed salt

Investgation on crushed salt:
Grain size distribution



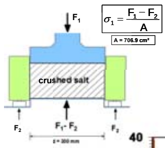
Grain size distribution of crushed salt

Grain size distribution curves of crushed salt used for drift or borehole emplacement.

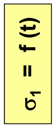
Grain size curve of WIPP run-of-mine crushed salt

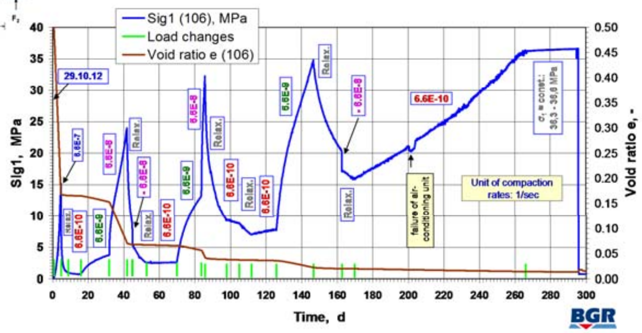
3000 and 2000 g

Reconsolidation of crushed salt



Oedometer test 106:
Strain controlled compaction of crushed salt
As z2SP + 0.6% brine, d_{max} = 8.0 mm, T = 50°C



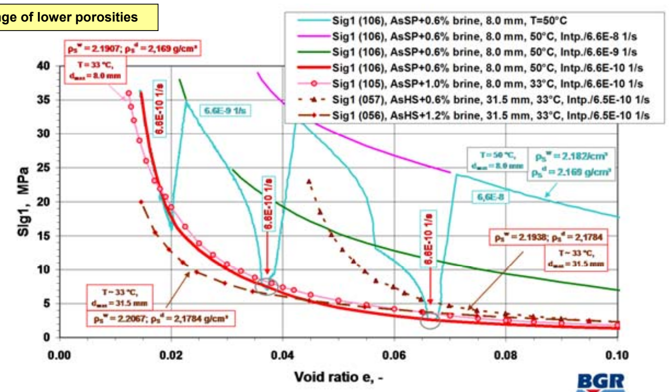


Reconsolidation of crushed salt

Oedometer test 106: Strain controlled compaction of crushed salt
As z2SP + 0.6% brine, d_{max} = 8.0 mm, T = 50°C; and further results

$\sigma_1 = f(e)$

Range of lower porosities



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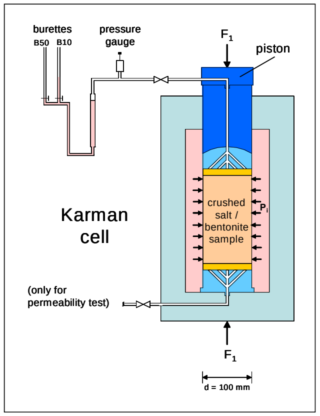
Reconsolidation of crushed salt



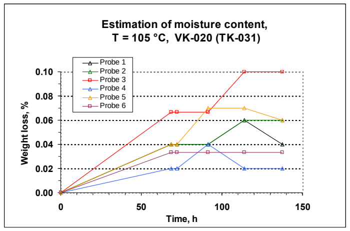
Test equipment TRE-2001 (M6)

Triaxial compression test TK-031

Determination of the spatial stress state used to derive a constitutive law

$$\sigma_1 = \frac{F_1}{A} \qquad \sigma_3 = p_i \qquad \sigma_m = \frac{1}{3}(\sigma_1 + 2\sigma_3)$$

Creep compaction of „dry“ crushed salt



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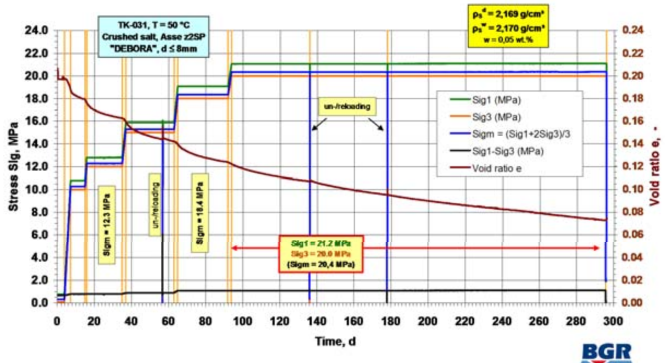
Reconsolidation of crushed salt

Triaxial compaction test TK-031, T = 50 °C:
As z2SP, w ≈ 0.05 wt%, d_{max} = 8.0 mm, T = 50°C

$\sigma = f(t)$



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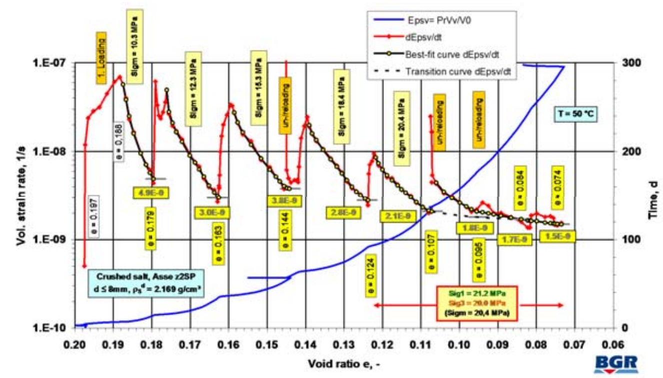
Reconsolidation of crushed salt

Triaxial compaction test TK-031, T = 50 °C:
As z2SP, w ≈ 0.05wt%, d_{max} = 8.0 mm, T = 50°C

$d\varepsilon_v/dt = f(e)$, $\varepsilon_v = f(t)$



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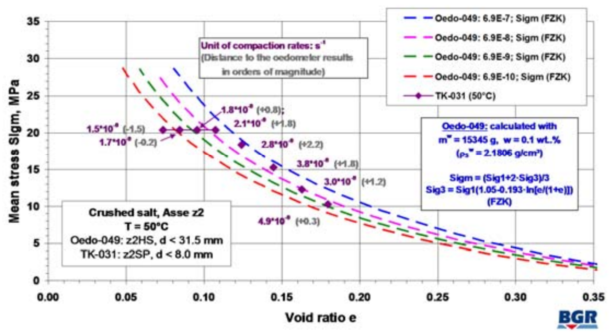
Reconsolidation of crushed salt

Comparison of volumetric strain rates

Oedo-049 - TK-031, T = 50 °C

$\sigma_m = f(e)$



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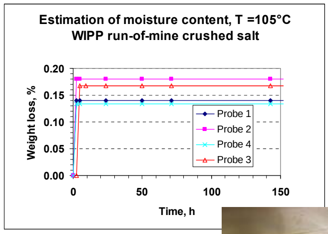
Reconsolidation of crushed salt

WIPP crushed salt (run-of-mine material)

Shipment Mai 2013

Moisture content



Average moisture content:
0.16 wt.%

Planned oedometer test:
- "original" grain size distribution
- strain controlled
- T = ?
- w = ?

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Reconsolidation of crushed salt

Summary and conclusions:

The required moisture content in terms of "rapid" crushed salt compaction can be optimized using the results of strain controlled oedometer tests at lower porosities.

The results of strain controlled oedometer tests with "dry" crushed salt leads to the assumption that the compaction rate drops considerably in the case, when the host rock pressure approaches its maximum due to the backfill resistance. Hence, compaction rates in situ may become so small that a sufficient backfill compaction in a repository may not be reached within a reasonable time scale.
This apprehension has not been confirmed by the results of the triaxial creep compaction test TK-031. At all compaction phases with constant loads (σ_m < 20.4 MPa) the volumetric strain rate did not fall below 10^{-9} s^{-1}, down to a void ratio of 0.074.

The average moisture content of the WIPP crushed salt shipment was determined to 0.16 weight%.

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Reconsolidation of crushed salt

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Crushed salt compaction – experiments and CODE_BRIGHT model calibration

K. Wieczorek, O. Czaikowski, K.-P. Kröhn

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

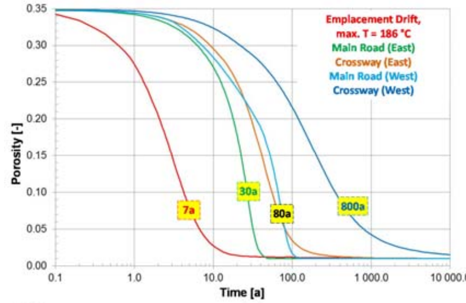
Introduction

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

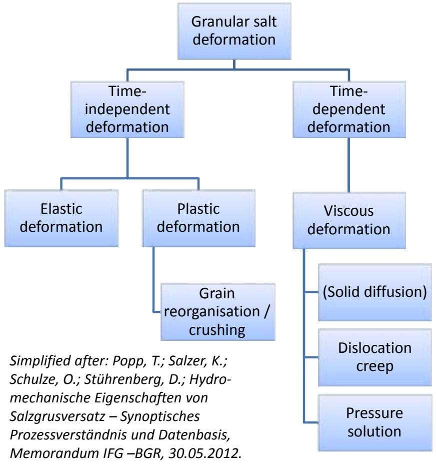
- Is the required low-permeability state reached, and how long does it take to reach it? What is the corresponding porosity range?

Calculated backfill porosity evolution in a repository (VSG project). CODE_BRIGHT simulation.

Problem: Currently only partial parameter calibration / validation



Deformation mechanisms of granular salt



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

Controlling factors:

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

Modeling approaches:

- Empirical models integrating all mechanisms (e.g., Zhang's model)
- Models differentiating between mechanisms (e.g., CODE_BRIGHT)

CODE_BRIGHT model (currently in calibration)

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

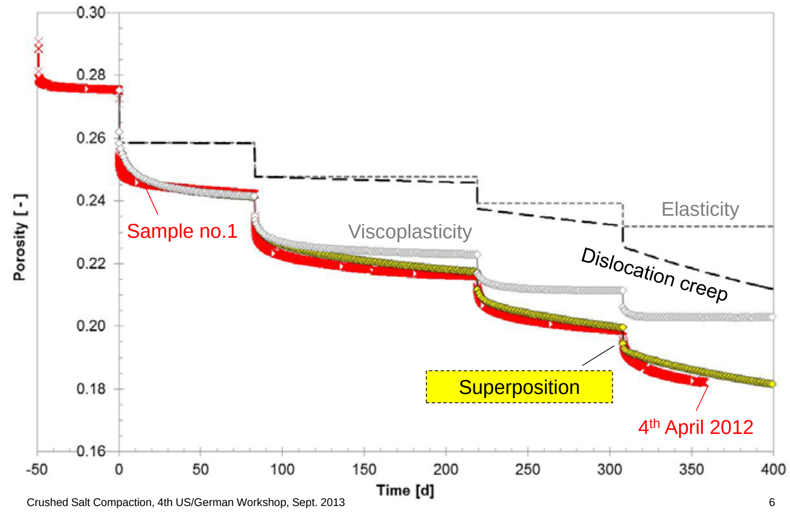
- FEM-Code for coupled THM-analysis of multiphase flow in geological media (3D)
  - Superposition of deformation mechanism, *Olivella & Gens (2002)* :
    - $\dot{\varepsilon}_{CS} = \dot{\varepsilon}^{EL} + \dot{\varepsilon}^{DC} + \dot{\varepsilon}^{VP} + \dot{\varepsilon}^{FADT}$
- Elastic deformation 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 behavior
  - 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)*

Model calibration using load controlled laboratory tests

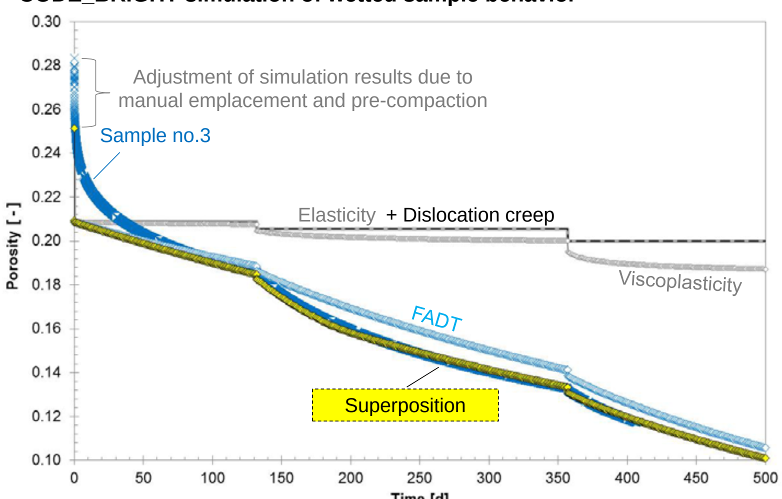
- Calibration of granular salt compaction needs lab tests under well-defined conditions
- Load controlled tests appear more suitable for model calibration than deformation rate controlled tests
  - They allow the distinction between time-independent and viscous behavior, especially for multistep loading
  - Problem: Time needed to achieve low porosity at relevant stress states (in the past, no such tests reached porosities below 10 %)
- 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

In the frame of the REPOPERM project, GRS has been performing **three oedometer tests** on crushed salt compaction which started in February 2011 and are still in operation. These are used for parameter calibration. Currently, a **blind prediction exercise** for the further evolution is in progress.

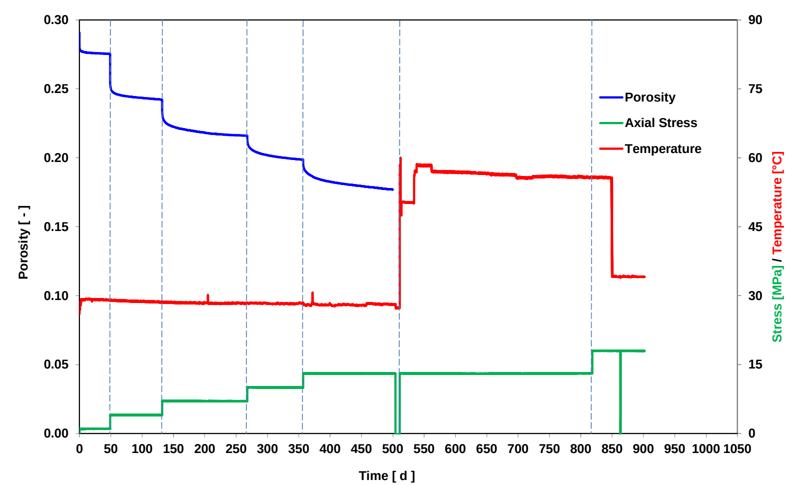
CODE_BRIGHT simulation of dried sample behavior



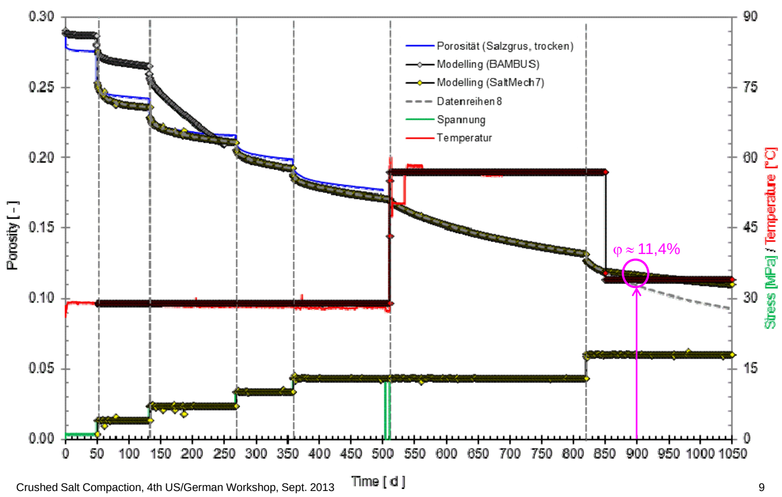
CODE_BRIGHT simulation of wetted sample behavior



Blind prediction exercise - Sample 1 (dried)



Blind prediction exercise - Sample 1 (dried)



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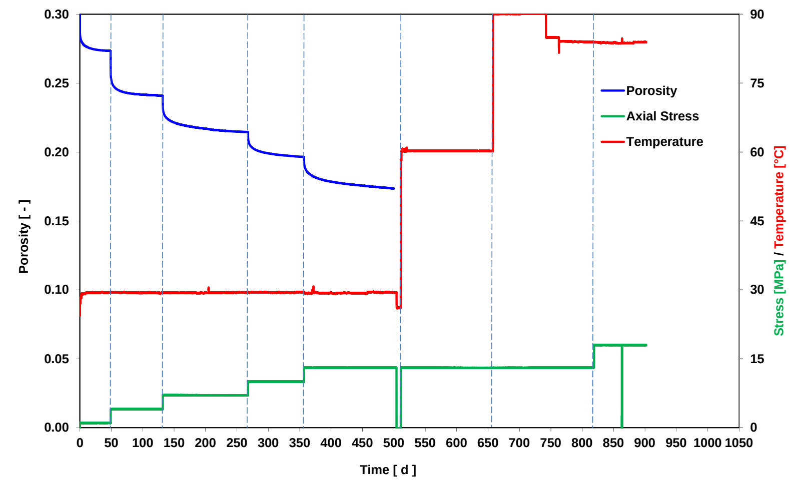
Blind prediction exercise - Sample 2 (natural-dry)



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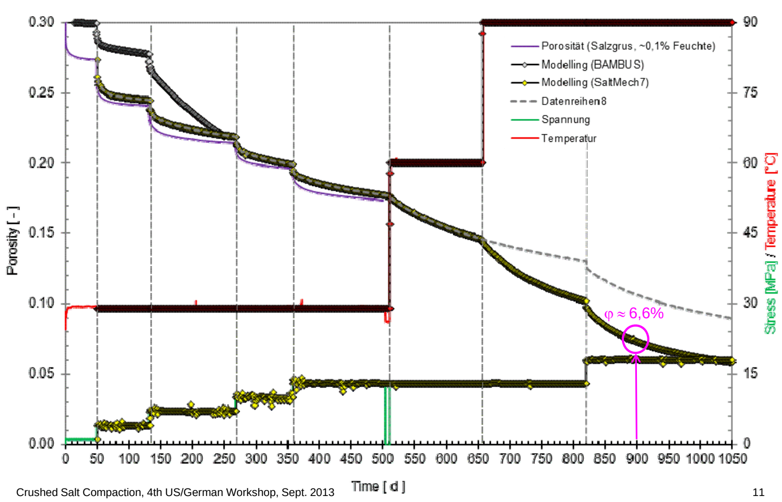
Blind prediction exercise - Sample 2 (natural-dry)



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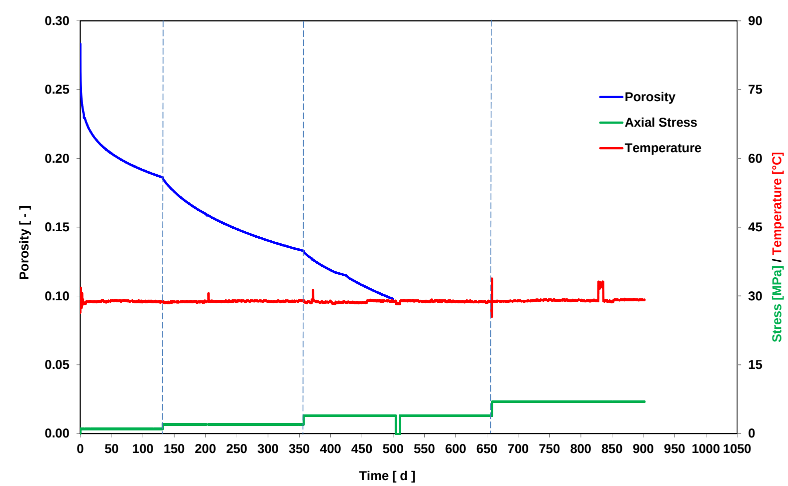
Blind prediction exercise - Sample 3 (wetted: w_{brine}~1%)



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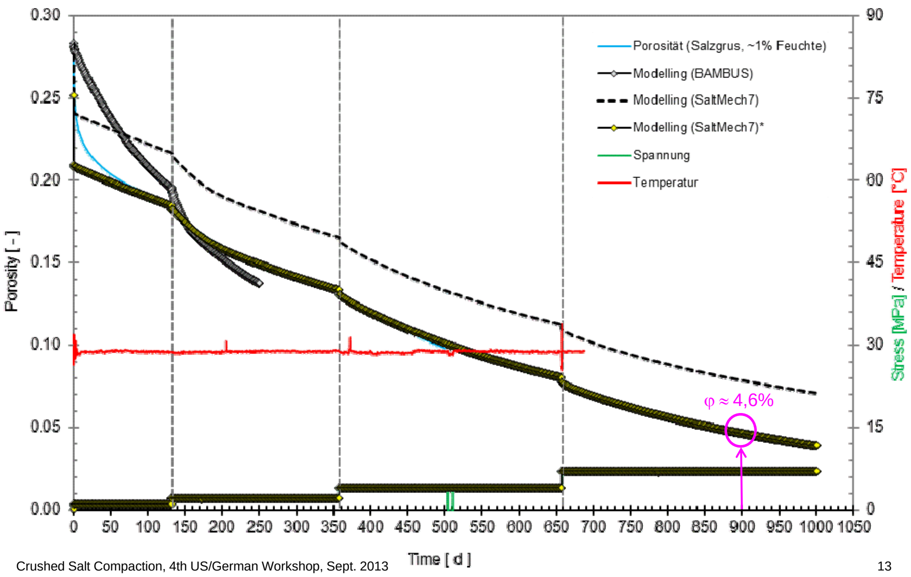
GRS

Blind prediction exercise - Sample 3 (wetted: w_{brine}~1%)



GRS

Summary of current state

Status of experiments

- Three oedometer tests (dried crushed salt, natural dry crushed salt, artifially wetted crushed salt with 1 % of brine) have been running since February 2011.
- The non-wetted tests are now running at elevated temperature in order to investigate the impact of temperature and to accelerate compaction.

Status of model calibration

- The CODE_BRIGHT model has been calibrated using the evolution during the first 500 days of the tests.
- Calibration is not (yet) confirmed for porosities below 10 % and for increased temperature.
- A blind prediction exercise is currently performed for the later phases of the experiments including elevated temperatures.

Remaining Issues

- Additional calibration work (besides low porosity) is needed to capture variations in grain size distribution and to further investigate the moisture influence. Preferably, future experiments should be performed as triaxial tests and involve also WIPP crushed salt for comparison.
- It has to be confirmed that the laboratory calibration is also valid for in-situ compaction behavior.
- Assessment of the permeability / porosity relation of crushed salt compacted under relevant conditions is needed.

The presented work was funded by the German Federal Ministry of Economics and Technology (BMWi) under the contracts no. 02E10477 and 02E10740 (REPOPERM).

Practical Monitoring Experiences

Univ.-Prof. Dr.-Ing. Joachim Stahlmann

In the repository for radioactive waste at Morsleben in Germany (ERAM), low-level and medium-level waste with a volume of about 37,000 m³ is disposed of in different sites of the mine. The decommissioning concept intends to backfill the mine with a high degree of stabilizing material. This leads to a system, where no brine inflow into the repository is expected, although no one can exclude totally this scenario. Therefore the sealings have to constrain possible infiltration of brine into the disposal chambers and, in the far future, the migration of radionuclides into the biosphere. In lack of generally accepted codes of practice there are many complex engineering performances necessary dealing with the dam materials, the behavior of the host rock, the interaction between the dam and the excavation damaged zone. Due to the functions of the dams, the investigations cover the geomechanical behavior of the host rock and dam materials as well as the hydromechanical behavior. In consequence, the Federal Office for Radiation Protection decided to construct an in-situ dam as an experimental set-up comparable to the future real dams. To get the necessary information, a comprehensive monitoring program was installed.

Based on the geomechanical and hydromechanical behavior of the salt rock, the design of the dams has to fulfill various requirements. One of the main objectives is the impermeability of the system covering the dam, the excavation damaged zone and the host rock as well as the structural safety. Dams in salt rock profit by the creeping of the salt. So the dam material could have a small shrinkage if the short term function can be warranted by injections.

If an immediate effect of the dam stability is necessary in order to transfer a hydrostatic load, the radial stress in the interface between dam and host rock is relevant. To estimate the real stress-strain behavior of the dam and the enclosed salt rock as well as the interaction between the elements of the system, measurements of the time-depending shrinkage, the internal stresses of the dam material, the radial stress etc. are carried out. Furthermore, the pore pressure is measured because the dam is pressurized by brine via a pressure chamber at the end of the dam. To determine all these parameters with an ensured quality, a comprehensive measurement program is required, while the functionality of the building must not be restricted.

Even with careful planning, constructing and monitoring of the measurement program for the in-situ test, many challenges arise in the analysis and interpretation of the measured values. This is to be expected for long-term monitoring programs and it is especially difficult when the measured values deviate from the model ideas. Partial higher pressures were measured, as were abandoned in the fluid chamber. Normal stresses in the contact zone showing no state of equilibrium. This means that only local stresses to be measured.

This is due to the fact that that ideal installation conditions for the structure and the sensors cannot be expected. There are also inhomogeneous conditions in distribution of permeability and stress in the contact zone so the pore pressures and normal stresses are influenced by local conditions. Furthermore, there is no uniformly progressing of the fluid front to be expected. Probably homogenisation of the local state occurs during time but the question remains, how to provide the evidence, so the model ideas have to be adapted to the captured values.

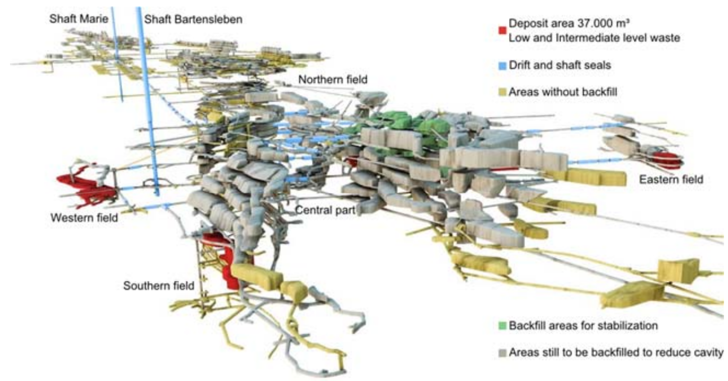
Monitoring of Sealing Dams – Experiences from a Test Set-up at the Repository ERAM

Univ.-Prof. Dr.-Ing. Joachim Stahlmann,
Technische Universität Braunschweig

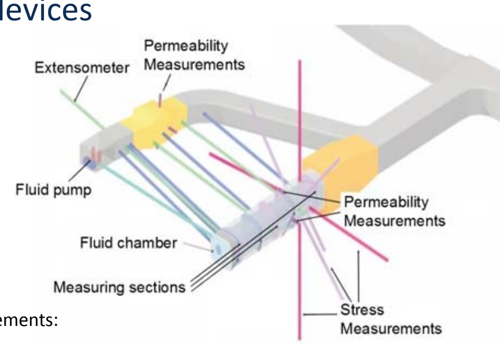
4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

ERAM – Repository for radioactive waste



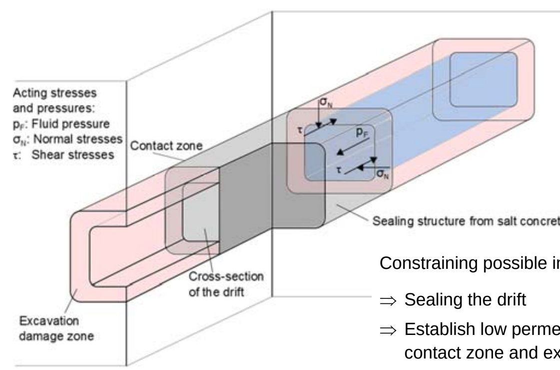
In situ test site with external measurement devices



Performed external measurements:

- Stress by hydrofrac tests
- Strain and displacement by convergence and extensometer measurements
- Permeability in the host rock and the contact zone by surface and borehole tests

Schematic image of a sealing structure



Constraining possible infiltration of brine

⇒ Sealing the drift

⇒ Establish low permeability of dam material, contact zone and excavation damage zone

⇒ Ensure stability concerning position and failure

Why and where measuring?

Tasks:

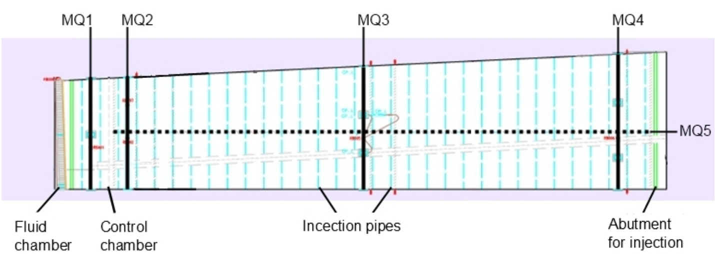
- Functionality has to be achieved and improved in a short time after installation!
- Stability concerning position and failure has to be guaranteed
- Shear strength depends on the cohesion of the materials as well as the normal stress perpendicular to the contact surface
- Normal stress influences the acceptable shear stress as well as the time depended change of permeability
- Opposing trends in development of normal stress in the contact zone due to creeping of the salt and shrinkage of the concrete has to be considered
- Time behaviour of the stability and the permeability have to be observed

Measurements:

- Development of normal stresses in the contact zone taking into account the creeping of the host rock and the shrinkage of the salt concrete over the whole length of dam
- Development of the pore pressure to interpret the flow front as a basis to calculate the permeability. Due to the assumed low permeability the measurement devices are located near the fluid chamber

This presentation focuses on the measurements in the contact zone and the dam without taking into account the influences of the hydration process.

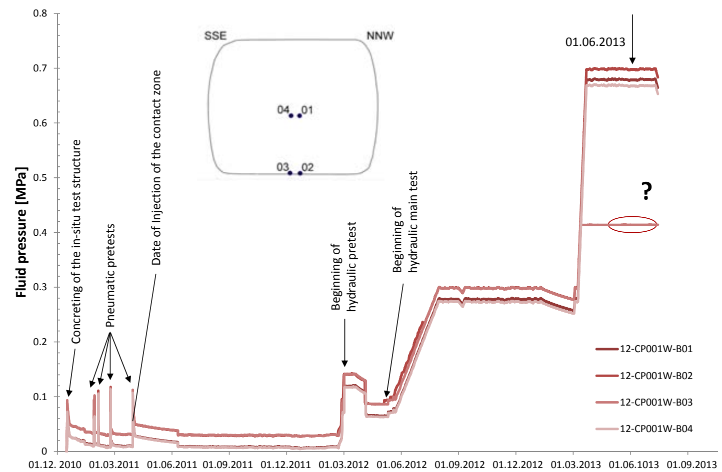
Longitudinal section of the dam with measuring sections



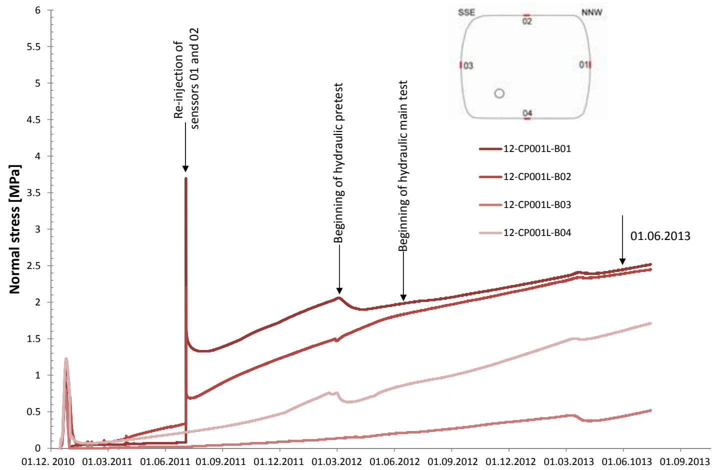
Performed internal Measurements:

MQ 1	stress, temperature and fluid pressure tests
MQ 2	stress, strain, temperature and fluid pressure tests
MQ 3 and 4	stress, strain, temperature and fluid pressure tests
MQ 5	strain and temperature tests

Fluid pressure in the fluid chamber



Normal stress in section MQ 1



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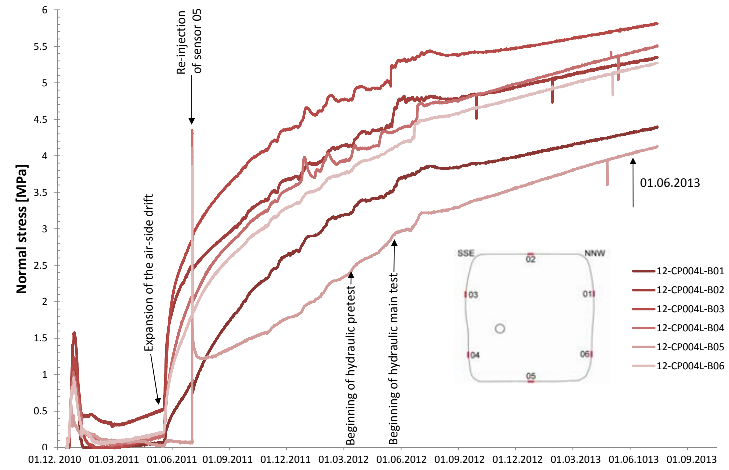
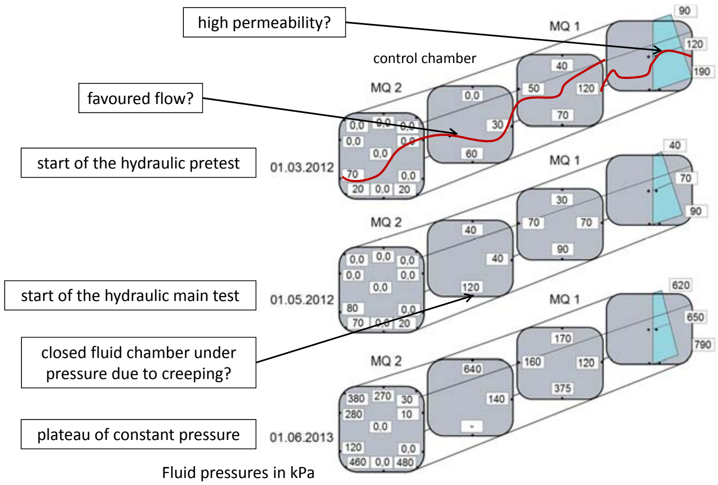
Normal stress in section MQ 4



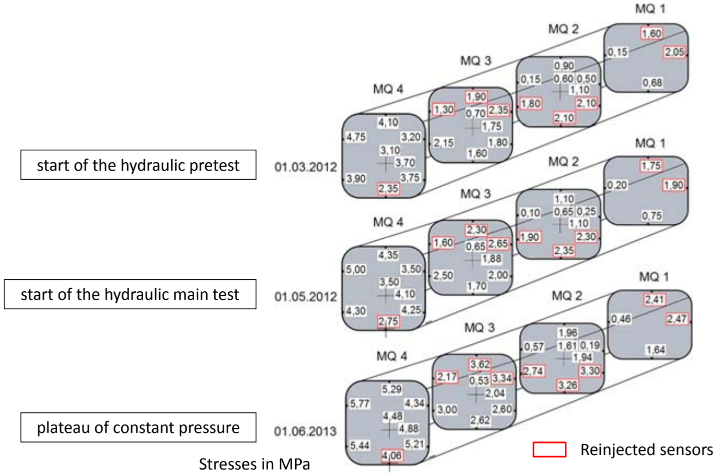
10

Fluid pressure at selected dates



11

Normal stresses at selected dates



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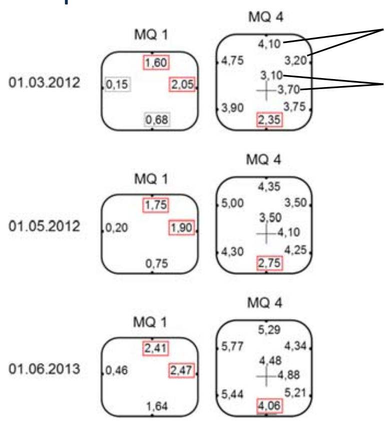
Equilibrium state?



Stresses in MPa — Reinjected sensors

- There is no equilibrium state to determine
- The measured stresses seem to be local

but

- The stress rates are feasible
- With the assumption, that an equilibrium state has to be established the measured stresses must converge to absolute stresses over time

13

Experience for a monitoring program – Lessons learned

- Ideal installation conditions for the structure and the sensors cannot be expected
- There are inhomogeneous conditions in distribution of permeability and stress in the contact zone so the pore pressures and normal stresses are influenced by local conditions due to the degree of separation in the contact zone
- Due to the concrete shrinkage a form and force closure between the host rock and the dam material is very difficult to realize and to ensure even if an injection was carried out
- Obviously the routing of the measurement wires in boreholes perpendicular to the dam axis has no influence
- There is no uniformly progressing of the fluid front to be expected
- Many challenges arise in the analysis and interpretation of the captured values even with careful planning of the measurement program and installation of the devices
- Probably homogenisation of the local state occur during time but the question remains, how to provide the evidence

14

„Mit dem Wissen wächst der Zweifel.“
(With knowledge doubt increases)
J. W. von Goethe

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15

Practical Monitoring Experience

Frank Hansen
Sandia National Laboratories, Albuquerque New Mexico USA

Abstract

Performance confirmation monitoring evolves as the repository design concept and regulations mature. The stepwise process for repository development includes site characterization, licensing, construction, operations and closure. The interpretation and technical bases for the features, events and processes evolve as data, results and observations accumulate. The evolutionary process of confirmation requires inherent flexibility and synchronization with the staged repository milestones. An on-going science program must be effective in defending the licensing bases, incorporate societal input, provide for a responsive performance confirmation program, and continue appropriately scoped elective scientific investigations to advance the technical baseline.

Technical objectives of performance confirmation monitoring program derive as natural components of the science program. Objectives might equally be called monitoring requirements because parameters and on-going science investigations will be predicated on those elements of the safety assessment that most strongly influence risk, dose, uncertainty or other metrics of the performance assessment deemed important within the regulatory framework.

Practical monitoring experience from two mature nuclear waste repository programs in the United States is reviewed in the associated presentation. These include compliance monitoring parameters for the Waste Isolation Pilot Plant and performance confirmation for the Waste Isolation Pilot Plant. The important differences between performance confirmation monitoring and other testing and monitoring objectives are explained. An approach for developing, evaluating and implementing the next generation of performance confirmation monitoring is given.

Performance confirmation parameters should be demonstrably linked to the safety assessment. In some manner, performance confirmation begins during site characterization but formally becomes a commitment when it is included in a license submittal. Performance Confirmation test plans require detail including acceptable ranges and relevance to performance assessment.

Sandia National Laboratories is a multi-program laboratory 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. Abstract of SAND 2013-7039P

Exceptional service in the national interest

Practical Monitoring Experience

Frank D. Hansen PhD PE

4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany
September 17-18, 2013

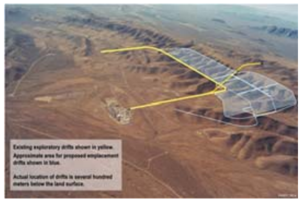
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2013-7039P

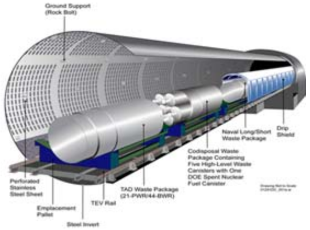
Introduction

- Performance confirmation monitoring versus other testing and monitoring objectives
- Performance confirmation for the Waste Isolation Pilot Plant
- Performance confirmation for Yucca Mountain
- An approach for developing, evaluating and implementing the next generation of performance confirmation monitoring

2

WIPP and Yucca Mountain





3

Repository Monitoring Requirements

OPERATIONS

1. Engineering Systems Testing & Evaluation
2. Design, Construction & Operations Testing
3. Health, Safety & Effluents
4. Security and Emergency Testing
5. Licensing Specifications

LONG-TERM SCIENCE

6. Regulatory Directed Testing
7. Elective Testing
8. Performance Confirmation

4

WIPP Performance Confirmation

- Multi-phase program with different goals/objectives
  - Site characterization Testing and Monitoring
    - To Build a Performance Assessment (safety case)
  - Operational Phase Monitoring
    - To verify basis of Performance Assessment/Results
  - Post-Closure Monitoring
    - To enhance institutional controls and long-term stewardship

5

WIPP Operational-Phase Monitoring

- EPA Regulations govern program
  - Monitoring is an Assurance Requirement
  - *"The Department shall conduct an analysis of the effects of disposal system parameters on the containment of waste in the disposal system …. The results of the analysis shall be used in developing plans for pre-closure and post-closure monitoring…."*

6

WIPP Operational-Phase Monitoring

- Analysis addressed significant disposal system parameters defined by their
  - effect on the system's ability to contain waste
  - effect on the ability to verify predictions about the performance of the disposal system
- Addressed an important disposal system concern
- Obtained meaningful data in a short time period
- Will not violate disposal system integrity
- Complemented existing monitoring programs

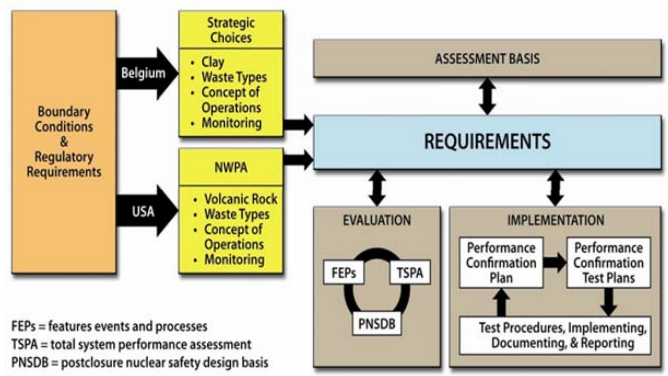
7

Performance Confirmation for WIPP since 1999

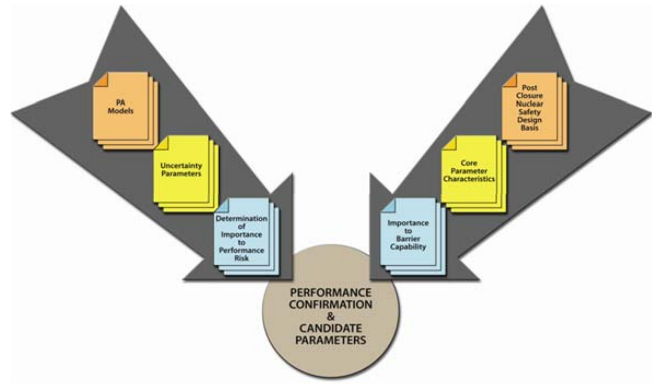
1. Creep Closure and Stresses
2. Extent of Deformation
3. Initiation of Brittle Deformation
4. Displacement of Deformation Features
5. Culebra Ground Water Compositions
6. Change in Culebra Ground Water Flow
7. Drilling Rate
8. Probability of Encountering a Castile Brine Reservoir
9. Subsidence Measurements
10. Waste Activity

8

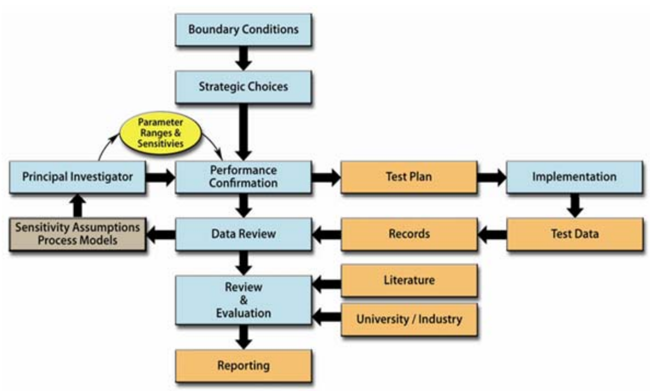
Developing and Assessing Performance Confirmation



Confirmation Parameter Sources



Implementation



Performance Confirmation for Yucca Mountain

In September 2011NRC released its findings on the performance confirmation section of the SAR.

"*The NRC finds that the performance confirmation program is consistent with the NRC's Yucca Mountain Review Plan (YMRP). The SAR includes a description of the Performance Confirmation Program, which evaluates the adequacy of the supporting assumptions, data, and analyses in the SAR…On the basis of the NRC staff's review of the SAR and other information submitted in support of the SAR, the NRC staff notes that DOE has provided a reasonable description of its Performance Confirmation Program that is consistent with the guidance in the YMRP.*"

Concluding Remarks

- Performance confirmation parameters should be demonstrably linked to the safety assessment
- In some manner, performance confirmation begins during site characterization but formally becomes a commitment when it is included in a license submittal
- Because PC test plans require detail including acceptable ranges and relevance to performance assessment, care should be exercised in development of and commitment to each PC test plan

References

- Hansen, F.D. 2012. *Repository Performance Confirmation*. SAND2011-6277C-12119. WM2012 Conference, February 26-March 1, 2012, Phoenix, AZ--Also SAND2011-6277. Sandia National Laboratories Albuquerque, New Mexico.
- Hansen, F.D. and S.W. Wagner. 2013. *Confirmation Monitoring of Repositories in the United States*. SAND2012-10498C. Monitoring in Geological Disposal of Radioactive Waste – Conference and Workshop. Luxembourg.
- MoDeRn Project, Monitoring development for salt repository operation and staged closure: www.modern-fp7.eu
- http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/yucca-lic-app-safety-report.html

Sandia National Laboratories DBE TEC PTKA

Monitoring IGD-TP

W. Steininger
4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

- EC FP 7 – Project *Monitoring development for salt repository operation and staged closure (MoDeRn)*
- International conference and workshop held in Luxemburg in March 2013
- MoDeRn Project finished this summer
- IGD-TP: Monitoring Key Topic 6
  - Practical monitoring strategies including techniques for implementation. This includes monitoring strategies for site characterization, facility construction and operation.
  - Monitoring strategies for current and future requirements for steps leading to closure of the facilities in an operational disposal system. It would also consider requirements for post closure monitoring of this geological disposal system and monitoring of progress in relevant scientific and technological areas.
- Ideas for continuation (final meeting, kick-off-meeting (TSWG), draft proposal to the EG of IGD-TP, support for a new collaborative project
- Proposed working areas
  - Technology
  - Implementation
  - Strategy
  - Communication & stakeholder involvement

- **Technology**
  - Not (passive) safety influencing sensors and sensing techniques
  - Wireless communication systems (different ranges)
  - Smart power supply systems (sensors and transmission)
  - Long-term behavior and durability of materials and components
  - Data management and interpretation
- **Implementation**
  - Development of disposal specific monitoring plans (nat. & EB systems)
  - Integration of monitoring requirements in concepts (design relevant)
  - Demonstration of integrated monitoring systems
  - Data analysis and monitoring implications for the SC (& feedback to PA)
- Strategy
  - Links between monitoring plans and SC (requirements)
  - Procedures for data management and analysis (system evolution)
  - Monitoring in repository phases, URLs, test and pilot facilities
- Stakeholder & Communication
  - Expcetations of roles and relationships, strategies for stakeholder involvement, communication of monitoring results (confidence building)

- EG decided to move on with this topic (need for further R&D on different monitoring technologies)
- Presentation and discussion in a WS during the next Exchange Forum in Prague, October 29 – 30, 2013.
- Interested parties. Besides TP members, 4 further institutions (e.g. RWMC)
- Possibility to make a proposal to HORIZON 2020

Future Underground Research Labs in Salt: An Expert Survey

Christi Leigh and Frank Hansen
Sandia National Laboratories, Albuquerque New Mexico USA

Abstract

Creation of new underground space at the Waste Isolation Pilot Plant (WIPP) provides an exceptional opportunity to further advance the scientific basis for disposal of heat-generating waste in salt. Recognizing that mined space is an expensive and limited resource, this opportunity comes with a significant responsibility to use the space as strategically and cost-effectively as possible. Activities within the underground will be highly visible and have an obligation to serve the generic needs of US national repository programs, as well as other complementary programs. Plans for the underground research laboratory (URL) must be prepared with the highest scientific rigor. Proposed uses of the URL must focus on addressing those issues essential to examining the safety of disposing heat-generating waste in deep salt formations, and research must be planned in the context of the existing body of salt science. Against this backdrop, carefully considered science and engineering demonstrations could further bolster the strong position for salt disposal through confirmation and research activities in underground space at WIPP.

Sandia National Laboratories is a multi-program laboratory 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. Abstract of SAND 2013-7522C.

Exceptional service in the national interest — Sandia National Laboratories

Sandia National Laboratories

DBE TEC — DBE TECHNOLOGY GmbH

PTKA — Project Management Agency Karlsruhe — Karlsruhe Institute of Technology

U.S. Department of Energy — NNSA

Future Underground Research Labs in Salt: An Expert Survey

Christi Leigh and Frank D. Hansen

4th US/German Workshop on
Salt Repository Research, Design and Operations

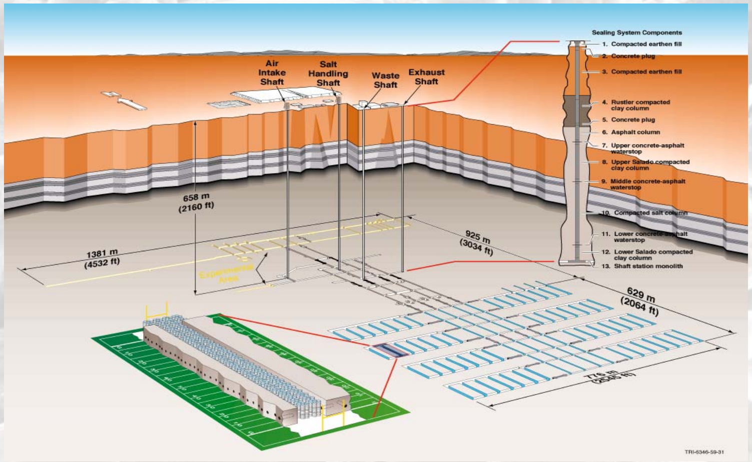
Berlin, Germany
September 17-18, 2013

Survey Purpose and Format

- Last Year's Survey was written, filled out ahead of time, and results were presented by Kris Kuhlman to the group and then documented in the workshop proceedings
- Since the workshop last year, we have had a number of exchanges in the U.S that have furthered the conversation about potential uses of a WIPP URL.
- Frank will summarize that information for the group
- Then, Christi will facilitate a discussion designed to identify the relative merits of alternative test proposals.

2

WIPP Facility Layout



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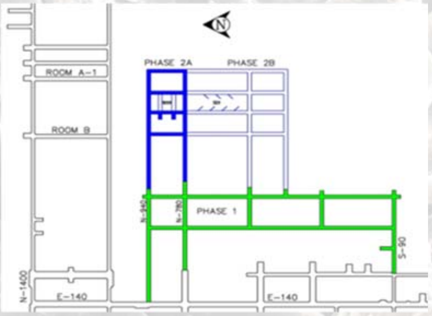
Layout of URL at WIPP



4

Potential/Intended Uses of WIPP URL

- Salt Defense Disposal Investigations (SDDI)
- Salt Disposal Investigations (SDI)
- Large-Scale Seal Demonstration
- Mining Research
- Wedge Pillar Test
- Mine-By DRZ Measurement
- Single Heater Test
- In Situ Consolidation
- International Test Bed—Suggestions from US/German Workshop #3

5

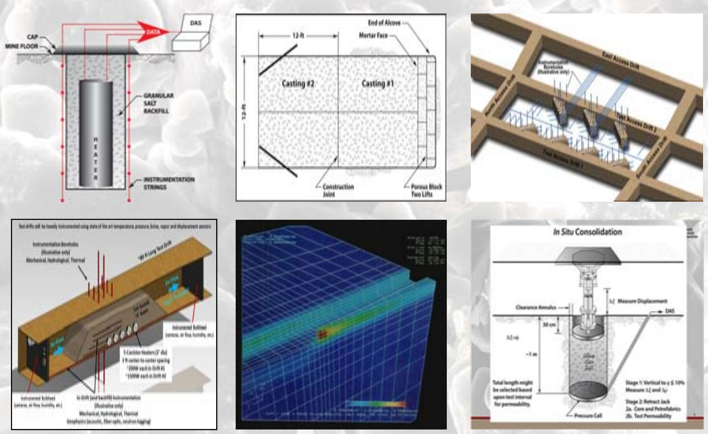
Uses of WIPP URL suggested by partners

1. Single heater test
2. Large seal test for crushed salt parameters
   - Two phase flow
   - Heat transfer
   - Diffusion coefficient of crushed salt
3. 1:1 scale heating test
   - emplacement demonstration and/or
   - collaboration on designing
   - preliminary TM(H) calculations

Salt concrete or MgO concrete large-scale seal test
   - Heated chamber behind the seal
   - Thermal behavior of concrete, host rock, EDZ
   - TM(H) behavior

6

Schematics of Main URL Activities



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Facilitated Discussion of Proposed Test Merits

8

WIPP Far-Field Hydrology

Kristopher L. Kuhlman
Sandia National Laboratories

Abstract

At the Waste Isolation Pilot Plant (WIPP), the regional hydrology of the Culebra Dolomite of the Permian Rustler Formation is an important factor in overall repository performance assessment. The Culebra is a possible offsite radionuclide pathway in human repository intrusion scenarios. The presentation summarizes past and present characterization techniques used at the WIPP. Hydraulic conductivity of the Culebra varies over at least 10 orders of magnitude, as estimated from results of single-well, small-scale multi-well and large-scale pumping and tracer tests.

Large-scale pumping and tracer tests can be difficult and costly to execute, so we are also evaluating the use of new characterization approaches using ongoing "natural" stimuli. These stimuli include both natural effects (e.g., precipitation, barometric pressure fluctuations, and earth tides) and non-WIPP man-made effects (e.g., oil and gas well drilling and potash mine collapse). Each of these stimuli has its own unique signature observable in the pressure transducer data recorded every 15 minutes in 65 wells completed to the Culebra and other formations. We are working to integrate data collected relative to natural stimuli with the conceptual model derived from traditional pumping and tracer tests. The primary challenge in synthesizing all this data is dealing with the wide range of scales, from a few meters to many kilometers.

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WIPP Far-Field Hydrology

Kristopher L. Kuhlman
4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

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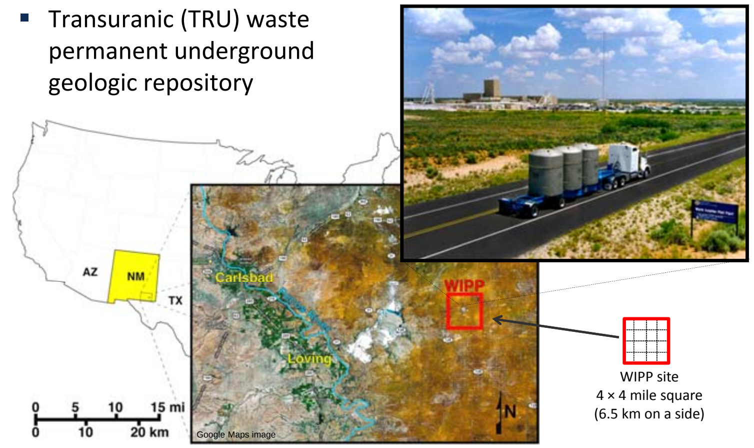
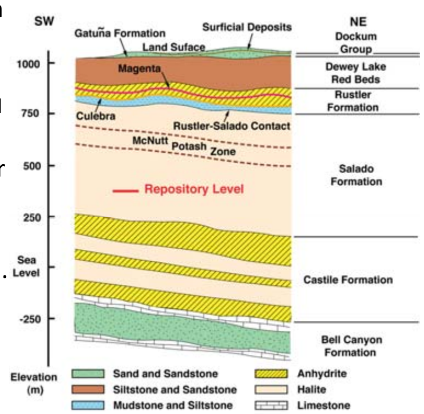
Waste Isolation Pilot Plant (WIPP)

- Transuranic (TRU) waste permanent underground geologic repository

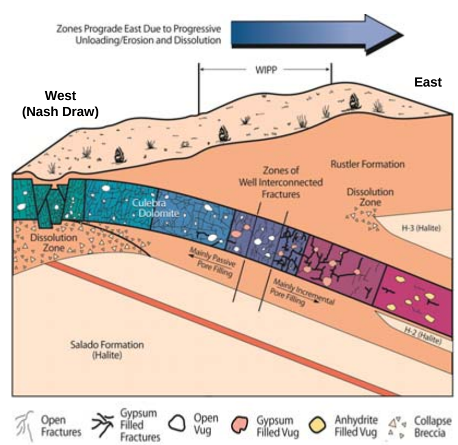


WIPP Hydrogeology

- Repository in Salado Permian bedded salt
  - >500-m thick salt unit
  - Immeasurably low undisturbed permeability from surface
- Human Intrusion required for repository breach
  - High-pressure Castile brine
- Culebra Member Rustler Frm.
  - Most permeable unit
  - Laterally extensive
  - ~7.5-m thick dolomite
  - Fractured (dual-porosity)
  - Focus of hydrologic testing



Culebra Conceptual Model

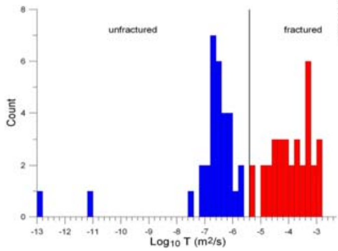


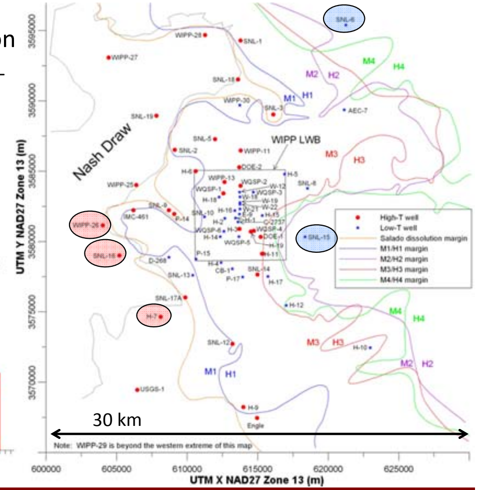
- Two types of processes control Culebra transmissivity (T)
  - Depositional
    - Lateral deposition of sediments or evaporites (mudstone/halite facies)
  - Alteration
    - Fracturing
    - Salado dissolution
    - Fracture in-filling
- High T in West
  - WIPP-26 : -2.9 $\log_{10}(T)$ m^2/s
- Low T in east
  - SNL-15 : -12.9 $\log_{10}(T)$ m^2/s

Part I: Traditional Hydrologic Characterization

Single-Well Hydraulic Tests

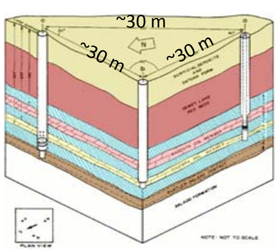
- >90 tested Culebra location
  - Doesn't include slug or drill-stem tests
- Single-well tests show **10 orders of magnitude** variation in *T*

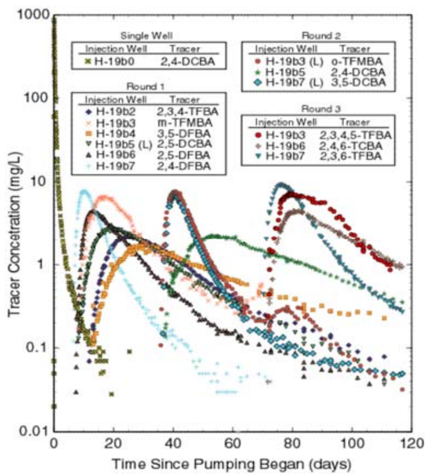




Multi-Well Hydraulic/Tracer Tests

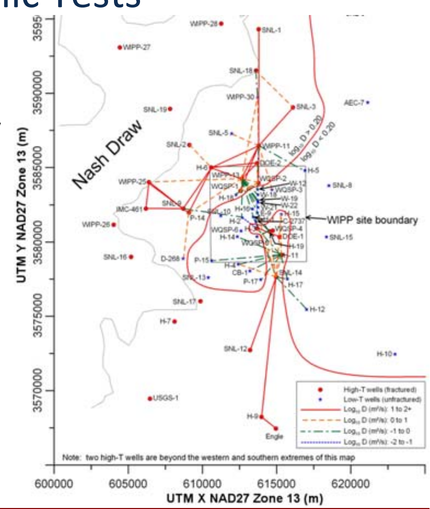
- 20 pad-scale pumping tests
  - 10 pads / 20 tests / 36 wells
- 8 multi-well tracer tests
  - Convergent/Dipole/Single-Well Injection-Withdrawal
  - H-19: drilled 7 wells for tracer test in 1990s





Multi-Pad Hydraulic Tests

- 17 multi-pad pumping tests
  - Up to13 observation wells/test
  - Observations up to 11 km away
  - 73 pump/observation pairs
  - Q up to 2.6 L/s (42 gpm)
  - Up to 63 days of pumping
- Diffusivity (*D*=*T*/storativity) used to characterize multi-well response
- Close match to single-well fractured/un-fractured distinction



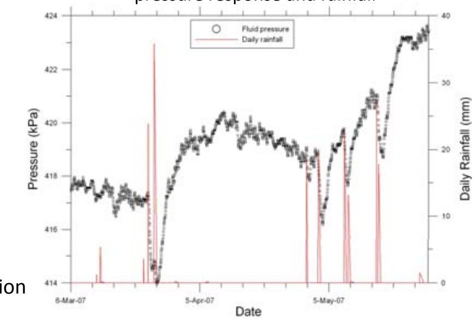
Part II: Alternative Hydrologic Characterization

9

Large-Scale Natural Stimuli "Tests"

- Growing database of high-frequency observations.
- Natural stimuli have large-scale effects
  - Precipitation
  - Barometric pressure
  - Earth-tides
  - Oil/gas/potash drilling
  - Mine collapses
- "Free" testing stimuli
  - Poor source characterization
  - Hard to untangle multiple effects

IMC-461 (in Nash Draw) pressure response and rainfall



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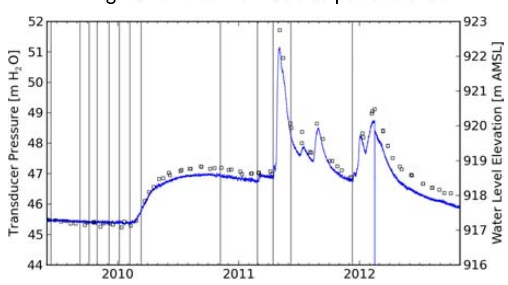
Oil/Gas/Potash Drilling

- Not natural stimuli, uncontrolled and ubiquitous
- Discrete location/time affects smaller area (< 5km)
- Questionable info available regarding "spud" dates
- Simulation?
  - 2D groundwater flow due to pulse source



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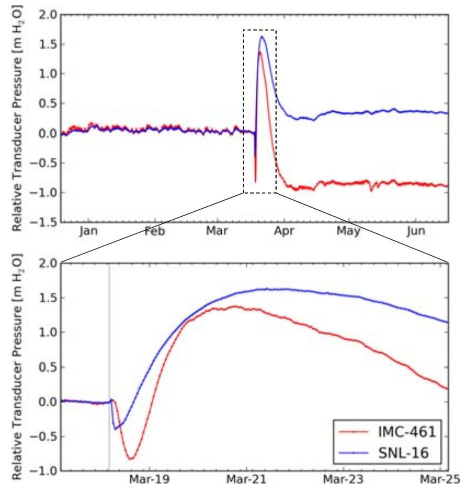
Potash Mine Subsidence

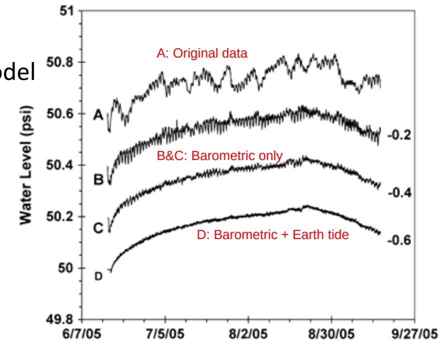
- March 2012 large mine collapse (unoccupied)
  - ~1.5 km of roof fell
  - 3.0 magnitude event reported by USGS
- 2 Culebra wells near collapse showed significant shifts in water level
- Oscillatory response is not purely hydraulic
  - Model a geomechanical response?



12

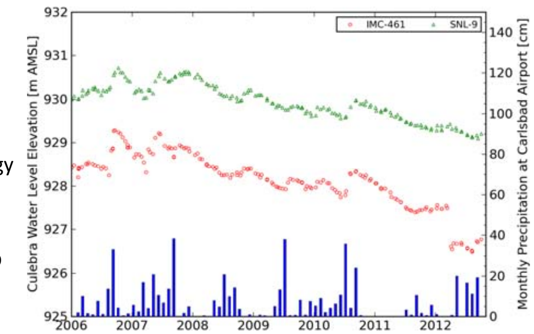
Barometric Pressure & Earth-Tides

- Previously removed to analyze pumping test data
  - Statistical approach (moving average least-squares fit)
- Alternately, use physical model to explain effects
- Estimate:
  - aquifer T, S, and porosity
  - vadose zone air permeability
- Source is well defined
- Simulation?
  - 1D vertical pressure wave
  - Solid stress/strain relation



Precipitation

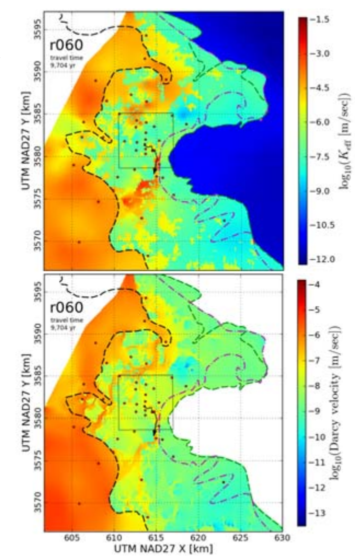
- Most rain in a few major storms in Chihuahua Desert
- Shallow system dries out between rain events
- Source poorly characterized spatially
- Karst plumbing in Nash Draw is complex
  - Complex geology
  - Difficult to simulate hydrology
- Simulation?
  - Include precip as source term in 2D model



Part III: Bringing it all together

Culebra in WIPP PA

- Created 1000 random base realizations (GSLIB)
  - Large-scale pumping tests
  - Culebra gypsum content
  - Fracture presence
  - Overburden thickness
- Calibrated 100 realizations to observed data
  - Pumping tests
  - Freshwater head piezometric surface
- Ensemble prediction for solute transport in PA



Summary

- Culebra Characterization historically focused on well testing
- New focus on "data mining" existing and future high-frequency monitoring records
- Use modeling to bring multiple scales of data together

Stimulus	# Tests	Scale
Single-well pumping	~100	1 m – 10 m
Single-pad multi-well pumping	20	5 m – 50 m
Multi-pad pumping	15	0.4 km – 9.5 km
Oil/Gas/Potash drilling	dozens per year	0.5 km – 4 km ?
Precipitation	2-3 per year	1 km – 30 km ?
Barometric/ Earth tide	continuous	1 km – 30 km ?

Conclusions

- SNL testing Culebra at a range of scales @ WIPP
- Working to incorporate all data in site PA flow model
- Methodologies applicable to other sites
- Far-field hydrology is always very visible to stakeholders and regulators

Sandia National Laboratories DBE TEC PTKA

d^3f and r^3t – modelling tools for density-driven flow and transport

Anke Schneider, Klaus-Peter Kröhn, GRS
4th US/German Workshop on
Salt Repository Research, Design and Operations

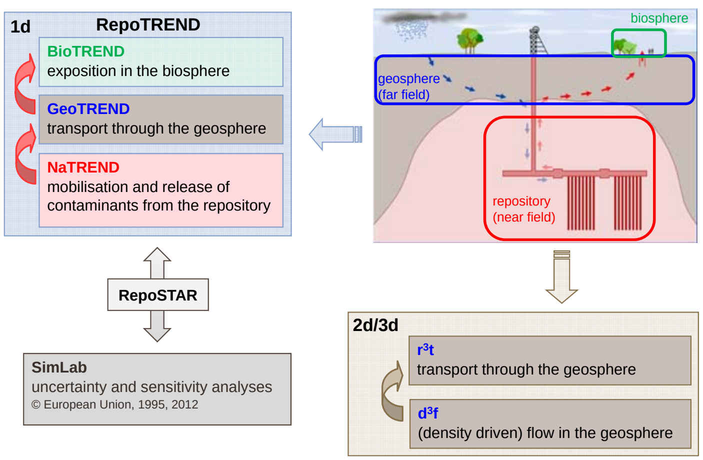
Berlin, Germany September 2013

GRS Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH

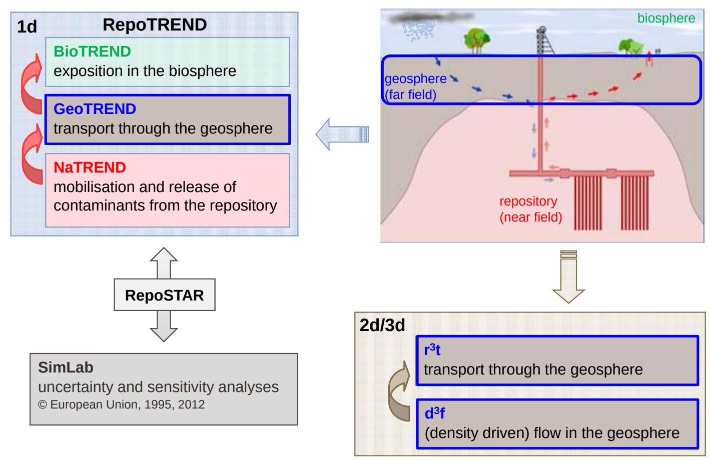
Outline

- Introduction
- Flow and transport codes
- Example 1: Gorleben salt dome
- Example 2: Äspö Hard Rock Laboratory
- Example 3: WIPP Site
- Conclusions

GRS tools for post-closure safety assessment



GRS tools for post-closure safety assessment

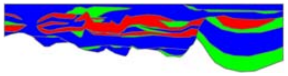


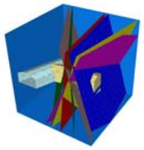
Developing a modelling tool

- 1990: catalogue of requirements (GSF, GRS, BGR, BfS, BMBF, PTE)
- 1992: decision to develop a new groundwater code
  - 3d density-driven flow in porous media
  - cutting-edge numerics
  - easily to extend and
  - to keep at the state of the scientific knowledge
- 1995: start of the development of d^3f (distributed density-driven flow) as a joint project in cooperation with 5 universities (BMBF, 02 C 0465 0)
- 1998: start of the development of r^3t (radionuclide, reaction, retardation, and transport) (BMWi, 02 E 9148 2)
- 2007: E-Dur – extention to fractures, heat transport, phreatic flow (02 E 10336)
- 2009: A-Dur – representation of inhomogeneities, adaptive discretisation of fractures (02 E 10558)
- 2012: H-Dur – speed-up of both codes (multi-core and graphic processors) (02 E 11062 A)

d^3f: distributed density-driven flow

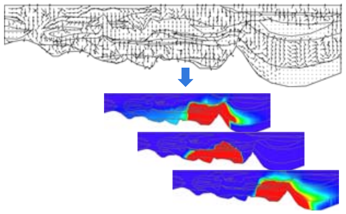
- 2d and 3d density-driven groundwater flow
- salt and heat transport
- advection, diffusion, dispersion
- fluid density and viscosity depending on concentration and temperature
- porous and fractured media
- confined aquifer, free groundwater surface
- completely coupled equations (no Boussinesq approximation)
- salt concentrations up to saturation
- permeabilities varying over some orders of magnitude
- sources and sinks
- permeability: constant, function, or stochastic
- user-defined functions (initial and boundary conditions, parameters)

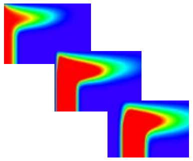




r^3t: radionuclide, reaction, retardation, and transport

- based on d^3f velocity field
- sorption
  - equilibrium sorption
  - kinetically controlled sorption (linear and non-linear)
  - "smart K_d-concept"
- precipitation/dissolution
- diffusion into immobile pore water
- element-dependent, anisotropic diffusion
- element-dependent porosities
- contaminant dependent decay
- complexation
- colloid-borne transport
- coupling with PHREEQC





Equations of d^3f

$$\partial_t(\phi\rho) + div(\rho\mathbf{q}) = 0$$ mass conservation of the fluid

$$\partial_t(\phi\rho\omega) + div(\rho\omega\mathbf{q} + \mathbf{J}_\omega) = 0$$ mass conservation of the brine

$$\mathbf{J}_\omega = -\rho\mathbf{D}\nabla\omega$$ Fick's law

$$\partial_t\left[\left(\phi\rho C_f + (1-\phi)\rho_s C_s\right)T\right] + div\left(\rho C_f T\mathbf{q} + \mathbf{J}_T\right) = 0$$ heat conservation

$$\mathbf{J}_T = -\Lambda\nabla T$$ Fourier's law

$$\mathbf{q} = -\frac{k}{\mu}(\nabla p - \rho\mathbf{g})$$ Darcy's law

ω	mass fraction of the brine		
p	pressure	ϕ	effective porosity
T	temperature	C_f	heat capacity of the fluid
$\mathbf{q}$	Darcy velocity	C_s	heat capacity of the solid (rock)
$\rho = \rho(\omega,T)$	fluid density	ρ_s	rock density
$\mu = \mu(\omega,T)$	viscosity	Λ	hydrodynamic thermal dispersion tensor

Equations of r³t

$$\partial_t(\phi\rho\chi_i) + div\left(\rho\chi_i\mathbf{q} + \mathbf{J}_{\chi_i}\right) = Q_i$$

mass conservation of the contaminant

$$\mathbf{J}_{\chi_i} = -\rho\mathbf{D}\nabla\chi_i$$

Fick's law

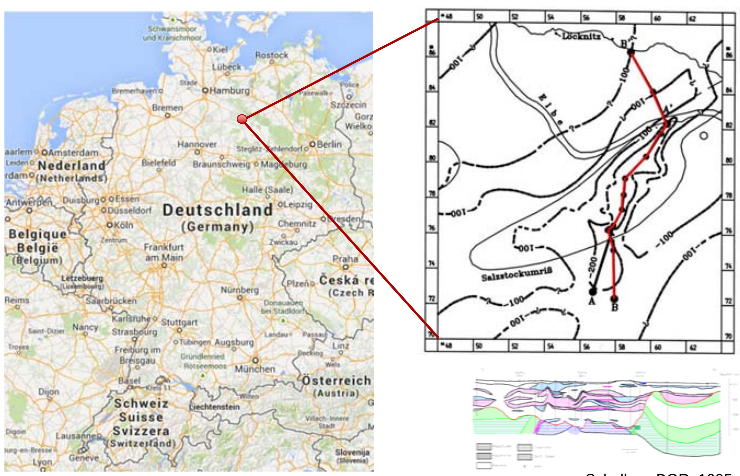
$$\partial_t\left(\phi\rho\chi_i^l + \phi\rho\chi_i^p + (1-\phi)\rho_s\chi_i^{ad}\right) + div\left(\rho\chi_i^l\mathbf{q} + \mathbf{J}_{\chi_i^l}\right) = Q_i$$

χ_i	mass fraction of the i[th] radionuclide (contaminant)
χ_i^l	mass fraction of the dissolved nuclide
χ_i^p	mass fraction of the precipitated nuclide
χ_i^{ad}	mass fraction of the adsorbed nuclide
Q_i	source term of the i[th] nuclide

Numerics

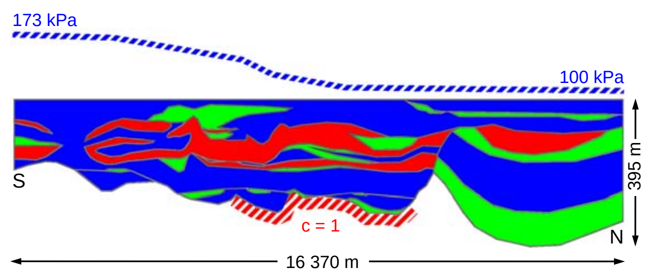
- based on UG (Frankfurt)
- finite volume discretisation
- grids
  - unstructured
  - tetrahedral and hexahedral elements
  - fractures lower dimensional
  - adaptive in space and time
- upwind strategies
- linear geometric and algebraic multigrid solvers
- r³t: operator splitting (radioactive decay)
- completely parallelised (dynamic load balancing): LINUX-PC to massively parallel computers (> 100 m elements, > 2 000 processors)
- interactive, graphical pre- and postprocessors

Gorleben salt dome



Schelkes, BGR, 1995

Overburden of the Gorleben salt dome: 2d hydrogeological model



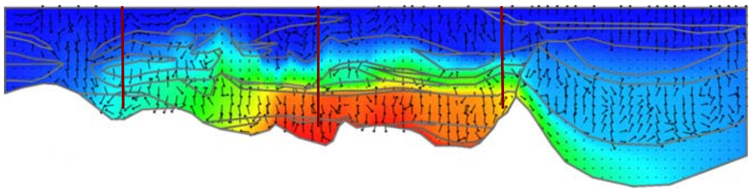
Aquifer,	$k = 10^{-12}$ m²
Aquitard,	$k = 10^{-14}$ m²
Aquiclude,	$k = 10^{-16}$ m²

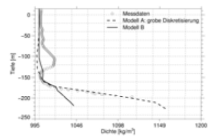
10 times exaggerated

top: atmospheric pressure, fresh water inflow
other boundaries: impermeable
hatched in red: contact with salt dome
initial state: c = 0

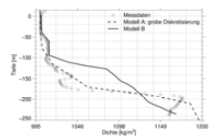
after Schelkes, BGR, 1995

Gorleben salt dome: salt concentration and velocity field (2000)

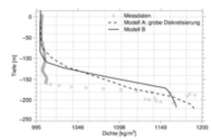




gohy 193

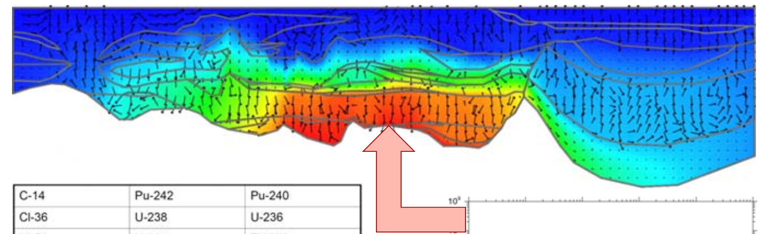


gohy 483



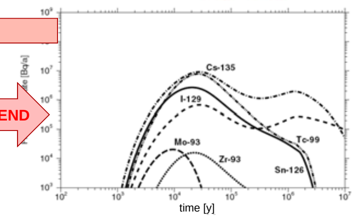
gohy 674

Gorleben salt dome: release of 28 radionuclides

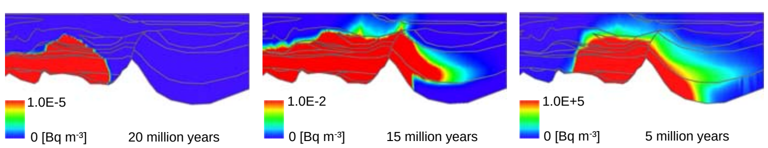


C-14	Pu-242	Pu-240
Cl-36	U-238	U-236
Ni-59	U-234	Th-232
Se-79	Th-230	
Zr-93	Ra-226	Cm-245
Mo-93		Pu-241
Tc-99	Am-243	Am-241
Sn-126	Pu-239	Np-237
I-129	U-235	U-233
Cs-135	Pa-231	Th-229

NaTREND



Gorleben salt dome: distribution for different radionuclides (r³t, 2005)



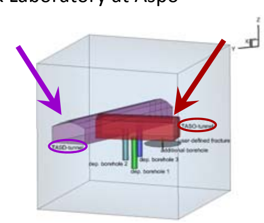
	Cs-135	U-238	I-129
half-life [a]			
	$2.0 \cdot 10^6$	$4.468 \cdot 10^9$	$1.57 \cdot 10^7$
K_d-value [m³/kg]			
sand	0.07	0.002	0.002
silt, clay	0.4	0.08	0.002

Äspö Hard Rock Laboratory

Field data from the Swedish Hard Rock Laboratory at Äspö

Model geometry

- domain
  - a cube with a side length of 40 m
- geotechnical openings
  - two drifts

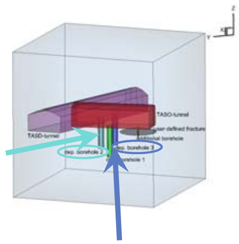


Äspö Hard Rock Laboratory

Field data from the Swedish Hard Rock Laboratory at Äspö

Model geometry

- domain
  - a cube with a side length of 40 m
- geotechnical openings
  - two drifts
  - two real boreholes

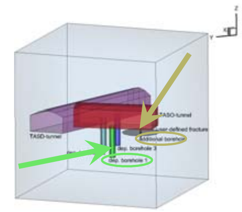


Äspö Hard Rock Laboratory

Field data from the Swedish Hard Rock Laboratory (HRL) at Äspö

Model geometry

- domain
  - a cube with a side length of 40 m
- geotechnical openings
  - two drifts
  - two real boreholes
  - two hypothetical boreholes

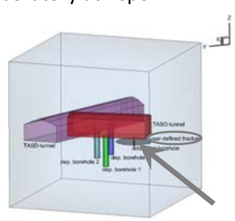


Äspö Hard Rock Laboratory

Field data from the Swedish Hard Rock Laboratory at Äspö

Model geometry

- domain
  - a cube with a side length of 40 m
- geotechnical openings
  - two drifts
  - two real boreholes
  - two hypothetical boreholes
- one „user-defined" circular fracture



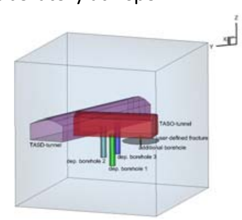
Äspö Hard Rock Laboratory

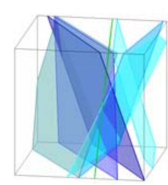
Field data from the Swedish Hard Rock Laboratory at Äspö

Model geometry

- domain
  - a cube with a side length of 40 m
- geotechnical openings
  - two drifts
  - two real boreholes
  - two hypothetical boreholes
- one „user-defined" circular fracture
- seven large-scale fractures

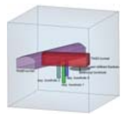
Hydraulic boundary conditions

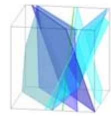


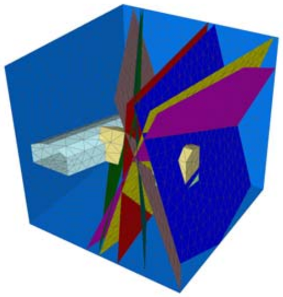


Äspö Hard Rock Laboratory

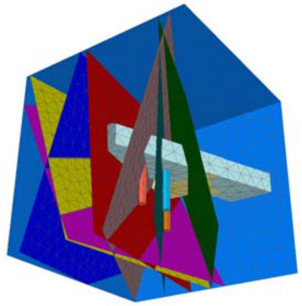
Coarsely discretised model (25 000 elements)







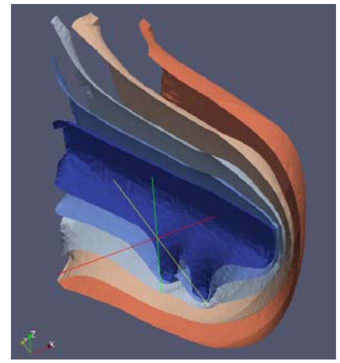
view from above

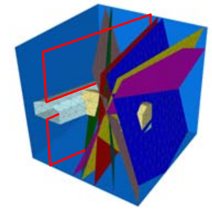


view from below

Äspö Hard Rock Laboratory (2011)

isoplanes representing dynamic pressure
-3.5, -2.75, -2.5, -2, -1.5 MPa

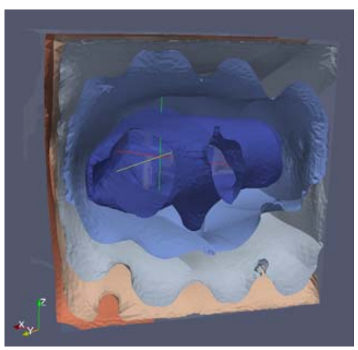


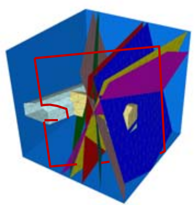


- pressure decreases from the cube surface to the openings
- highest gradient at the end of the TASD-tunnel
- the contour plane of lowest pressure (blue) follows loosely the surface of the openings.
- isoplanes have a rather smooth look

Äspö Hard Rock Laboratory (2011)

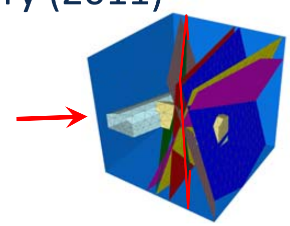
cross-section cutting through several fractures
wave-like disturbances in the pressure

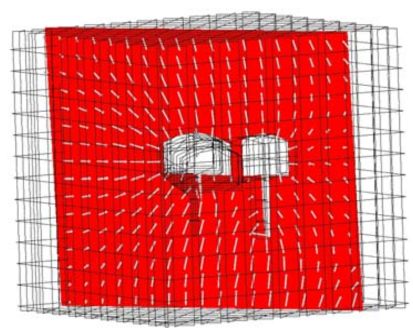




Äspö Hard Rock Laboratory (2011)

velocity field in the fracture
exemplary fracture highlighted in red
equally spaced velocity vectors





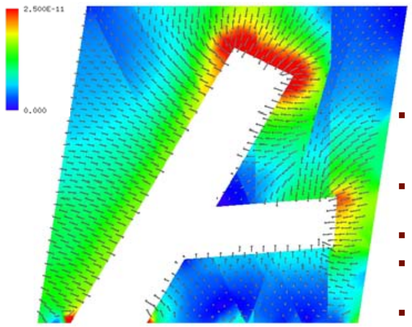
- flow from model surface to openings
- fractures
  - comparable orientation
  - connecting model surfaces with the geotechnical openings
- comparable pressure gradients in the fractures
- little interference

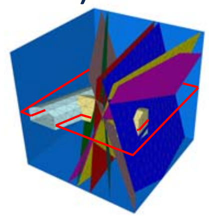
Äspö Hard Rock Laboratory (2011)

velocity field in the matrix

horizontal cross-section

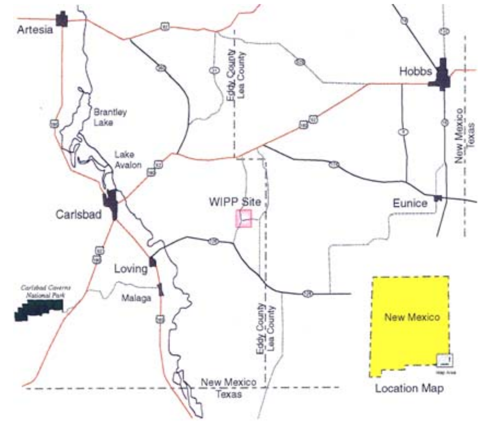
- flow direction → vectors
- flow rates → underlying contour plot





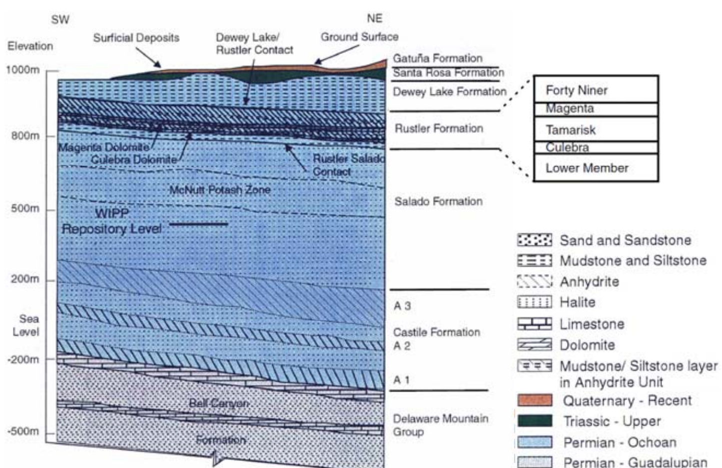
- intersections with the fractures
  → colour changes in the contour plot
  → deflecting the stream lines
- highest flow velocities at the end of the TASD-tunnel
- fractures provide hydraulic shortcuts
- calculated water flow into the openings: approx. 180 g/s
- measured inflow: 50 ml/s

WIPP Site



Data: US/DOE: Compliance Certification Application for the Waste Isolation Pilot Plant (WIPP), Title 40 CFR 191, Vol. 1. CAO-1996-2148, United States Department of Energy, 1996.

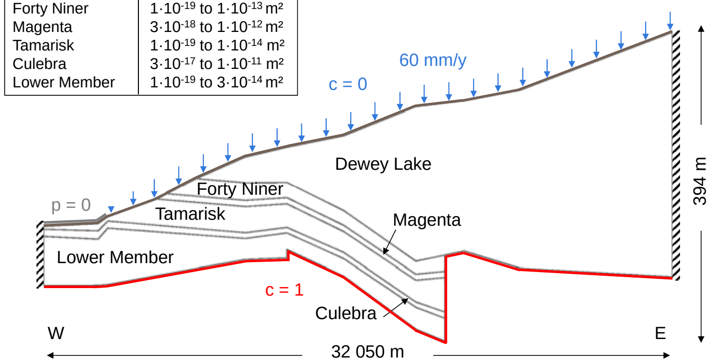
WIPP Site



Source: US/DOE

WIPP Site: model settings (2003)

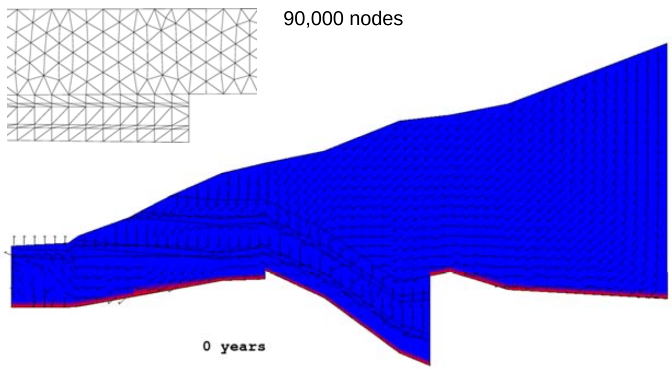
Dewey Lake	$1 \cdot 10^{-15}$ m²
Forty Niner	$1 \cdot 10^{-19}$ to $1 \cdot 10^{-13}$ m²
Magenta	$3 \cdot 10^{-18}$ to $1 \cdot 10^{-12}$ m²
Tamarisk	$1 \cdot 10^{-19}$ to $1 \cdot 10^{-14}$ m²
Culebra	$3 \cdot 10^{-17}$ to $1 \cdot 10^{-11}$ m²
Lower Member	$1 \cdot 10^{-19}$ to $3 \cdot 10^{-14}$ m²



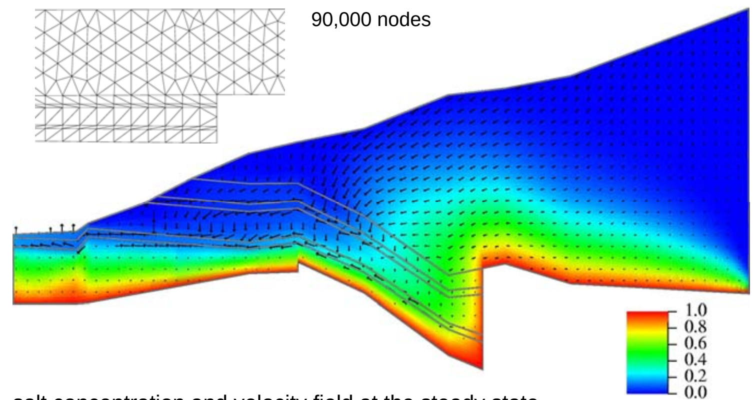
40 times exaggerated

after Schelkes, BGR, 1995

WIPP Site: 2d model (2003)

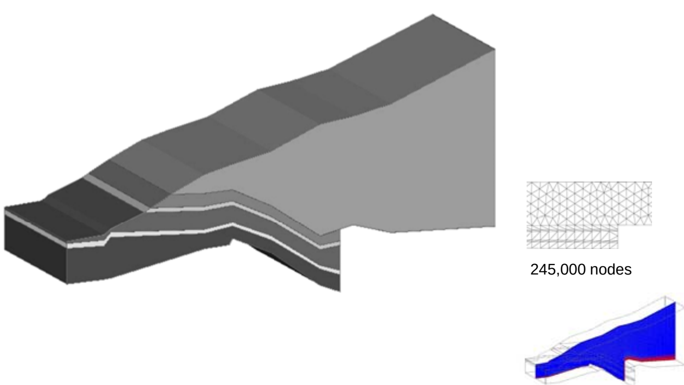


WIPP Site: 2d model (2003)

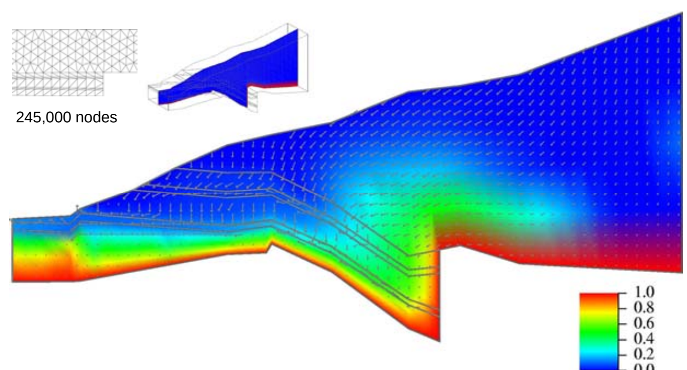


salt concentration and velocity field at the steady state
40x exaggerated

WIPP Site: 3d model (2003)

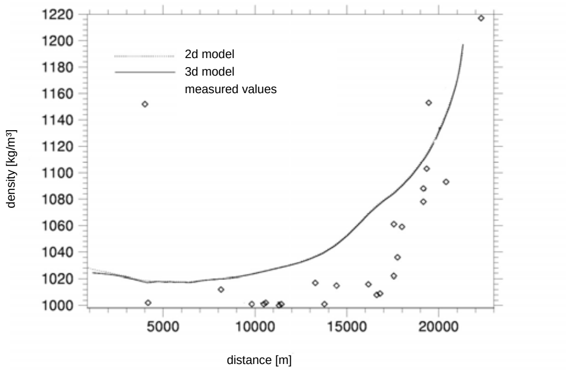


WIPP Site: 3d model (2003)



salt concentration and velocity field at the steady state
40x exaggerated

WIPP Site: fluid densities within the Culebra Dolomite



Conclusions

- d³f and r³t are powerful tools that are able to meet the needs of far field modelling
- applicable to porous as well as fractured media and to heat transport
- WIPP Site model 10 years ago
- open to cooperation, new modelling, new data…

Thank you for your attention!

This work was financed by the German Federal Ministry of Economics and Technology (BMWi) under Contract Nos. 02 C 0465 0, 02 E 9148 2, 02 E 0628 4, 02 E 9934, 02 E 9239, 02 E 10336, 02 E 10558, 02 E 11062 A and 02 E 11213.

Outlook on the Mechanical Behavior of Salt VIII

Lance A. Roberts, Ph.D., P.E.
4th US/German Workshop on
Salt Repository Research, Design and Operations

Berlin, Germany September 2013

The Conference

The *Mechanical Behavior of Salt* conference was initiated at The Pennsylvania State University, USA, in 1981.

Since that time, the conference has been held in:

1984 – Hannover, Germany
1993 – Palaiseau, France
1996 – Montreal, Canada
1999 – Bucharest, Romania
2007 – Hannover, Germany
2012 – Paris, France
2015 – USA

The Conference

The *Mechanical Behavior of Salt* conference topics:

- Research and management of underground structures in salt formations.
- State-of-the-art on applications of salt mechanics in mines and storage caverns for gas/hydrocarbon, radioactive waste, and toxic waste disposal.
- Laboratory experiments.
- Constitutive / numerical modeling.
- Field investigations.
- Creep, damage, THMC coupled effects.
- Lessons learned.

The Venue

The *Mechanical Behavior of Salt VIII* ("Salt Mech 8") is proposed for May 2015 and will be held in Rapid City, South Dakota, USA at the campus of the South Dakota School of Mines and Technology.

- Established in 1885 as the Dakota School of Mines to provide instruction in mining engineering.
- Current enrollment of approximately 2,400 students with 125 faculty.
- Offers BS and MS degrees in sixteen engineering and science disciplines:
  - Mining Engineering & Management
  - Geological Engineering
  - Geology
  - Materials and Metallurgical Engineering
  - Civil Engineering
  - Mechanical Engineering
  - Mathematics

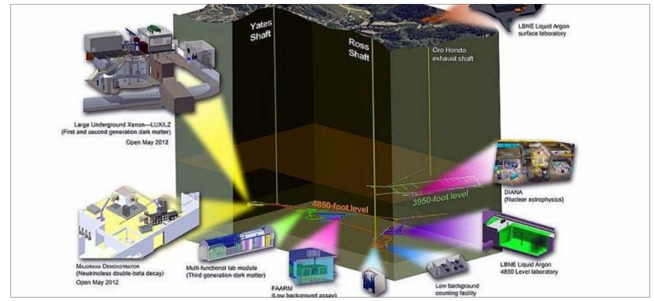
The Venue

Rapid City, South Dakota:

- Corporate Office of RESPEC.
- Within 25 miles of Mt. Rushmore.
- Within 35 miles of Custer State Park.
- Within 45 miles of Crazy Horse Memorial.
- Within 50 miles of Deadwood.
- Within 50 miles of Sanford Underground Lab.

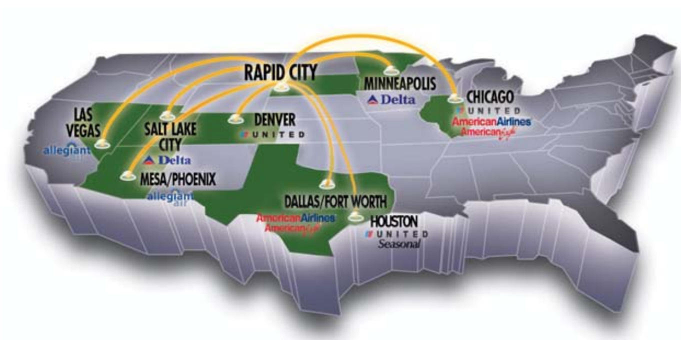
Sanford Underground Lab

The Sanford Underground Research Facility (SURF) is located at the former Homestake Gold Mine and contains a physics laboratory at a depth of 4,850 feet. Other research includes geology, biology, and other engineering disciplines.



The Venue

Air access to Rapid City, South Dakota:



Advisory Committee

- Frank Hansen, Sandia
- Leo Van Sambeek, RESPEC
- Pierre Bérest, École Polytechnique
- Karl-Heinz Lux, TU Clausthal
- Wolfgang Minkley, IfG

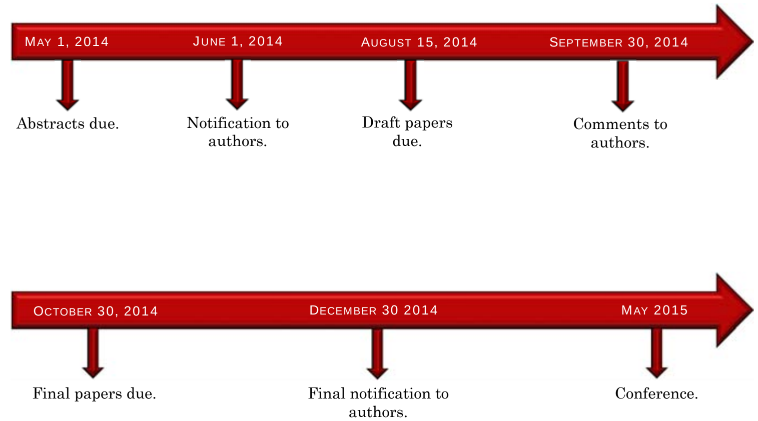
International Scientific Board

- To be determined

Organizing (Local) Committee

- Lance A. Roberts, RESPEC
- Leo L. Van Sambeek, RESPEC
- Kirby D. Mellegard, RESPEC
- Jay R. Nopola, RESPEC
- Sara Olivier, RESPEC
- Ronald J. White, SDSM&T
- William M. Roggenthen, SDSM&T
- Jeanette R. Nilson, SDSM&T

Proposed Timeline



THANK YOU!!

OECD NEA activities in safety case development of geological repository for radioactive waste

Gloria Kwong
OECD / NEA Radioactive Waste Management Division, Gloria.kwong@oecd.org

Abstract

The Nuclear Energy Agency (NEA) created the Integration Group for the Safety Case (IGSC) in 2000 and its mission is to assist member countries to develop effective safety cases supported by robust scientific technical bases. The IGSC evaluates safety related aspects in all developmental stages of repository implementation and provides a platform for international dialogues between safety experts to address strategic and policy aspects of repository development.

The IGSC carries out meetings with in-depth discussions of emerging issues and trends in developing safety cases for radioactive waste management. The working group also organizes technical projects and workshop to investigate specific topics of the implementation of radioactive waste repositories.

Since its formation in 2000, the IGSC has achieved many accomplishments in addressing safety case related issues. Safety cases are instrumental in demonstrating the long term safety of a DGR. A safety case compiles the evidence, analysis and arguments that quantify and substantiate a claim that the repository will be safe. In continuing its mission, the IGSC maintains a work programme to further develop, evaluate and communicate safety cases as bases for confidence and decision-making for radioactive waste disposal repositories. More information of the IGSC accomplishments, project publications, as well as current IGSC activities are available on the IGSC webpage: http://www.oecd-nea.org/rwm/igsc/. Other outcomes of the IGSC studies are also published in flyers, publicly downloadable from the above IGSC webpage.

In October 2013, the IGSC held an International Symposium on Safety Case for DGR in Paris. The symposium focused on the safety case of deep geological disposal facilities and addressed all stages of repository development. Current issues and challenges in safety case development, the interplay of technical feasibility, other issues related to engineering design, operation and post-closure safety were also discussed.