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Proceedings of the 5th US/German Workshop on Salt Repository Research, Design, and Operation

Fuel Cycle Research & Development

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Used Fuel Disposition Campaign
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ACKNOWLEDGEMENTS

We are delighted with the organization and assembly of these Proceedings provided by Laura A. Connolly of Sandia National Laboratories. LeAnn Mays, Shannon Casey and V. Dina Howell of Sandia National Laboratories were instrumental in organizing and facilitating the workshop in real-time. Of course, the value of this workshop is measured by advancement of the safety basis for salt disposal. To that end, the authors of these Proceedings owe a debt of gratitude to contributing researchers, who continue to illuminate the path of excellence.

ABSTRACT

The 5th US/German Workshop on Salt Repository Research, Design, and Operation was held in Santa Fe New Mexico September 8-10, 2014. The forty seven registered participants were equally divided between the United States (US) and Germany, with one participant from The Netherlands. The agenda for the 2014 workshop was under development immediately upon finishing the 4th Workshop. Ongoing, fundamental topics such as thermomechanical behavior of salt, plugging and sealing, the safety case, and performance assessment continue to advance the basis for disposal of heat-generating nuclear waste in salt formations. The utility of a salt underground research laboratory (URL) remains an intriguing concept engendering discussion of testing protocol. By far the most interest in this years' workshop pertained to operational safety. Given events at the Waste Isolation Pilot Plant (WIPP), this discussion took on a new sense of relevance and urgency.

The Proceedings summary is divided into a four major areas of discussion, which include operational safety, geomechanics issues, URL concepts, and capturing early evolution of excavation in salt. Performance assessment and the safety case are also central and ongoing themes of these workshops and have been summarized in previous Proceedings. Details can be found in Appendix E, where all presentations and abstracts are available.

1. Operational Safety. Operational safety was undertaken as a new topic. The workshop agenda was established before the incidents at the WIPP occurred: a truck fire on February 5 and a radiological release on February 14, 2014. However, these serious operational events provided sharp focus and tangible reality to the topic of operational safety. Participants gained deeper appreciation for the seriousness of operational safety and the complexity involved with recovery from off-normal events. Design of salt repository for high-level waste and spent nuclear fuel takes into account retrievability and safety requirements. Examples are provided in the main text as well as a synopsis of material presented on this topic at the 5th Workshop.

2. Geomechanics Issues. As the participants continue collaboration we examine the scientific basis for disposal of heat-generating nuclear waste in salt. With an abundance of scientific information in hand, the group is challenged to articulate remaining geomechanics issues for this purpose. The scientific technical foundation supporting a licensed salt repository has been developed in the US and Germany for many years. Although the level of effort has been inconsistent and discontinuous over this period, site characterization activities, laboratory testing, field-scale experiments, and advanced computational capability provide information and tools required for a license application, should any nation make that policy decision. Ample scientific bases exist to develop a safety case in the event a site is identified and governing regulations promulgated. Some of the key remaining geomechanics issues pertain to application of advanced computational tools to the repository class of problems, refinement of constitutive models and their validation, reduction of uncertainty in a few areas, operational elements, and less tractable requirements that may arise from regulators and stakeholders. These issues pertaining to salt repositories are being addressed in various research, development and demonstration activities in the US and Germany, including extensive collaborations. Research areas such as constitutive models and performance of geotechnical barriers have industry applications beyond repositories. The workshop context pertains to development of a license application, rather than an exploration of the entire breadth of salt research. While esoteric salt-specific phenomenology and micromechanical processes remain of interest, they are not specifically examined in these collaborations to date. The importance of various geomechanics issues and their associated prioritization are subject to ongoing discussion.

3. Underground Research Laboratory. Evaluating the basis of need for a URL for salt science and engineering is imperative because of the significant commitment of time and money required.

Decades of salt repository studies, numerous experiments, and sophisticated modeling capabilities underpin the scientific basis that supports safe disposal of nuclear waste in salt. The safety case for disposal of non-heat-generating waste such as transuranic waste interred at the WIPP is robust, with the only long-term releases to the environment projected to be by way of human intrusion. The scientific evidence also favors safe disposal of heat-generating waste. Technical evaluations for disposal of heat-generating waste in salt experienced a rather long hiatus in the US subsequent to certification of the WIPP (1999) and issuance of the Nuclear Waste Policy Act Amendment (1987) that ended salt disposal research for the civilian nuclear waste program. Similar salt repository research in Germany was delayed by a ten-year moratorium that ended in 2010. In collaboration with German peers, the US Department of Energy has reviewed and evaluated thermally driven processes in salt disposal and identified key technical areas in which to prioritize resources. The goal for disposal research in salt is to provide sufficient technical information to license a repository successfully. The necessity or utility of a salt underground laboratory is to be evaluated in the context of an overall research agenda that supports a license application. It is to be mentioned that both in the advanced programs and also in the less advanced ones URLs are considered to be indispensable especially to perform experiments and demonstration activities under repository like conditions.

4. Capturing Early Evolution of Salt Excavations. In situ tests implemented in a research facility mined from salt deposits, if planned appropriately, provide an opportunity to characterize the evolution of the host rock before, during, and after excavation of test rooms. Characterization of the test bed is essential to interpret structural deformation, formation and evolution of the disturbed rock zone, and measurement of first-order properties as the salt evolves from an impermeable undisturbed state to a more-permeable state. Geophysical measurements are identified to characterize the initial state of a test bed and its evolution over the course of a field test. Discussion includes what measurements could be made, why the measurements would be made, how they are made, and how accurately they need to be made. Quantifiable parameters will establish field-scale boundary conditions and data quality objectives to characterize the test bed in an underground salt research facility. This work ties together model prediction and confirmation of geophysical phenomena that are basic to the goals of the US/German salt workshops.

Principal evolutionary measurements make it possible to monitor geomechanical response and the associated changes in permeability. This progression will help establish boundary conditions for later tests conducted within the excavations. Pretest predictions of the response include strain magnitudes, room closure, and margins of the damaged zone. In turn, evolutionary measurements themselves will allow assessment of the predictive capability. Geomechanics modeling provides a basis for data quality objectives, which help define instrumentation requirements. Sufficient detail is provided to install gauges, conduct tests, and describe applicable functional and test-specific requirements. This type of forward thinking provides a primary means to reach and document consensus on all aspects of a test or experiment, including design, cost, schedule, interface controls, and data management. It might be interesting to consider such activities as a part of a monitoring program.

Collaborators continue to compile an international catalogue for Features, Events and Processes (FEPs) pertaining to the safety case for disposal of heat-generating nuclear waste in salt referring to existing catalogues for domal and bedded salt. Differences and similarities between bedded and domal salt are being examined. The goal is to have available a FEPs catalogue for use by the Nuclear Energy Agency (NEA) Salt Club members. The catalogue will identify and classify FEPs leading to a comprehensive list. A subset of the most important FEPs that individually or in combination contribute to long-term repository performance will be compiled using a new documentation template and numbering system. Overall, this is a large effort that will eventually become a product of the NEA Salt Club.

These Proceedings conclude with certain reflections on progress made. Our focus remains on issues pertaining to salt repository research, design and operation. We continue to challenge ourselves to develop products collaboratively that objectively document progress and deliver resources to external groups. As particular topics mature, new themes are added. In the following Proceedings, four selected topics noted above are developed in detail. Specific additional reference detail can be acquired from the abstracts, source references found throughout, and oral presentation slides included in Appendix D of this document.

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TABLE OF FIGURES

ACRONYMS

ABC	Actinide and Brine Chemistry (Workshop)
ARMA	American Rock Mechanics Association
BAMBUS	Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt / Germany
BGR	Federal Institute for Geosciences and Natural Resources (Germany)
BMU	Bundesministerium für Umwelt (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
BMWi	Federal Ministry for Economic Affairs and Energy (Germany)
BSEP	Brine Sampling and Evaluation Program
DBE Tec	DBE Technology GmbH
DOE	Department of Energy
DOPAS	Full Scale Demonstration of Plugs and Seals
DQO	Data Quality Objective
DRZ	Disturbed Rock Zone
EC	European Commission
EDZ	Excavation Damaged Zone
ELSA	Schachtverschlüsse für Endlager für hochaktive Abfälle (Shaft Seals for Repositories for High-Level Radioactive Waste)
EM	Office of Environmental Management
EPA	Enivronmental Protection Agency
EWG	Containment Providing Rock Zone
FEPs	Features, Events, and Processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
IfG	Institut für Gebirgsmechanik GmbH
IGD-TP	Implementing Geological Disposal of Radioactive Waste Technology Platform
KIT	Karlsruhe Institute of Technology
MoDeRn	Monitoring Development for Safe Repository Operation and Staged Closure
MoU	Memorandum of Understanding
MPBX	Multipoint Borehole Extensometer
NE	Office of Nuclear Engineering
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Agency
NWTRB	Nuclear Waste Technical Review Board
OECD	Organisation for Economic Co-operation and Development
PTKA-WTE	Project Management Agency, Water Technology and Waste Management
R&D	Research and Development
RD&D	Research Development and Demonstrations
REPOPERM	Restporosität und permeabilität von kompaktierendem Salzgrus-Versatz
SIERRA	Sandia Integrated Environment for Robust Research Algorithms

SNL	Sandia National Laboratories
THM	Thermal Hydrological Mechanical
TU	Technical University
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 5th US/German Workshop on Salt Repository Research, Design and Operation

Meeting Venue: La Fonda Hotel
Santa Fe New Mexico
September 8-10, 2014

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1 STATEMENT OF SIGNIFICANCE

The German Ministry collaborates with the United States (US) salt researchers under a Memorandum of Understanding signed by the US Department of Energy (DOE) and Federal Ministry for Economic Affairs and Energy in Germany (BMWi), a reflection of a long and trusted cooperation. This agreement has allowed salt repository engineers and scientists to advance the basis for salt disposal in the US and Germany.

Through these collaborations, past-present-and-future research is evaluated, which in turn illuminates the frontier of salt repository research, development and demonstration. In addition, collaboration between the US and Germany helps preserve knowledge, while at the same time mentoring the next generation of salt repository scientists. Together, the nations of Germany and the US define and explore salt-repository knowledge established in both countries over many years.

Under the patronage of the Organisation for Economic Co-operation and Development’s (OECD´s) Nuclear Energy Agency (NEA), recent collaborations have advanced an international Salt Club which permits stewardship of national programs in Germany and the US while providing derivative benefit to the international community.

Building the scientific basis for salt disposal combines the extensive knowledge from Germany on domal salt structures with that from the US on bedded salt formations. Collectively, salt researchers combine the technical basis for salt disposal in either geologic setting as their national site selection programs moves forward.

Partnerships among researchers on salt repositories ensure that science and engineering effective at the state of the art is accomplished. Bringing together the best minds in salt repository research, design and operation addresses a wide breadth of issues and facilitates the capability to dive deeply into selected issues.

Collaboration helps extend budgets of both countries, broadens personnel capabilities, and improves productivity over time. A prime example is a Joint Project (JP) between German and US modelers. This benchmarking exercise tests the best-in-the-world salt constitutive models on high-end computing platforms. This collaboration will identify the best modeling tools for future salt repository design, analysis, and performance assessment.

Although Germany and the US have collaborated for many years, workshop proceedings document solidification of the recent relationships enriched by the historic past and which sets the mutual programs on a productive course.

2 INTRODUCTION

Proceedings of the 5th US/German Workshop on Salt Repository Research, Design, and Operation provide a summary of the sequence of presentations and discussions and deliver a record of our workshop activities. Since restarting close US/German collaborations in 2010, annual workshops have assembled invited key investigators in salt repository science and engineering to address a coordinated research agenda. The authors of these Proceedings have functioned as the primary coordinators of these workshops and they are responsible for the scientific agenda and reporting. The 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 collaborated in salt repository research since the 1970s, where early collaboration between the US and West Germany involved thermal testing in the Asse Mine. Steininger and Hansen recount a chronology of salt repository research in the first presentation of these Proceedings. Note: all workshop presentations are provided in Appendix E. Techniques for waste emplacement and demonstration have been executed in Germany and the US. Instruments, tools and methodologies for modelling used in the safety assessment have been substantially developed and applied. Scientific work on salt repositories for nuclear waste is augmented by national programs in solution mining, strategic petroleum reserve, and traditional salt and potash mining where real-world applications are proven.

Direct collaborations between Germany and the US on salt disposal of heat-generating waste experienced a ten-year hiatus between 2000 and 2010 owing to political decisions and a formal moratorium in Germany. When the moratorium lifted in 2010, representatives of institutions in both countries wished to renew collaborations and cooperation on overall salt repository science, to coordinate a potential research agenda of mutual interest, and to leverage collective efforts for the benefit of their respective programs. Thereupon, the ***first*** of the new US/German Workshops on Salt Repository Research, Design and Operation collaboration was organized. Initial intentions were to exchange experiences and know-how to inculcate external expertise and feedback. Perceived benefits were first to make science-based recommendations on the pros and cons of the host rock, to add mutual value while sharing costs, and to garner internationally held opinions as well as facts.

> *This annual workshop is a poster child of our cooperation. There is a long tradition of co-operation between the US and Germany dating back to the 1970s. Some of our American colleagues were part of the research being done then, especially in the underground laboratory in the Asse research mine in Germany. We well remember the famous "BAMBUS" project, the world's first long-term demonstration experiment.*
>
> *Changes in political priorities in both countries repeatedly led to the joint research work being put on hold. However, in the scientific community the view prevailed that it is indeed technically feasible to construct, operate, and safely close final repositories within salt rock formations.*
>
> *Starting in 2009, both countries have again been more open-minded about rock salt to host final repositories and thus reverted back to the long-standing tradition of German-US co-operation in this area. So far, four workshops have been held as part of the effort to share scientific experience and resume our fruitful co-operation.*
>
> Dr. Pape—Welcome Address Excerpt
>
> (Complete Text in Proceedings)

By the time of this 5th Workshop, accomplishments and on-going activities include an impressive portfolio, [Steininger et al. 2013] all recorded and accessible electronically at our website (http://energy.sandia.gov/page_id=17258). At a high level, US/German collaboration is conducted under a Memorandum of understanding between our federal agencies. Results of our cooperation contribute to the OECD/NEA Salt Club. Significant reported work thus far includes natural analogues, a FEPs catalogue for salt, a state-of-the-art report on granular salt reconsolidation and a salt knowledge archive.

Engagement between researchers has given rise to many derivative activities. Notable is collaboration in the Joint Project on benchmarking constitutive models for rock salt between Sandia National Laboratories (SNL) and German organizations. Presentations on the third part of the Joint Project (JPIII) are provided by Hampel and Argüello in Appendix E. Collaborators also advance salt science in related conferences and workshops, such as the American Rock Mechanics Association (ARMA) conferences, Mechanical Behavior of Salt Symposia, and the annual Waste Management conference. Reinvigoration of salt research is strikingly apparent at the 2014 ARMA conference, which entertained five sessions on *salt* with many contributions made by US/German collaborators. Collective efforts were completed and reported in the European Commission (EC) Euratom-Project 7th Framework Program called Monitoring Development for Safe Repository Operation and Staged Closure (MoDeRn). Ongoing collaboration and information exchange in the area of safety case encompass a joint activity on *Handling of Uncertainties* in the framework of the IGD-TP (Implementing Geological Disposal of Radioactive Waste Technology Platform http://www.igdtp.eu).

This 5th Workshop carries on a content-rich tradition with the addition of the topic of Operational Safety. A keynote address was provided by J. Stephen Rottler of SNL (complete presentation is provided in Appendix E). In addition to JPIII modelling, laboratory testing, repository design, plugging and sealing, safety case and performance assessment, notes from the Salt Club, and other collaboration topics were covered at the 5th Workshop. As always, advanced and mature considerations are documented and published, allowing room for introduction of other relevant areas of mutual interest.

3 DESIGN AND OPERATIONAL SAFETY

In this section, we describe retrievability and safety requirements pertaining to design of a repository for high-level waste and spent fuel (HLW and SF).

3.1 Design Safety

The first generic repository concepts for the disposal of heat-generating waste and spent fuel in salt formations in Germany have been developed on the basis of safety requirements in the 1980s. A continuous improvement process led to a reference concept. Full-scale transport and emplacement technologies have been tested successfully in surface test facilities, again in compliance with safety requirements. In 2010, the Bundesministerium für Umwelt (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) [BMU 2010] issued the new *Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste*. The safety requirements focus on retrievability and make it a strict licensing requirement. According to the safety requirements, retrievability is considered as the planned technical option to remove emplaced radioactive waste containers from the repository during the operational period. In order to meet these requirements, adaptations to existing repository concepts must be analyzed. These adaptations and modifications could include

- an optimization of the spacing between waste containers and drifts
- the installation of adequate drift or borehole lining systems where necessary
- adaptions to the ventilation system
- the implementation of cooling systems
- monitoring and radiological protection measures during the retrieval process

As an example for the analysis of the necessary design adaptions the drift disposal concept was considered. It comprises the emplacement of heat-generating radioactive waste and spent fuel in standardized POLLUX® casks (casks with a cylindrical shape, a diameter of 1.5 m and a length of 5.5 m) on the floor of emplacement drifts of a repository. The layout is characterized by two access drifts from the two shafts. The access drifts are connected by cross-cuts which provide access to the emplacements drifts (parallel blind-ending drifts). The dimension of the emplacement device defines the minimum cross section of 17 m² for the emplacement drifts. Directly after emplacement, the remaining space inside the drift will be backfilled with crushed rock salt. The emplacement equipment (shaft hoisting system, transport unit and emplacement device) was successfully tested by DBE in the mid-nineties. These surface demonstration tests showed the technical feasibility of the emplacement concept and the reliability of the technical devices.

One option to retrieve POLLUX® casks from the emplacement drifts is the re-mining strategy. This strategy includes the re-excavation of the backfilled emplacement drifts, the access drifts and the cross-cuts (Figure 3.1). The new retrieval drifts will be excavated in three steps. First, two small drifts will be excavated at both sides in parallel to the waste containers. They will be connected with the nearest cross-cuts and will provide continuous ventilation and cooling. Afterwards, the remaining pillar between the two drifts will be removed by road headers and modified mining equipment. Eventually, the final retrieval drift provides a cross section sufficiently large to pick up the POLLUX® casks with a modified emplacement device. It is necessary to adapt the supporting frame for lifting and carrying the POLLUX® cask and to change the rail-bound system for retrieval. The modified emplacement device will transfer the POLLUX® cask to a transport cart. The transport back to the shaft and afterwards to the surface will be realized in reverse order to the emplacement process.

However, it is noted that before the POLLUX® casks can be retrieved, a concept for their subsequent handling and storage aboveground must be implemented. In the context of a research and development (R&D) project on behalf of the Karlsruhe Project Management Agency, DBE Tech will analyze in more detail the technical consequences of the retrieval requirement and the subsequent management of waste container. There still is a series of questions to be answered before state-of-the-art system has been achieved. Eventually the retrieval technique has to be confirmed in a series of demonstration tests.

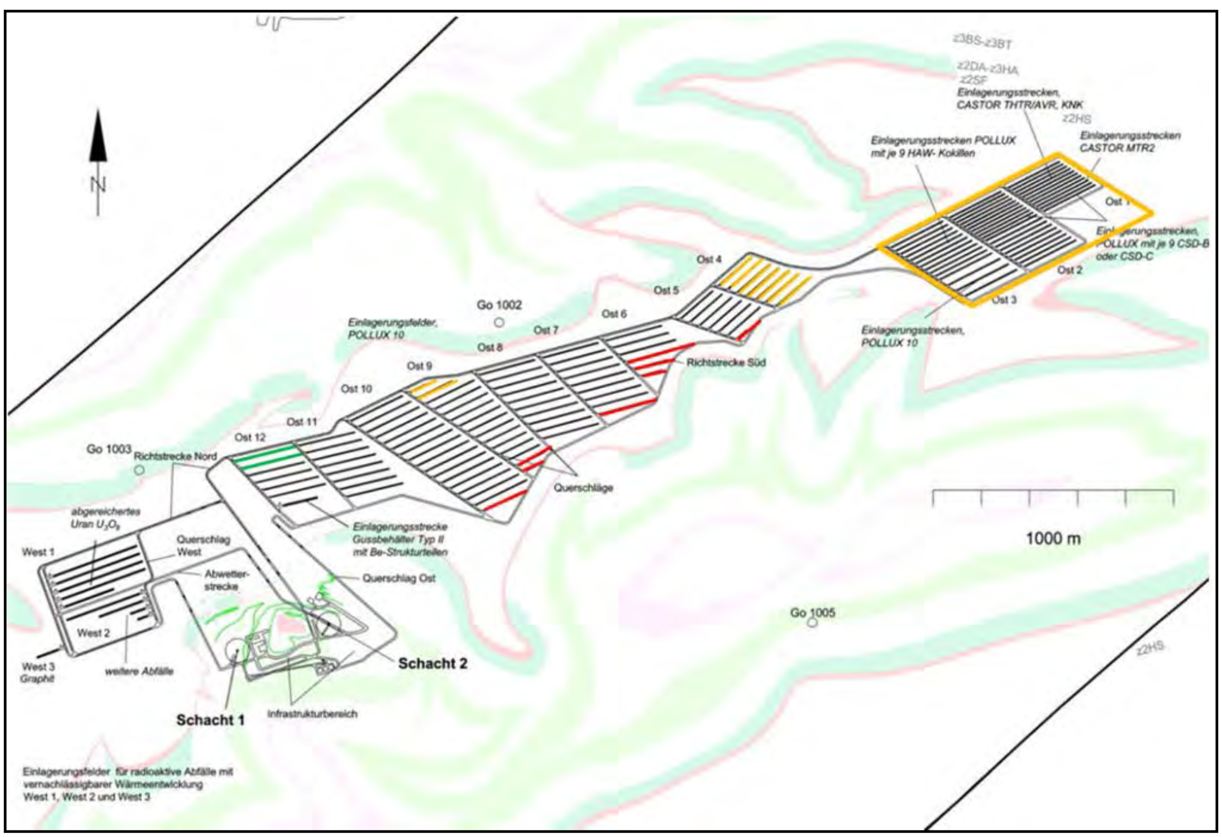


Figure 3.1: Site-specific design of a repository- drift disposal concept (basis: VSG design) in view of retrievability

Detailed planning of retrieval actions:

- green: retrieval drifts
- red: retrieval drifts not connected with a second crosscut
- yellow: retrieval drifts connected with main transport drift North
- yellow frame: prior to excavation start need for geomechanical proof of pillar stability)

3.2 Operational Safety

Operational Safety is an overriding concern from the first design of a repository for HLW and SF in salt formations to the closure phase. As geologic repository projects advance throughout the world, implementors and regulators are increasingly concerned with operational issues. In parallel, regulatory regimes develop further from pure deterministic to probabilistic approaches for nuclear installations in general. At present, only Germany and the US have real experience in the operation of geologic repositories. Hence, at last year's US/German Workshop it was agreed to organize this year a session specifically dedicated to operational safety. The two unfortunate events early in 2014 at the WIPP imparted an unexpected relevance to operational safety.

The relevance became obvious in that a central topic of the keynote address had been precisely operational safety. Insights were given to operational safety across a wide spectrum of activity of SNL. Dr. Rottler highlighted examples spanning a variety of research, design, development, prototype, qualification and production activities, where the breadth of work encompasses micro- to macro-scale efforts with varying levels of complexity. For the 2718 labs located within Sandia National Laboratories, multiple hazards in combination typically have to be considered. To ensure safety in this highly complex environment the approach of Engineered Safety had been developed and introduced at SNL. Engineered Safety means that operational systems are systematically and critically analyzed to identify ways in which they can fail to perform as intended, and, hence, are designed and validated to prevent identified failure modes and to mitigate the consequences of a failure should one occur. At each planning and design step safety is considered by systematically asking guiding questions involving the entire staff and management. How the approach is implemented in reality was explained by Dr. Rottler by means of the examples of a bioremediation project, a polymer R&D laboratory, and the Z-Machine accelerator containment system. A very important basis for gaining safety is implementing a Critical Thinking Mindset which means to encourage critical thinking in daily life.

Concerning geologic repositories, safety is governed by requirements from nuclear regulation, mining regulation, and public law. A similar approach is followed in Germany for geologic repositories as it is the case for SNL. Safety is key for the design of technology and for its operation. But safe designs and procedures must be backed by the right mindset of the staff. If the staff is not fully and wholeheartedly committed to safety, all safety would be ineffective. But even in normal and undisturbed operation the potential occurrence of hazards has to be considered in order to be prepared in case that a hazard actually does happen. Protecting people has highest priority in case of a hazard. Hence, staff has to be sufficiently trained and safety equipment and systems have to be adequately designed.

Developments and changes occur in the approach to safety, and also the evaluation of safety. A very recent and important development is the increasing relevance of probabilistic approaches in the regulation of geologic repositories. The shift from deterministic to probabilistic approaches is clearly exemplified in the US DOE nuclear facility safety analysis (WIPP Documented Safety Analysis) and the Yucca

Mountain License Application. For the Yucca Mountain Project probabilistic requirements have even been formalized in the U.S. safety regulation (10 CFR Part 63). The approach is evolutionary in that event compilation, sequence development, and hazard analysis are performed using traditional methods, combined with probability estimation under uncertainty, and explicit simulation of dose consequences for comparison to quantitative regulatory screening criteria. It can be seen that operational safety analysis is changing, at the same time that safety experience is accumulating at existing facilities. Especially for new systems and technologies, probabilistic approaches provide important supplements for safety demonstration. Nevertheless, since probabilistic approaches for large-scale systems are yet under development it is of vital importance to facilitate an international exchange in order to avoid diverging methodologies, respectively to build up confidence in probabilistic approaches.

Real life implication of operational safety issues could be observed in the unfortunate sequence of events and combination of events which happened in the WIPP facility in February 2014. Two incidents, a truck fire and an apparently unrelated radioactive release, occurred after fifteen years of successful operation. Despite the independence of the two events, a root cause was found to be insufficient safety culture [DOE 2014], which resulted in ineffective nuclear safety, maintenance, radiation protection, and emergency management programs. However, a route to overcome deficiencies and an approach to bring WIPP back into operation has been developed. Despite the unfortunate sequence of events, the idea of isolation of radioactive waste in geologic formations is not questioned.

In addition to the description of the events and the formal criticism, there are also positive findings to be recounted. Warning and mutual assistance of workers underground was effective and personnel exhibited detailed knowledge of the underground and ventilation splits. On-site medical response was effective in treating personnel. Technically, it can be concluded that the mine remains safe and stable. On that basis the main immediate activities have been developed and implemented. Special attention is directed to the evaluation of the situation in the area of the mine in which the radioactive release occurred. A key conclusion, which also closed the loop of the session, was that nuclear safety culture is a driving factor for WIPP’s future.

The discussion at the end of the session showed that operational safety considerations are an important contribution to the US/German workshop. While operational safety activities on site are very much dependent on the governing general regulatory regime and existing culture, regulatory requirements and methodologies for the assessment and evaluation of operational safety are still in development. Hence, chances were seen by the workshop participants to fruitfully and constructively contribute to the development by joint activities. Nevertheless, it was also seen as being meaningful to mutually follow operational activities on site as well in the course of the US/German workshop.

4 GEOMECHANICS ISSUES

This section provides several examples of direct collaboration in the area of geomechanics, which advance salt repository science. To capture the extent of the geomechanics issues, background information is provided to demonstrate historic perspective of the research agenda. Geomechanical response of the geologic formation to perturbations caused by excavation, structural evolution over time, subsequent disposal of heat-generating waste, and emplacement of sealing systems are first-order concerns for heat-generating nuclear waste disposal in salt. Use of salt formations for toxic waste and transuranic waste disposal is supported by broad technical understanding and experience gained from operating facilities in the US and Germany. The WIPP in New Mexico represents a successful process of site characterization and licensing of a salt repository in the US, while Germany has compiled the Preliminary Safety Analysis for Gorleben (Vorläufige Sicherheitsanalyse Gorleben or VSG) [GRS 2012]. Sufficient scientific bases exist to develop a viable safety case for heat-generating waste if a national program should decide to move in that direction.

Ongoing collaborations between US and German salt researchers continue to add to the imposing scientific basis for permanent disposal in salt. In this section, it is possible to present only a few highlights of salt-repository scientific inquiry. Additional detail of the most recent several years of accomplishment can be found on our website [http://energy.sandia.gov/?page_id=17258]. Collaborations facilitate evaluation of many elements of salt research, design and operation, which include testing on all scales, advanced thermal-mechanical modeling and benchmarking, and seal system performance, to name a few. Laboratory and field testing applied to nuclear waste disposal, particularly dealing with temperature effects, has been conducted since the 1960s. Decades of R&D have rendered a mature understanding of salt formation behavior as well as interactions between the salt and engineered and geotechnical barriers. The maturity of the technical basis for salt disposal also facilitates identification of areas where uncertainty can be reduced, areas where advanced computational capabilities can be brought to the problem and areas where operational and long-term improvements can be gained.

The US DOE's goal is to have a repository sited by 2026; the site characterized, and the repository designed and licensed by 2042; and the repository constructed and its operations started by 2048 [DOE 2013]. Given this time line, one daunting challenge will be preservation of accumulated knowledge and competence maintenance over the next 20 years. Ongoing international salt research collaboration is one well recognized development that contributes to knowledge preservation, which is systematically achieved by mentoring the next generation of scientists.

The geomechanical reaction to excavation establishes the starting point for all repository activities that ensue. Section 4.1 provides a brief description of the mechanical response and evolution of the salt underground initiated by excavation. These inescapable developments establish boundary conditions for the concept of operations, long-term repository evolution, and any field-scale testing that might be undertaken. Section 4.1 also provides an overview of ongoing geomechanics matters pertaining to room closure. Section 4.2 reviews code benchmarking of salt constitutive modeling and implementation using large, modern computational capacity. Section 4.3 summarizes progress made through international collaborations, particularly with German research groups. As documented in Section 4.5, the experience of preparing the preliminary safety assessment for Gorleben represents not only a high level of knowledge and advanced long-term safety analyses, but helped also to identify specific areas for additional research. US/German workshops on salt repository research, design and operation have progressively identified and addressed common issues, many of which pertain to geomechanics. Section 4.6 summarizes some of the geomechanics issues that can be constructively addressed in the near future. This section includes information that is being prepared for an invited, external publication [Hansen and Popp 2015].

4.1 Evolution

The technical basis for salt disposal of nuclear waste resides in salt's favorable physical, mechanical and hydrological characteristics. Undisturbed salt formations are essentially impermeable and exist in essentially isostatic equilibrium. When openings are created the state of stress is altered and salt deformation ensues. Understanding the features of salt deformation constitutes the bulk of geomechanics addressed in this section. Salt deformation can occur while preserving constant volume (isochoric) or can include damage, which increases permeability. Salt damage can be reversed under certain stress conditions and fracture healing is a vital feature of operational and long-term salt repository performance. Room closure is a combined result of isochoric creep at some distance from the opening, damaging salt deformation proximal to the free surfaces, and discontinuity contributions from interbeds, such as anhydrite and clay. Depending on design and operational choices, room closure eventually brings formation salt into contact with material placed within the openings, whether it is waste packages, geotechnical barriers, or run-of-of-mine salt used for backfill. Reconsolidation of granular salt constitutes another fundamental process that must be understood to ensure operational and long-term sealing performance. Geomechanics is concerned with all these phenomena, including possible thermal effects.

Accurate prediction of salt repository response is enhanced by a thorough understanding of the mechanistic processes and application of valid models. In the instance of a salt formation providing the host medium, the scientific community has made great strides toward formulating and using models that capture observed physical phenomena in computational mechanics applications. Incorporation of micro-mechanics helps explain history effects, normal and inverse transient responses, and dependence of creep rate on stress difference and temperature, which are direct consequences of existing and evolving substructures. If one understands the physical processes, operational and long-term predictions can be made with a measure of confidence.

Extension of this principle to micromechanics of deformation at very low stress difference is especially challenging. Minute strain measurements require extreme load and temperature control, although some outstanding experiments have been conducted [Bérest et al. 2005]. Changes to the microstructure would likely be below detection and documentation using normal microscopic techniques. Nonetheless, creep behavior of salt at low stress differences appears to be substantially faster than predicted from extension of power law models based on dislocation creep mechanisms parameterized from tests under repository conditions as shown in Figure 4.1. Conventional laboratory experiments, usually performed at differential stresses > 5 MPa, reflect steady state dislocation creep rate as a function of stress difference raised to a power greater than one, of which 4.9 is typical [Hardin et al. 2014]. When this relationship is extrapolated to low stress levels, the creep rate is much less than measured. Recently, an extensive series of creep lab tests on clean WIPP salt was performed using a new sophisticated creep test approach consisting of a series of single tests with load and unloading steps at overlapping stresses [Günther et al. 2014]. The test results confirm qualitatively the suggested dependence of creep behavior according to different stress regimes and show, in addition, the overlapping effect of temperature. A reasonable approximation of creep behavior is obtained using the advanced Günther/Salzer material law, but the remaining uncertainties at low stresses are obvious. Therefore, further work is needed to evaluate creep at low stress and high temperature levels and to resolve the deformation mechanisms.

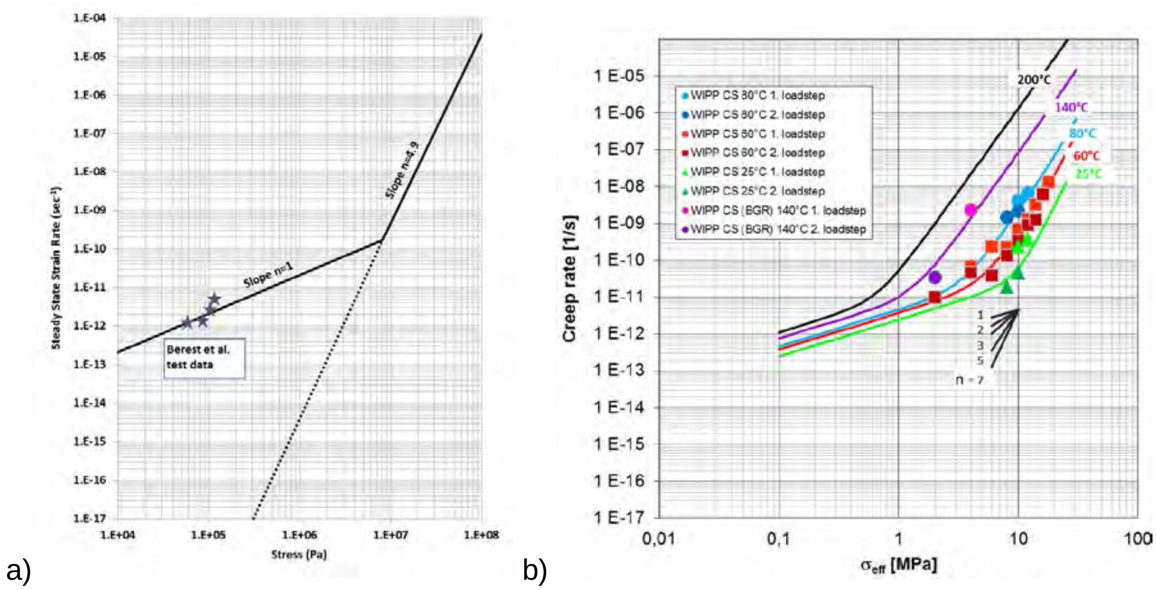


Figure 4.1. Creep of rock salt. a) Extension of a power law creep model to low stresses compared to measurements at low creep stresses. b) Creep tests results of WIPP-samples at different temperatures (clean salt strata), approximated with the constitutive Günther-Salzer law.

Upon mining, a salt formation experiences damage in the near-field rock proximal to the mined opening and salt permeability increases dramatically. The volume of rock that has been altered by such damage is called an excavation damaged zone (EDZ) or disturbed rock zone (DRZ). Creation of the DRZ can enable formation brine to flow into the mined opening via increased permeability. The mechanical response to excavation initiates several important changes to the favorable characteristics that exist in salt formations before excavation takes place. Investigations that utilize the underground for experimental activities would benefit greatly from the knowledge of initial, undisturbed conditions, the evolutionary changes imparted by excavation, and the boundary conditions extant when field activities are undertaken. This concept is developed further in Section 6 of these Proceedings and is being prepared for external publication [Hansen et al. 2015]. Regulatory compliance of a geologic repository in salt is demonstrated in part by credible representation of DRZ development and healing around panel and shaft seals to prevent this zone from becoming a pathway for radionuclide movement. Understanding DRZ development is essential to design and analysis of waste containment systems during disposal operations as well as to the design and analysis of repository sealing systems to fulfill permanent closure functions. Looking forward, ongoing research in these areas provide the basis for modular repository design, including closure systems in drifts, sectional closure, performance assessment, and input to sequential licensing.

Concepts for disposal operations and seal systems often include elements of crushed salt. Disaggregated salt can reconsolidate to a state approaching the native, undisturbed salt. Mechanical, thermal, and hydrological properties change as a function of porosity. Of these, the permeability/porosity function is the most important in terms of repository performance. Considerable research has gone into illuminating mechanical processes responsible for the observed permeability/porosity relationship illustrated in Figure 4.2 [IfG 2012; Kröhn et al. 2009]. The preponderance of consolidation experimental work, as well as analogue examples, suggest that reconsolidating granular salt will achieve a state of extremely low permeability. Development of the arguments is still advancing, which include new experiments that consolidate salt/bentonite mixtures. How quickly granular salt reconsolidates to performance specifications remains a key question. Construction techniques can utilize research results to place crushed salt seal elements to maximal density using optimal additives.

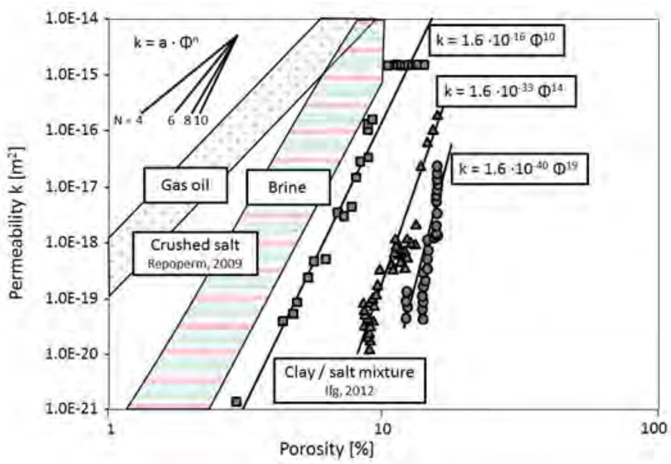


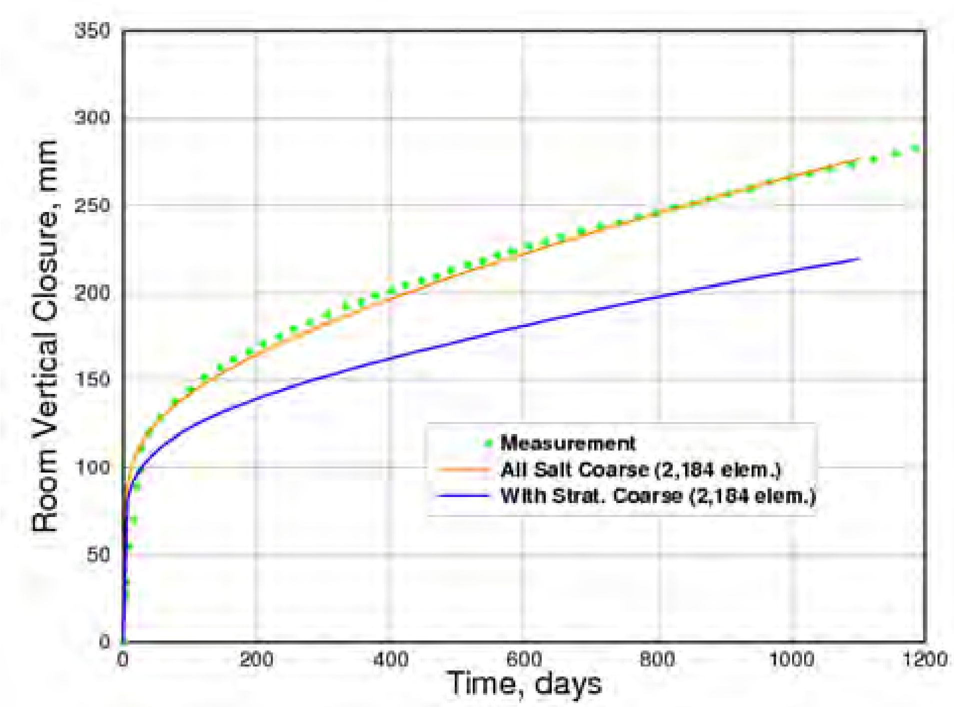
Figure 4.2. Permeability-porosity data sets for crushed salt and mixtures.

4.2 Modeling

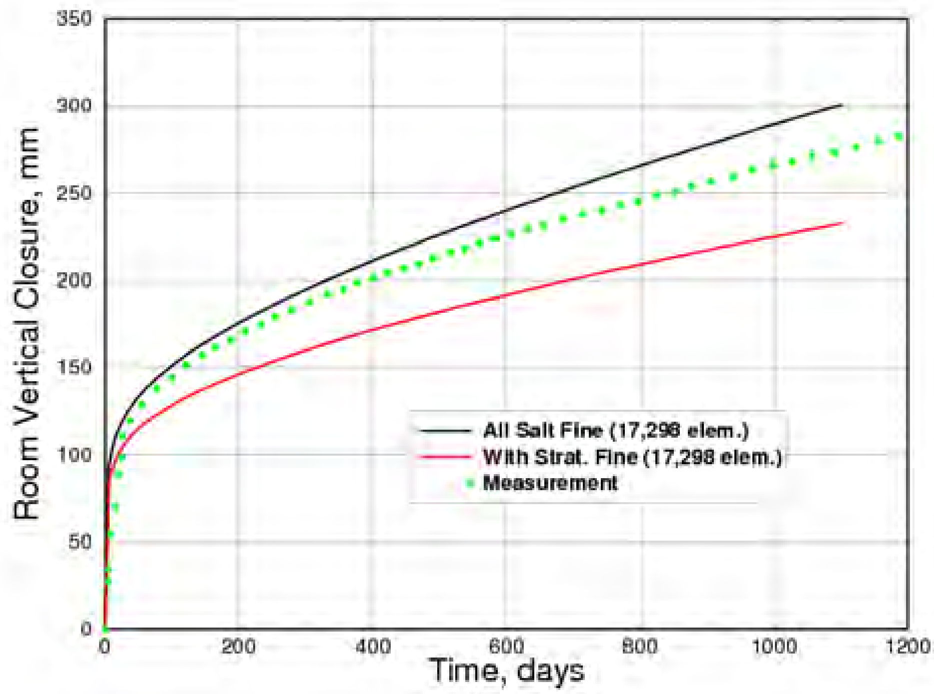
Computer-based geomechanical modeling of salt repositories has been one of the most important activities in salt repository science and remains so today. Remarkable progress is possible because computational hardware has advanced significantly over the last 20 years. Modeling capability includes representation of thermal-mechanical behavior over long time periods, appreciable variations of temperature, nonlinear large deformation (finite strain) and other phenomena associated with salt deformation in the repository setting. Integral to modeling studies are conventional issues of discretization, stability, and accuracy. A current research challenge is to identify best-in-class constitutive models, simulation architecture, and solution algorithms appropriate for analyzing the performance of underground salt repositories. To this end, a consortium called the Joint Project between SNL and

German partners is comparing constitutive models and simulation procedures. Modeling will simulate WIPP Rooms B and D, of identical geometry but different thermal loads. Calculations are isothermal, thermal-mechanical uncoupled, and thermal-mechanical coupled. Sandia uses a state-of-the-art Sandia Integrated Environment for Robust Research Algorithms (SIERRA) solid and thermal mechanics computer codes [Argüello 2014], while the German partners use their respective codes and models as described by Hampel et al. [2012; 2013]. All calculations use highly advanced constitutive laws that mathematically describe deformational processes inherent to those found in nuclear waste repository environment. The first goal of the project is to check the ability of numerical modeling tools to correctly describe relevant deformation phenomena in rock salt under various influences.

Twenty years ago or longer, models of WIPP large-scale experiments often matched the field data well [Munson et al. 1988; 1990]. Despite limited discretization, modeling symmetry assumptions, two-dimensional plane strain grids, field test results could be remarkably well reproduced by finite element models. Validation modeling in the Joint Project will include existing ambient and elevated temperature room response data to compare current constitutive models and simulation procedures for calculations of the thermal-mechanical behavior and healing of rock salt. A preliminary example of these benchmarking legacy calculations of WIPP Room D is shown in Figure 4.3. In Figure 4.3a) an all-salt idealization with relatively coarse mesh matched the vertical closure precisely, while a model with more detailed stratigraphy resulted in calculated closures below the measured values. By comparison, using a mesh about 8 times finer, Argüello [2014] obtains the results shown in Figure 4.3b). As Argüello points out, an under-refined mesh is typically stiffer, but it would appear that parameters and features, such as the coefficient of friction of clay seams, were adjusted to match test results in legacy calculations. In lieu of testing, assumptions were made about the clay seam behavior in closure measurements associated with Rooms B and D. These are just examples of challenges being addressed by the Joint Project partners.



a)



b)

Figure 4.3. Benchmarking Room D deformation.

International collaboration on model benchmarking is complemented immensely by additional testing of WIPP salt cores by German research laboratories. In concert with benchmarking of WIPP in situ experiments, German research groups are parameterizing their respective model variables through a series of special laboratory tests on WIPP salt. Thus their codes and models, which have been thoroughly calibrated against in situ experiments conducted in domal salt formations, will be appropriately parameterized for generic salt repository analysis with the inclusion of parameters representative of bedded salt. The benchmark problem extent, geometry, initial and boundary conditions and history will be established from well-documented technical information from existing WIPP literature. Thus far, preliminary benchmark validation efforts suggest that additional characterization of non-salt elements such as anhydrite and clay seam would improve model fidelity. Results from independent calculations will be compared and critically reviewed to assess how well the respective modeling and simulations capture full-scale field response. Continued work on the leading-edge constitutive models will provide the next generation of modeling capability that would then be applied to salt repository design, operations, seal systems, in situ test prediction, and performance assessment.

4.3 US/German Collaboration

In addition to the specific benchmarking discussed above, German and US salt researchers are addressing numerous salt repository issues, both technical and societal. The US DOE offices of Environmental Management and Nuclear Engineering (DOE/EM and DOE/NE) have collaborated on international salt repository research under the auspices of a 2011 Memorandum of Understanding with the German Ministry. Consistent with this agreement, collaboration in laboratory and field testing and geomechanical modeling has advanced significantly [Hampel et al. 2012; 2013]. This work has ensured validated and verified computational capabilities for both bedded and domal salt are being developed and parameterized. In addition to a technical mission, the scope of international collaborations explores public outreach initiatives implemented successfully in other countries to help frame a societal strategy.

International collaboration on salt repository research, especially between the US and Germany builds and reinvigorates previous partnerships.

Recent developments in Germany and the US have renewed efforts in salt repository investigations. On a yearly rotational schedule, workshops including representatives of institutions in both countries have reinitiated collaborations and cooperation on overall salt repository science. Workshops showcase accomplishment witnessed in several areas, such as repository analogue studies [NEA 2014], treatment of uncertainty, granular salt reconsolidation, seal systems, constitutive modeling, thermal effects on mechanical deformation, knowledge archive, a salt underground research laboratory (URL), an international catalogue for features, events, and processes (FEPs) for a salt repository [Freeze et al. 2014]. Progress made on these also contributes to the OECD/NEA *Salt Club* (http://www.oecd-nea.org/rwm/saltclub/). Close technical ties with the international nuclear waste disposal community allow the US salt repository program to capitalize on research being supported by other countries and to develop and have at its disposal the best salt repository capabilities in the world. The scope of these initiatives advances our nation's international repository position by leveraging collaborative salt science at favorable return on investment.

4.4 Lessons Learned from the VSG

In Germany, salt domes have been discussed as possible sites for a repository for heat-generating radioactive waste since the 1960s. As a candidate site, the Gorleben site located in Northern Germany has been investigated since 1979, at first from the surface and since 1986 from underground, when shaft sinking started [Bornemann et al. 2011]. The investigations were ceased between 2000 and 2010 based on an agreement between the German Government and the electric utilities. In 2010 site investigations were resumed and the preliminary safety assessment for the Gorleben site [VSG] was completed.

It should be noted the Project VSG is not intended as a safety demonstration for a possible later licensing procedure, which is still required by the Atomic Energy Act. Rather the objective was to prepare a comprehensive safety analysis for a salt dome with focus on long-term safety. An important part of work was also the identification of needs for future research and development and possible additional Gorleben site investigation. With elaboration of an overall synthesis the project ended in an orderly manner in 2013. A short project overview was given by Bracke and Fischer-Appelt [2013]. The complete reports (written in German) are available from GRS [2012].

The salt dome is 4 km wide and nearly 15 km long. It is composed of different salt rock types of the Zechstein (Upper Permian) series and extends to a depth of more than 3 km (Figure 4.4). As shown by Bornemann et al. [2011], in the course of the salt dome formation the salt was moved and uplifted several kilometers resulting in extensively folded, complex internal structure. During the uplift competent anhydrite layers were broken to isolated blocks. In the core of the salt dome the Hauptsalz forms a homogeneous halite body with a volume of several cubic kilometers. Contemporaneous with the diapiric movement of the salt, the effective stresses repeatedly fractured the rock salt and then healed it again, due to its high creeping capacity. This caused the Hauptsalz to become homogenized into a mixture in which blocks of primary rock salt crystals and shredded anhydrite fragments float in a matrix of recrystallized rock salt. Thus in the central part of the Hauptsalz no lithological or stratigraphical discontinuities such as bedding exist.

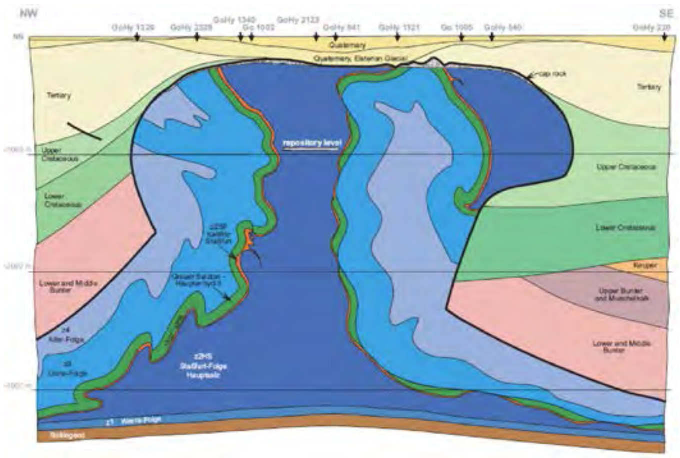


Figure 4.4. Simplified NW-SE geological cross-section of the Gorleben salt dome.

The Hauptsalz contains small amounts of gaseous and liquid hydrocarbons in separated zones of decimeter to meter dimensions. Brine reservoirs with fluid volumes in the range of liters to hundreds of cubic meters exist in certain regions of this part of the salt dome. The average water content of the Hauptsalz is below 0.02 %. Interconnected pores do not exist in the salt rock outside of fluid bearing or fractured area, i.e., the salt rock is impermeable.

Following the German safety requirements, released in 2010 by BMU, initially, a safety concept and a concept for demonstrating long-term safety were developed, that provided the basis for the design of the repository and the safety assessments performed in the Project VSG. Based on the safety concept specific requirements were derived concerning the site, the repository concept, the design of the mine buildings and the assessments to be performed within the Project VSG. The requirements concerning the site have to be fulfilled by the characteristic properties of the host rock and the overall geological situation. The main objective of the disposal is to contain the radioactive waste inside a defined rock zone, which is called containment-providing rock zone (EWG). The radionuclides shall remain essentially at the emplacement site, and at the most, a small defined quantity of material shall be able to leave this rock zone. This shall be accomplished by the geological barrier and a technical barrier system, which is required to seal the inevitable penetration of the geological barrier by the construction of the mine.

The repository is planned in a depth of 870 m below surface and will have a maximum length of approximately 4 km and a width varying between 300 m and 700 m, according to the geology and depending on the emplacement concept. An overview about the technical design of the repository and the detailed design of the geotechnical barriers is given by Bollingerfehr et al. [2013]. In addition to special designed engineered barriers (e.g., dams made of MgO-concrete), implemented in the drifts at selected locations and in the shafts, backfill made out of crushed salt is the main technical long-term barrier. The backfill compacts due to the convergence of the surrounding rock thereby sealing the backfilled drifts. The estimate for the minimum porosity that the backfill can achieve is 1 % ± 1 %. Since moisture accelerates the compaction of backfill, slightly moistened backfill is emplaced in the main drifts (0.6 wt.-% moisture).

According to the objective of safe waste containment, a crucial part of the Project VSG was to analyze the integrity of the geological barrier in order to determine whether stresses, which occur over time as a result of the forecast behavior of the geologic repository system, could violate the integrity of the barrier over the specified verification period. In other words, it was necessary to investigate whether the properties of the geological barrier forming the effective isolation system are maintained over the verification period. The geomechanical integrity analysis was jointly performed by the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, and the Institute for Geomechanics (IfG), Leipzig, [Eickemeier et al. 2013], considering two concepts: (1) the emplacement of Pollux casks in drifts and (2) the emplacement of BSK3 fuel element canisters in boreholes [Kock et al. 2013]. Both institutions used different material models, whose parameters were derived from site-specific investigations, according to the different rock units as illustrated in Figure 4.4.

To assess the barrier properties of rock salt layers under the influence of thermo-mechanical effects associated with the release of heat in the emplacement zone, computer simulations are carried out on the geomechanical processes which give rise to the creation of micro-fractures due to mechanical damage or fluid-pressure-driven opening up of grain boundaries. Understanding this process is important because the migration paths created in this way could ultimately cause liquids to penetrate the emplacement zone. This conceptual procedure means that the assessment of the hydraulic barrier properties is undertaken on the basis of mechanical parameters. This involves the use of the dilatancy criterion and the minimal stress criterion as proof of the BMU-safety requirements [BMU 2010] according to the two well-known mechanisms of hydro-mechanical integrity loss:

- deviatoric stress induced growth and connection of intercrystalline and transcrystalline cracks, which is assessed by the dilatancy criterion
- fluid pressure driven crack and grain boundary opening and their interconnection, which is assessed by the minimum (or fluid) stress criterion

2D models (IfG) and 3D models (BGR) were used for the thermo-mechanical calculations, illustrating all relevant loading conditions at different scales, i.e. in the proximal field in the emplacement zone (near field), including the drifts and emplacement containers, as well as to investigate the thermal effects on the salt dome as a whole (far field).

The realized integrity analysis clearly documents the high level of safety analysis based on geomechanical modelling demonstrating the requested geological barrier integrity for the site Gorleben for at least one million years. Additional studies on liquid and gaseous transport of radionuclides [Kock et al. 2013] confirm that the compaction behaviour of crushed salt backfill is one of the most relevant factors for the hydrodynamic evolution of the repository and the transport of contaminants.

Focusing on the geomechanical integrity, future safety analyses should involve more detailed investigations on the pressure-driven infiltration of fluids, e.g., along stratigraphic boundary horizons (bedding) within salt rock masses or zones where the integrity criteria are not fulfilled. Coupled THM calculations on fluid infiltration into the barriers (both geological and technical) require further developments of appropriate numerical tools supplemented by a comprehensive experimental data base, e.g., about discontinuities acting as mechanical and hydraulic weakness planes.

4.5 Geomechanics Going Forward

US scientists continue to cooperate with international peers to establish the integrity of salt repositories. Although a strong basis for salt disposal exists, analysis tools can be improved and updated, special studies to reduce uncertainty can be championed, and process improvements are always possible. This section stresses geomechanics issues, while recognizing importance of societal, stakeholder, operational, and regulatory input to the licensing processes. Confidence toward licensing a salt repository is couched in many instances by our deep understanding of the geomechanical behavior and our ability engineer safe systems.

The Joint Project III [Hampel et al. 2012; 2013] provides a prime example of updating analysis capabilities, which can applied to a salt repository for heat-generating nuclear waste. The best available constitutive models and computational methods provide the tools for next generation of design, analysis, operations, sealing, and performance assessment. New testing of WIPP salt coupled with existing data from bedded and domal salt allow for timely assessment of generic differences and similarities as regards repository geomechanics. A compendium that compares and contrasts bedded and domal salt as applicable to repositories would be beneficial for US and international salt repository programs.

The Project VSG represents a milestone of extended German research activities aiming toward establishing an underground repository for heat-generating radioactive waste in domal salt formations. The outcome provides convincing results demonstrating not only the highly developed level of safety analyses, but also supporting the general assumption of suitability of salt formations. A homogeneous halite body with a large enough volume was identified as possible host rock unit. The occurrence of fluid inclusions (brine or locally hydrocarbons) of Permian age confirms tightness which was preserved over geological time scales. As major part of the safety analysis the geomechanical modeling demonstrates the integrity of the salt barrier under consideration of likely and unlikely load conditions, especially with respect to heat-generated effects. The overall synthesis confirmed the adequacy of the approach, indicated the compatibility with the German safety requirements, and allowed the interpretation that there are no findings which actually contradicted the suitability of the location. In the VSG report on future R&D, open questions were addressed, i.e., concerning the integrity criteria. This confirms the need for development and improvement of advanced numerical tools for coupled hydro-mechanical calculations of pressure driven fluid transport in the salt mass (and the technical barriers). In addition, crushed salt backfill compaction was identified as one of the most relevant factors for the hydrodynamic evolution of the repository and the transport of contaminants.

Granular salt is likely to be used in the mine design for repository applications to provide structural support and other operational functions, thus reconsolidation processes and properties as a function of porosity continue to be key areas of ongoing research. Analogue evidence of reconsolidation to conditions that mimic native salt is substantial and supports the proposition that granular salt becomes effectively impermeable under many conditions. Owing in part to difficulty in measurement, uncertainty remains concerning flow behavior at very low porosities. Because characteristics that approach undisturbed salt are desired for many repository safety functions, demonstration is potentially more influential in the licensing arena than is model prediction of performance. Repository functions of granular salt can be advanced via analogue studies, evaluation of low porosity characteristics, and enhanced engineering performance attained by additives to the crushed salt. Until recently, most backfill research and design used run-of-mine crushed salt without additives such as bentonite. Evidence suggests that performance characteristics could be improved with admixtures that enable placement at greater density with lower initial permeability and porosity. This engineering achievement reduces uncertainty and perceived reliance on modeling. Repository designs, analyses and performance assessment for heat-generating waste will hinge on our state of knowledge concerning reconsolidation of granular salt.

A salt repository for heat-generating waste should take advantage of experience gained at WIPP, Project VSG and elsewhere. Rooms can be designed structurally stable to minimize geotechnical ground support. Forward looking engineering and performance assessment is likely to require intrinsic modular closure, which will no doubt include drift seal elements comprising reconsolidated granular salt. A recurring debate is the prerequisite that seals need to be demonstrated at full scale. In principle this can neither be attained in any reasonable time nor can the functionality be monitored. On the positive side, multiple construction demonstrations of various seal elements have been completed. In addition to crushed salt, the other most important engineering materials are concrete and bentonite. Looking forward, salt repository collaborators should consider compiling seal-system information into a document nominally called *A Synthesis of Salt Repository Seal Systems.* Such a jointly authored state-of-the-art report could include reconsolidation analogues, experience with bentonite and performance of special concretes. In the meantime, tests with admixtures are further enhancing the database.

A generic description of the evolution of the underground setting expounding upon geomechanics highlights as identified in this section would be of utility for analysts new to the field. The scientific community has firmly established knowledge of salt underground workings that should be recognized by modelers new to the field. Perhaps it would be useful for US and German collaborators to write another position paper that describes the evolution, properties and mitigation of the salt DRZ. Creation of a DRZ in salt is well recognized and for many engineering purposes sufficiently understood to provide confidence in its forward evolutionary characteristics and its mitigation through healing processes. However, quantification of anisotropic permeability associated with damage levels is elusive. Time-wise healing has little full-scale documentation aside from bulkhead (dammjoch) measurements being modeled in the Joint Project [Hampel et al. 2012; 2013]. It will be mandatory to close a repository; therefore, it is essential to establish that it can be sealed by appropriate and integrity-proven seal systems, including both shaft and drift settings. Fruitful collaboration is ongoing in the US/German workshops.

Salt remains a well characterized material for waste isolation. However, the future path is projected to be very long. The US repository program has identified a goal of 2048—and the German future repository policy is embarking on a review of the site selection process. Considering the very long times projected before a salt repository site is established through a new consent-based negotiated-consultancy siting process, it may be worthwhile for the established salt scientists to write a geomechanics salt repository primer that documents fundamental concepts. Such a book would be useful today as a means of knowledge preservation and for education purposes for the next generation of salt repository scientists and engineers.

5 A URL IN THE CONTEXT OF SALT DISPOSAL RESEARCH

Given the long history and encyclopedic information that underwrites salt repository science, what is the role for a URL at this stage? Salt disposal research provides many of the building blocks for licensing a salt repository. The question pursued in this section is twofold: Does URL testing reach a high priority in today's salt research, development and demonstration program, and if so, how are URL tests to be evaluated and prioritized? As of today, neither the US nor any other country has an operating URL in salt. It is widely believed that further salt testing in a URL is not required to address a perceived technical deficiency to be answered as a prerequisite to preparation of a safety case for salt disposal of heat-generating HLW. The technical basis for salt disposal provides strong and pervasive evidence that radionuclides in a salt repository will not migrate from the disposal horizon. Current knowledge of thermal effects supports viable concepts for disposal operations and underground evolution. The suitability of salt as a disposal medium has been recognized by national and international repository programs. Therefore, the scientific community must balance perceived necessity for field experiments with the recognition that a very strong scientific basis already exists for salt disposal of nuclear waste.

The essence of this section will be prepared as an external publication [Hansen 2015], which sets forth principles as well as a methodology for evaluating proposed URL activities. Because field testing is costly, any such test will necessitate commitment of money and time. Given the vast and compelling basis for successful waste isolation in salt, a choice to perform field-scale tests must be based on merit and a tangible connection to the Safety Case. Scientific investigations to support a license application are broad in scope, including laboratory tests at ambient and elevated temperature that characterize such properties as salt creep, the potential for fracture damage and its mitigation, permeability functionality of seal system components, brine accessibility via induced damage, chemical conditions in the disposal environment, and a host of other primary properties pertaining to performance assessment. The general goals for any future site characterization and laboratory or field investigations should build upon earlier work to reduce uncertainty and to enhance the safety basis for salt disposal. This document briefly discusses characteristics and modeling pertaining to waste disposal in salt with the intent to assess how a salt URL fits into the research agenda.

How then will decisions be made for potential URL activities within a focused salt repository R&D program? In this section, guidelines are put forward that outline a review and prioritization process for large-scale underground testing. Implementation principles include analysis and justification for generic testing or demonstration activities that meaningfully address technical issues in a credible manner. Implementation of demonstration and confirmation activities, integrated with other beneficial uses, could help establish an expected precondition for public and political acceptance of salt disposal of heat-generating nuclear waste.

5.1 Discussion

In-depth explanation of salt attributes for permanent disposal of heat-generating waste can be found in Hansen and Leigh [2011] and on the SNL website for US/German collaboration (http://energy.sandia.gov/?page_id=17258). A brief review of these characteristics will help clarify the foundation from which salt repository research proceeds. Long-term behavior of salt, fundamental to repository applications, requires detailed understanding of deformational processes, such that extrapolation can be made beyond human experience.

The scale of research to date ranges from a microstructural level to full-scale demonstration in the underground. Under most conditions involving elevated temperature and modest confining pressure, salt deforms plastically. The phenomenon of flow without fracture (isochoric creep) is one of the attractive attributes of salt as a disposal medium. Advanced constitutive models in the US and Europe have been used to describe phenomena associated salt deformation and their dependence on different fundamental mechanisms. These constitutive models are currently being benchmarked in ongoing international collaborations. Advanced modeling capability provides a dual purpose for field testing—modeling can be used to design test configurations at the outset and subsequently validated by test results. Regardless of proposed field activity, structural mechanics modeling has a role in defining the test bed.

Laboratory investigations in Germany and the US have provided the background understanding of salt mechanical and thermomechanical responses to anticipated repository conditions. Temperature has a dramatic effect on salt deformation and, therefore, temperature and associated heat management are first-order concerns for disposal of heat-generating nuclear waste in salt. The importance of heat from radioactive decay depends on the effects that the induced temperature changes could have on mechanics, fluid flow, and geochemical processes within a salt formation.

Salt deformation in the laboratory and in the field can be accompanied by significant fracturing at room temperature, low confinement, and relatively high differential stress, conditions that occur near free surfaces of the repository openings. Under these conditions salt exhibits a measure of brittle deformation near the roof, floor and ribs, but deforms by constant volume processes at depth within the rock formation. The properties that typically define the DRZ include (1) fractures ranging from microscopic to readily visible scales, (2) loss of strength evidenced by rib spall, floor heave, roof degradation and collapse, and (3) increased fluid permeability via connected porosity. Extant DRZ characteristics define boundary conditions for activities conducted within the excavated space. The general setting evolves with time and deformation; however, fracture development near excavations occurs rapidly. Evidence shows that damaged salt can heal under certain conditions, which is another important phenomenon conducive to investigations in a URL.

The Joint Project III collaboration, called *Comparison of Current Constitutive Models and Simulation Procedures on the Basis of Model Calculations of the Thermo-Mechanical Behavior and Healing of Rock Salt* started in October 2010 [Hampel et al. 2012]. This project compares modeling capability for temperature influence on deformation and for sealing and healing of damaged and dilatant rock salt. The research group is in the process of benchmarking salt mechanics codes against WIPP field tests, which were conducted during site characterization. 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 chemical bonding along fracture surfaces. In the constitutive models of the partners, modeling these effects is based on a description of the healing rate as function of the current dilatancy and the stress state. Differences in the models arise from differing assumptions regarding the healing boundary. This phase comprises performance and back-calculation of specific laboratory tests as well as simulations of selected in situ structures. At the conclusion of this collaboration, the benchmarked codes will thereafter provide analysis tools for any possible test or demonstration in a salt URL.

A salt URL could potentially host a wide assortment of tests to confirm our collective (international) knowledge on the technical basis for salt disposal. Consistent with our goals of collaboration, URL space could be used to underwrite internationally significant science and engineering, such as demonstration of sealing elements and DRZ evolution and healing. An ongoing performance confirmation program would be an integral part of a license for regulatory approval of nearly any repository and a URL setting could host an array of performance confirmation measurements associated with safety case arguments. Ongoing science made available by a salt URL holds the potential to reassure societal and political stakeholders. Due diligence also demands ongoing scientific research to confirm the licensing basis, even though the safety case for a salt repository is robust and well substantiated.

5.2 Framework

The opportunity to set out a generic research strategy for salt disposal helps focus objectives, which can be justified in several ways. A test or demonstration might address specific features, events or processes to confirm our understanding and ability to model performance of a deep geologic repository for heat generating radioactive waste in salt. An activity might be proposed to build confidence that the safety functions of a deep geologic repository in salt are understood and can be forecast over regulatory time periods. A URL activity might be identified by consensus of international collaborations. Many test concepts pertain to design and operational practice, which embody model prediction and confirmation at full-scale. These particular objectives align with similar lists put forward by the International Atomic Energy Agency [IAEA 2001] and Nuclear Energy Agency [NEA 2013], which also point out the benefit of training and education of the next generation of scientists. Many objectives taken from the literature are intertwined and expressible in different descriptive forms. For example, *addressing FEPs* essentially means the same as *assessing performance of the repository system*. Building confidence by reducing uncertainty is a well-recognized basis for field testing. International collaboration is a goal and perhaps a strong justification for investing in a field activity of mutual interest.

Development of proposed testing activities will benefit considerably by integrating information from Performance Assessment into the planning and prioritization of science and engineering activities. The Performance Assessment methodology uses a hierarchy of upper tier requirements that drive data requirements to support safety case development. This structured framework can be used to prioritize activities and transparently communicate up-to-date understanding of the repository safety case. Information within Performance Assessment calculations can readily identify the nature and potential impact of remaining uncertainties, which provide measures of perceived benefit to be realized by testing. Fundamentally, activities to be undertaken in a salt URL would require justification on an objective basis, one of which is impact on Performance Assessment.

Given broad descriptions of objectives, how can various URL ideas be rated and evaluated? What process is available to differentiate and select URL activities? A commitment to pursue URL testing must be predicated on a structure to weigh relative merits of proposed activities. This process basically describes a simple progression from concept development to evaluation and selection in the following order:

1. Describe activity
2. Conduct independent review
3. Rank and prioritize
4. Make recommendations
5. Select, plan and budget

The framework concept is quite simple: describe proposed URL activities and assemble a small independent review panel to evaluate merit. A framework for conduct of URL studies facilitates objective, rigorous, and transparent science. With strategic planning, investigations conducted in the underground can address a number of salt-based disposal issues while supporting generic salt studies. If undertaken with a view toward the future, operations within a URL could become a national and international centerpiece for salt repository research. Involvement of the international community would add scientific credibility and further strengthen stakeholder confidence. Operating a URL should allow participation by the next generation of students and nuclear waste management scientists through provision of a unique laboratory for basic and applied model development, laboratory testing, and field investigations.

5.3 Use of the URL

There are many potential uses of a salt URL, so it is essential to have a process to evaluate and prioritize. Furthermore, a long-term view of URL functions is vital to assess dual-purpose synergy, test-to-test interference, data acquisition, and infrastructure. Although a URL would focus on issues related to nuclear waste disposal, the overall portfolio would also include repository design and operation issues that can be isolated from heat effects, such as engineered barrier construction.

The idea of salt disposal, as well as disposal in other media, was restarted after the Yucca Mountain Project was declared unworkable in 2008. Concepts to reinvigorate salt disposal investigations were also outlined at that time, including a sequence of laboratory testing, benchmark modeling, international collaboration, and field testing. Description of several large-scale tests and demonstrations has been published [Hansen 2013]. In addition to a series of public manuscripts describing possible tests within a salt URL, the US/German Workshops on Salt Research, Design and Operation examined a suite of the proposed URL activities. International collaborations between US and German researchers has availed the possibility to review and discuss various salt URL test concepts. At the 4th Workshop potential URL activities were reviewed, including those previously identified in the literature as well as some new ideas. Workshop participants were asked to provide high-level review and feedback concerning a sense of duration, cost, and merit among several potential activities. Physical phenomena such as thermally driven creep processes or damage healing also require relatively large scale and time-dependent evolution. Considering there is no salt URL operating in the world, salt repository programs are in a position at this time to reflect deliberately upon the matter of a URL in the context of an overall research, development and demonstration agenda.

A variety of approaches can be taken toward grouping field tests in terms of information to be obtained. For example, seal system testing could involve excavation, short term DRZ evolution, concrete placement and DRZ healing. Thereby operational construction issues, model validation, first-order properties and confirmation could be integrated into one sealing demonstration. Tests could be grouped in relation to expected phenomena, such as thermally driven processes. In turn, the thermally driven processes could be ramped up from relatively low temperatures and low areal thermal loading applicable to a certain waste inventory to high temperatures associated high-burn-up used fuel. In each case, the technical basis (justification for the activity) would be different. Tests may be grouped with respect to degree of difficulty or complexity and evaluated based on cost-versus-benefit analysis. International experience in salt and other geologies provide further insights into the proper design and operation of URL research programs for maximum utility. There are many possible uses of a salt URL, which highlights the need for review and consensus [Van Luik 2013].

5.4 Concluding Remarks on Salt URLs

The viability of salt formations to host a nuclear waste repository has been well established. Therefore, a salt repository program does not require a field-scale disposal demonstration to resolve an unknown technical issue before a license application can be prepared. This conclusion is based on a wealth of scientific information that supported both the WIPP compliance certification and the preliminary safety case for Gorleben. The former is in bedded salt and the latter in domal salt. Sufficient technical backing has therefore been demonstrated to produce a license application for a salt repository for heat-generating waste if US policy is set in that direction. On the other hand, if confirmation or demonstration of performance expectations is felt to be essential for public acceptance, then it is possible that confirmation testing or disposal demonstrations could be developed to address such a societal prerequisite. The use of a salt URL could also signal that the repository program for salt disposal is committed to performance confirmation.

Examples of field testing and engineered barrier construction could further demonstrate existing ability to seal a salt repository. The state of international repository research, design and operation has been discussed and published in several annual workshops between US and German researchers. International collaboration continues to advance the basis for salt disposal, with exceptional modeling of WIPP Rooms B&D and many new laboratory tests on WIPP salt. Within the context of salt R&D, the proposition of a salt URL requires justification and establishment of merit in an objective and open implementation framework. Given the likely programmatic outlay in terms of time and money, a careful assessment of the return on investment is imperative. Therefore, a framework for implementation has been provided to guide selection of the most promising uses of underground space.

A URL in salt would provide opportunities for advancing identified US/German research interests and university outreach. Collaboration with Germany and other nations with salt disposal interests (The Netherlands and Poland) would help assure credibility of proposed URL activities and could promote partnering on certain ventures. No matter what activity is selected for the URL, new excavation provides a test bed for measuring evolving formation properties before, during and after the openings are made. Advanced planning allows modeling prediction of deformation and changing permeability. Pre-test characterization sets up a code validation/confirmation exercise in the process of defining boundary conditions for tests involving excavations, which is elaborated upon in the next section.

6 CAPTURING EARLY EVOLUTION OF SALT OPENINGS

The bulk of this section will be presented and published at Geomechanics Conference of the ARMA [Hansen et al. 2015]. Salt formations hold many favorable characteristics that combine to make them promising sites for permanent waste disposal. Salt formations are plentiful in the US, providing ample areal extent and substantial thickness in aseismic geologic settings [Johnson and Gonzales 1978]. In addition to high thermal conductivity and plastic deformational response, undisturbed salt has extremely low permeability. Some of the favorable characteristics are modified during the excavation process and evolve during operations. If experiments or operational demonstrations are conducted in a salt underground research facility, rapid changes to the preexisting conditions create a new setting in the test bed. The DRZ near the excavation free surfaces provides access to formation brine in bedded salt and becomes an anisotropic, high-permeability region. Depending upon objectives, liberated brine can significantly influence evolution of the test bed. In addition, transient creep strain accumulates rapidly, but is usually not measurable because the rock mass would have to be instrumented before mining occurs. Therefore, potentially large strain accumulation in the salt formation can be overlooked. To model salt deformation completely, an accounting of the transient creep contribution is needed. Fortunately, evolutionary characteristics of salt are well known and straightforward engineering measures can be made to quantify early evolution, which allows the experimentalist to understand and mitigate deleterious effects.

Investigations that utilize a mined salt formation for experimental activities would benefit greatly from the knowledge of initial, undisturbed conditions, the evolutionary changes imparted by excavation, and the boundary conditions extant when field activities are undertaken. Here we describe the essence of a Test Plan to quantify conditions before space is opened and to measure the evolution of displacement, strain, damage, and permeability that occurs during and after excavation. Testing of this nature would support virtually any type of field demonstration or test that involves room-scale excavation in a geologic salt formation. Test methods are adaptable to essentially any configuration. In order to demonstrate the monitoring concepts, a hypothetical test configuration has been assumed.

At this point in salt repository collaborations, neither the US nor Germany has a salt URL. However, the concepts put forward here would be applicable in any salt formation, bedded or domal in the US or in Germany. In addition the particular size, length and geometry of the excavation are assumed for purposes of displaying this test strategy. The host-rock characterization program begins from a minimally disturbed state where instrumentation is installed at the periphery of test rooms *before* room mining begins. After mining begins, changes are measured as stresses are redistributed and damage processes ensue.

The primary approach for characterizing the DRZ is by use of fluid-flow test boreholes and injecting gas or brine in the areas of interest where mechanical changes occur. This testing program will make deformation and fluid flow measurements at similar locations so that unambiguous correlations can be established between rock deformation and permeability changes. The arrangement of instrumentation and measurement techniques allows establishment of initial (undisturbed or minimally disturbed) conditions, capture of the rapid transient response, and evolutionary monitoring as the salt creeps into the room. Measurement of mechanical response coupled with hydrologic changes establishes boundary conditions for any test or demonstration that might be conducted in the excavation.

An underground research facility in salt provides an opportunity to measure undisturbed permeability, which is expected to be almost immeasurably low. Such a measurement would confirm this widely recognized salt property. Excavation perturbs the stress state and the static salt formation begins to deform into the opening. The process of mechanical deformation creates fractures in the proximity to the openings. Fracture damage creates a permeability that did not exist before, and the accessible brine moves down the hydrologic gradient toward the opening. Some of the brine reaches the walls of the opening and is evaporated by ventilation air. Some of the brine remains in the DRZ and flows by gravitation into void space created in the floor region by flexure. The brine below the floor would continue to flow down the geologic slope of a bedded salt formation. The creation of the DRZ and its geometry and properties, as well as the availability of brine and its fate create initial boundary conditions of the site regardless of the technical purpose for which an excavation is used. These fundamental properties of the salt formation can be predicted by calculation, monitored for confirmation, thus validating the computational simulation.

6.1 Salt Behavior

To explain the testing strategy, some assumptions of the configuration are necessary, mindful that the philosophy, evolution, and measurement concepts are adaptable to essentially any reasonable opening geometry. The surrounding stratigraphy is predominantly halite, though bedding layers of clay and anhydrite are common and will be included in discussions here.

Mechanical deformation of the rock in a salt formation surrounding excavations controls the development of *initial* or *boundary* conditions for subsequent experimental work in the drifts. Geomechanical deformation comprises instantaneous elastic deformation, rapid transient creep, dislocation creep, and damage imparted to the host rock under certain stress conditions. Combined, these processes can be quantified through observations of deformation rates, finite displacements, and characteristics of the DRZ.

6.1.1 Geomechanical Measurements

Testing techniques proposed have been used previously in salt applications and can be considered generic. The instruments would be arranged around a to-be-mined drift configuration appropriate for geologic waste disposal. Testing and monitoring include primary measurements of deformation, strain rate, and brine and gas flow and secondary measurements of temperature and barometric pressure.

Salt creep has been extensively measured and characterized by US and German salt repository programs and other salt-based industries (e.g., salt and potash mining). Crystal plasticity is isochoric; therefore, it does not induce damage to the salt matrix. Damage occurs when the deviatoric (i.e., shear) stresses are relatively high compared to the applied mean stress. Salt damage manifests through time-dependent initiation, growth, and coalescence of microfractures. These processes lead to a bulk dilation of the affected rock, increasing the porosity and permeability of the salt to brine and gas flow. The extent of the DRZ surrounding mined salt openings has been measured directly at WIPP and elsewhere using techniques such as sonic velocity, brine and gas flow properties, and laboratory analysis of cores. Point geophysical measurements have validated the geometry and rock properties predicted by numerical damage models. These features and their measurements are discussed subsequently.

6.1.2 Room Closure

The test configuration described here would confirm the geophysical response of the test bed before, during and after the mining of the testing drifts. The bases for these proposed measurements draw from principles of salt deformation. A structural model prediction has been run to provide guidance for instrumentation placement. The calculation is based a salt-creep constitutive model that tracks stress/strain history of the host rock. Expected results from the structural calculation can be supplemented and corroborated by taking advantage of extensive database of geotechnical measurements made in connection with actual operations in salt. Classical strain-time behavior for salt includes rapid transient deformation that slows to a pseudo steady-state as substructure evolves with time. Model simulations can be used to provide a more complete deformation history, including hard-to-collect early-time data. Modeling results can be analyzed to include continuous predictions of DRZ extent and absolute displacement quantities.

6.1.3 Damage Evolution

Development of the dilatancy boundary represents an ongoing pursuit of German and US salt research scientists [Schulze et al. 2001]. A more sophisticated treatment of DRZ development would be expected for analyses of an actual URL test. For exemplary purposes we use a simple relationship relating volumetric strain and principal stresses [Van Sambeek et al. 1993]. Stress states that resulted in net volume increase (damage or dilation) were defined in terms of the first invariant of the traditional Cauchy stress tensor, I_1, and the square root of second invariant of the deviatoric stress tensor, J_2. These invariants are related to mean (or confining) stress and deviatoric stress, respectively, and a clear delineation in the $I_1 - J_2$ stress space exists between conditions that cause dilation and those that do not, regardless of the type of salt or type of test considered. A simple empirical relationship separates dilating stress states from nondilating stress states expressed as

$$\sqrt{J_2} = 0.27 I_1$$

This relationship is called the stress-invariant model and is used is this analysis.

Measurements of the DRZ around openings in salt have been made using various geophysical techniques. Predictions of the one-way evolution of the DRZ without subsequent long-term salt healing replicate geophysical observations. The size and shape of the DRZ around an opening based on a stress-invariant criterion are comparable to the size and shape derived from sonic velocity studies and from microscopy of core damage.

6.2 Structural Analysis

Results of the ongoing Joint Project collaborations should identify the best-available tools for structural analyses. Geomechanical model predictions should be integral to field test planning because they demonstrate that the experimental concept has been thought out, while calculations help clarify boundary conditions likely for the field test. Placement of gauges before excavation permits evolutionary measurements that can be predicted using a variety of models. Subsequent accomplishment of the test provides an opportunity to validate predictions. Predicted response coupled with practical experience provide the bases for instrumentation range, accuracy, and data quality objectives (DQOs), which quantify needed precision and accuracy based on how the measurement applies to safety functions.

6.2.1 Geomechanics Modeling

For illustrative purposes, a preliminary two-dimensional isothermal structural analysis of a proposed mine-by test has been performed [Holland 2014]. The primary reason for the calculation is to determine the extent of the damage zone around a potential test drift and to aid in the design and placement of instrumentation. If such an excavation is actually made at some future date, it would provide an additional opportunity to validate these calculations.

The finite element model used for this example represents a two-dimensional cross-section passing through the mid-length of a nominal test drift. A two-dimensional geometry was chosen for this example because the analysis was time-and-budget limited. A full three-dimensional model would more accurately represent a particular configuration. Material layering used in this example simulation is based on WIPP Room D stratigraphy, which can be considered typical for bedded salt. A final test location with site geology and mining sequences should be used to develop a three-dimensional geomechanical model of the actual area, especially since the purpose of this effort is to quantify damage of the salt and development of the DRZ surrounding test drifts.

6.2.2 Results

Geomechanical modeling can predict microfracturing using the stress-invariant criterion provides a tool for pre-test calculations of the test room conditions. The ratio of the square root of the second invariant of the deviatoric stress tensor (J_2) and 0.27 times the first invariant of the stress tensor (I_1) can be used to outline a zone with a *Damage Factor* > 1, as shown in Figure 6.1. This plot is a snapshot at 887 days, though the damage factor contours can be calculated at any time. Multipoint Borehole Extensometers (MPBXs) can now be situated to straddle the predicted extent of the DRZ using this type of information.

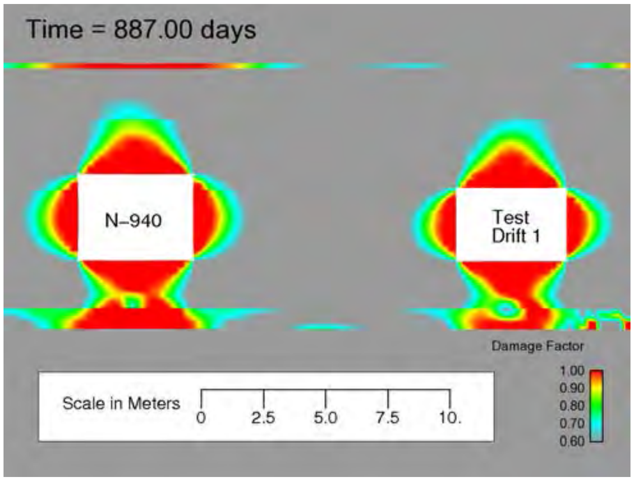
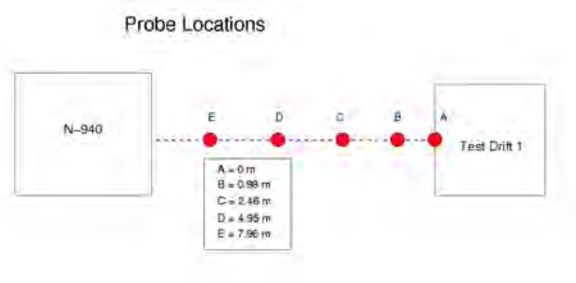


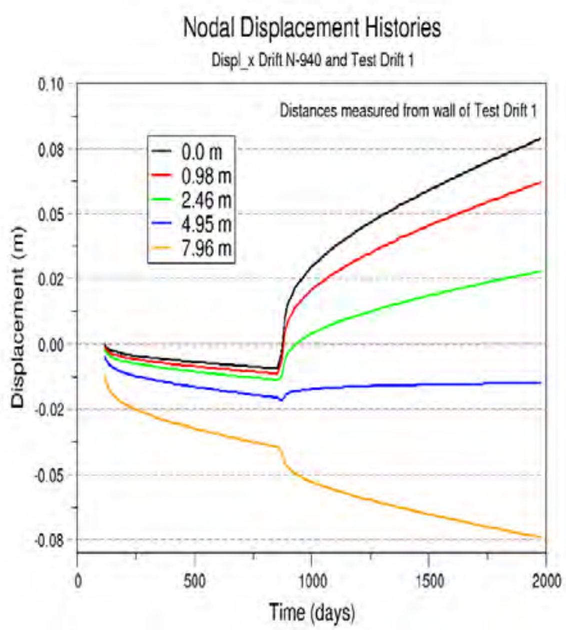
Figure 6.1. Damage contours from Geomechanics models.

To provide an estimate of the temporal change in the displacement field between the drifts a horizontal line of displacement probes is assumed between observation drift (N-940 in the example) and Test Drift 1 as shown in Figure 6.2a). Time histories of the horizontal displacements at these nominal locations are shown in Figure 6.2b). A positive value of the displacement means the probe location is moving toward the test drift excavation. In this simulation, the probes are installed soon after excavation of observational drift N-940. At first, all probe locations would be moving toward N-940. The kink in the displacement history curves occurs when the test drift is excavated.

Based on these calculations, the extensometers range and accuracy can be specified. For example, an anchor could be set at 0.5 m from the new excavation wall, with a measurement range of 0.10 m (double the expected displacement). The outer anchor would be set at about 5 m, which is approximately neutral between the two drifts. Displacement precision should be approximately 0.001 m (1 mm), which is 1% of range. Off-the-shelf extensometers are typically more sensitive than +/- 0.001 m. Final arrangements and gauge selection would be determined by the Principal Investigator, but this example shows how the prediction can assist with DQOs.



a)



b)

Figure 6.2 Displacements as a function of position between observation drift and test drift.

Temperature and mechanical deformation measurements will be collected at like locations to enable data collection for thermal-expansion compensation of the extensometers. Final design depths, ranges, and DQOs would be aided by final test site selection and preliminary geomechanical model predictions.

6.3 Permeability Measurements

Permeability testing boreholes would be situated in the expected DRZ. The combination of MPBX measurements strain and fluid testing will generate data to allow a correlation to be made between a 1-D stain level and a fluid flow potential. Intact geologic salt is essentially impermeable to brine or gas flow (permeabilities <10-20 m^2). In its undisturbed state, the intergranular porosity of intact salt is quite low (~1%), unconnected, and filled with saturated brine. Pressure within occluded pores would be equal to lithostatic pressure. Interconnected porosity, which can be created by salt dilation, is required to allow brine to flow under a stress or pressure gradient.

Once the changes to the porosity, intrinsic permeability, and brine saturation have occurred, brine flows into the DRZ under the influence of gravity, pressure, and capillarity. This redistribution of brine is slower than the initial mechanical response of the system, which creates the DRZ and largely air-filled zone surrounding the excavation.

Depending on the method used to characterize the DRZ, it typically develops from 1-2 meters up to one excavation “radius” into the host rock. Characterization of the DRZ provides concrete information regarding the initial and boundary conditions for the drift. The DRZ can act as a source, sink, and pathway for brine and vapor moisture. Characterizing the spatial extent and temporal evolution of the DRZ around excavations provides boundary conditions for any of the proposed experiments.

6.3.1 Gas Flow

Laboratory and in situ testing programs at WIPP have characterized both brine and gas flow through the DRZ [Freeze et al. 1997; Beauheim and Roberts 2002]. In general, gas flow measurements are simpler to conduct in areas where the air entry pressure is low enough (i.e., the DRZ), and provide a good diagnostic for delineating the extent of the DRZ. Estimates of DRZ extent and shape from gas flow measurements are qualitatively similar to those estimated from geomechanical model predictions and cross-hole sonic velocity measurements. Gas flow rate can be measured at a specified working pressure, into a short packed-off borehole interval. The test is relatively quick to conduct, and can be repeated across different intervals to assess the variability of the DRZ along the length of the borehole. Gas flow measurements will be made before during, and after excavation of test rooms to confirm initial absence of a DRZ and subsequently to confirm creation and evolution of the DRZ upon test room mining.

Gas is a non-wetting fluid, and would only displace brine (the wetting fluid) under relatively high pressures when intergranular porosity comprised pore diameters that allowed such displacement. Typical undisturbed salt has a pore structure that precludes gas displacing brine prior to reaching lithostatic pressure. Therefore gas flow measurements will essentially test only the air-filled porosity and relative gas permeability of the DRZ. Residual brine will remain in the DRZ, but this fraction of the porosity will be inaccessible to low-pressure gas. Attempting to make gas flow measurements at the far edge of the DRZ (where porosity is lower and therefore brine saturation is higher) or in areas where brine has flowed back into the DRZ, may result in gas displacing brine, which is a non-linear process that complicates test interpretation. Gas testing will essentially be used to quantify the extent of the DRZ, with some rough quantification damage. High gas flow rates can be associated with macroscopic fractures and bedding separations, often associated with non-salt, relatively brittle materials.

6.3.2 Brine Flow

Brine flow measurements are more difficult to make than gas measurements because brine is more viscous, and in a low permeability media, this contributes to very low or no flow in injection test configurations. Historic testing of brine permeability in boreholes was sometimes accomplished using a complex packer apparatus to minimize tool movement, measure borehole deformation, and accommodate high-pressure long-term tests [Roberts et al. 1999]. Characterization activities proposed here do not envision complex long-term brine flow tests, but will measure brine pressure in boreholes before and after test drift mining. If salt permeability and brine saturation are both high enough, brine pressure is expected to stabilize readily (indicating a meaningful inter-granular pore pressure can be interpreted). When this occurs constant pressure tests will be conducted to estimate brine permeability. But unlike gas flow tests, if a brine flow test interval is too damaged or dilated (high intrinsic permeability but low brine saturation), the shut-in pressure will likely not stabilize, indicating the brine is penetrating significant gas-filled DRZ porosity.

While brine will readily displace gas that is not trapped, the penetration of brine into an air-filled porous or fractured medium is a highly non-linear process. These types of tests would be difficult to analyze with linear well-test solutions developed for either brine or gas flow without significant simplifying assumptions of flow behavior around the borehole.

Interbeds comprising non-creeping minerals typically exist within salt formations. In excavations similar to that proposed for this test configuration, such interbeds become highly fractured due to the extent of the DRZ and brittle material behavior. The Brine Sampling and Evaluation Program (BSEP) conducted at WIPP from 1982 to 1993 included "water table" observations in vertical boreholes in the floor [Deal et al. 1989; 1995]. The BSEP investigations found brine readily flowed into boreholes completed in the marker bed, especially at the intersection of large drifts. Recognizing the connectivity of the DRZ below the rooms, particularly if a marker bed is intersected, brine accumulation could be monitored in vertical boreholes. Based on BSEP experience, a relatively brittle stratum located beneath an excavation will potentially act as a brine collection drain for the test drifts because of its stratigraphic location. Since vertical boreholes provide simple measurement opportunity, short pumping or purging tests may be conducted to estimate permeability of the damaged zone penetrated by these boreholes.

6.3.3 Data Quality Objectives

A quality scientific endeavor is predicated on sound application of the scientific method. This document provides a look forward to an opportunity for characterizing a future test or demonstration activity. Measurements include undisturbed conditions and transient characteristics during and after excavation. We therefore have an opportunity to confirm our understanding of these physical changes, while providing detailed boundary conditions for field experiments. In addition, results of these measurements provide opportunities for validation of modeling techniques.

Because of extensive history in this type of experimental work, both in the US and internationally, the basic material and geologic formation behavior is well known. Undamaged salt is essentially impermeable, while minimal damage (volumetric strains as small as 0.01%) will increase anisotropic permeability by 5-6 orders of magnitude. Reversing the stress state toward equilibrium and simultaneously reducing shear stress will heal salt fractures. Understanding these two processes of creating and healing the salt DRZ has been sufficient for engineering and seal system applications to date. Geomechanical simulations can track the stress state and post-process ratios of stress invariants for the damage contours as shown in Figure 6.1.

Modeling, testing, and measurement methods can be used to characterize a generic test bed in a salt formation. An actionable Test Plan to proceed with the described scope of work would conform to requirements of the sponsoring agency under the provisions of an appropriate quality assurance plan. In this preview, a means to collect relevant information has been presented. Creep deformation and evolution of damage around new excavations in salt greatly alter favorable characteristics of the virgin ground. Investigations and salt characterization, as described here, would provide boundary conditions for any particular test bed. Geomechanics simulation can be used to define DQOs and instrumentation specification, while measurements before during and after the test itself provide data for model validation.

7 CONCLUDING REMARKS

Collaboration between German and US researchers ensures that science and engineering at the state of the art is accomplished. Bringing together the best minds in salt repository research, design, and operation lets us address a wide breadth of subjects and dive deeply into selected issues [Howell 2014]. These sentiments are echoed in the Ministry address by Dr. Pape, which is provided in Appendix B. Mutual benefit is at the nucleus of these modern-day collaborations. Collaborations between scientists of American and German research institutions in the field of radioactive waste disposal in rock salt started in the 1970s and emphasized geomechanics and brine migration at the Asse Mine.

The cooperation activities particularly between researchers of SNL and several German research institutions (German Federal Institute for Geosciences and Natural Resources (BGR), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe (DBE Tech), and Institut für Gebirgsmechanik GmbH (IfG), to name a few) continued and culminated in the participation of SNL in the famous international EC-funded Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt / Germany (BAMBUS) experiment [Bechthold et al. 2004]. In the year 2000 political circumstances (nuclear phase-out talks in Germany and Gorleben Moratorium) led to a slow-down in salt repository research in Germany. In the US priorities changed as well and salt research was reduced and collaboration between the US and Germany slowed accordingly.

In 2009 policy changes in both countries (e.g., in Germany prospects to end the Moratorium and in the US a move away from Yucca Mountain) gave rise to positive and encouraging motivation for intensified resumption of salt research. Therefore, representatives of research institutions in the US and in Germany took the initiative to renew collaborations and cooperation on overall salt repository science, to coordinate a potential research agenda of mutual interest, and to leverage collective efforts for the benefit of their respective programs. This started in 2010 with the first common workshop on Salt Repository Research, Design and Operation, organized by SNL, DBE Technology, and KIT/PTKA in Mississippi, US.

As witnessed in this and previous Proceedings, this was the beginning of a very productive and successful collaboration. Since then five annual workshops were organized; collaboration in the Joint Project on benchmarking constitutive models for rock salt was pursued and showed impressive results; many common contributions to conferences, workshops and journals were made; participation in EC-projects (MoDeRn) and IGDT-TP activities (Joint Activity on Handling of Uncertainties) were initiated and performed. These workshops also address the fundamental challenges of maintaining and honing their respective current state-of-the-art core capabilities in rock salt repository science and technology.

All these activities were and are in accord with the 2011 Memorandum of Understanding (MoU) between US DOE offices and the BMWi. This MoU represents the umbrella for collaboration and signifies an important acknowledgement of the interest of the responsible authorities in the cooperation, the technical agenda, and the benefits for the national programs. The general issues addressed in the workshops, namely the safety case, salt repository concepts and designs, geomechanical response, groundwater flow and radionuclide transport, geotechnical barriers, and site/host-rock characterization, are scientifically up-to-date. To broaden the central construct of collaborations, flexibility and openness allow treatment of additional topics of arising interest. For example, the issue of operational safety was introduced in the 5th Workshop, serving as a trademark of these collaborations. Another important derivative was initiative to found the OECD/NEA Salt Club to bring together international multidisciplinary scientist working in the field of salt repository research.

Some of the lessons learned so far from the successful cooperation are

- comprehensive knowledge and sound expertise of US and German scientists in various fields of salt repository science and engineering can be applied to the problems defined and guarantee to tackle existing and future challenges
- ongoing activities and scientific results exemplify the benefits of this collaboration and prove the importance of international cooperation
- collaboration helps optimize scarce human resources in joint projects and activities
- duplication of efforts can be avoided in the process of adding value of shared national capabilities (e.g., computer resources, modeling, URL experiments, etc.)
- knowledge preservation, education and training (e.g., involvement of universities)
- different perspectives and diverse perception of identical issues support the finding of solutions
- cooperation with foreign partners (e.g., via the Salt Club, conferences and publications) generates great benefit for the national programs

In view of the future developments in HLW disposal in the US and Germany, especially in view of the Site Selection Act, cooperation becomes more and more important.

Concerning domal rock salt there are still open R&D questions that have been identified as a result of the preliminary safety analysis Gorleben (VSG). Moreover, conceptual questions concerning the disposal in bedded salt are to be addressed in Germany. This effort will draw on the expertise and experience of US researchers because of their extensive work on WIPP salt.

Summing up by referencing Dr. Pape´s (BMWi) welcome address:

> *The work that is being done as part of our US-German co-operation is important for us to gain detailed insights into the qualities of rock salt as a host rock and to bring older findings in line with the current state-of-the-art of science and technology. Our countries have similar salt formations, i.e. salt domes and bedded salt, and could use them in similar ways. This geological fact makes the US our most important international research partner on salt rock – and the fact, of course, that your country has excellent expertise in this area. As we address the challenges in hand, Germany will continue to add to its own long-standing expertise on salt rock and share it. Our co-operation makes it possible for both partners to create synergies in our work and thus advance our programs.*
>
> Dr. Pape—Welcome Address Excerpt
>
> (Complete Text in Proceedings)

On behalf of the organizers PTKA-WTE, DBE Technology GmbH and Sandia, we would like to make you aware of preliminary preparations for our 6th US/German Workshop on Salt Repository Research, Design, and Operation. At the 5th US-German Workshop held in Santa Fe, September 2014, it was decided to hold the 6th Workshop in Dresden, Germany. The workshop is again jointly organized by PTKA-WTE, DBE Technology GmbH, and SNL.

We have made tremendous progress since restarting collaboration in core research areas of geomechanics, constitutive benchmark modeling, plugging and sealing, and the safety case. Recently we added the important issue of operational safety. We will continue to build on these efforts as we open new areas of collaboration such as hydrologic modeling applied to salt repositories, comparison of bedded and domal salt, and the impact of extended storage. We will entertain related topics such as other country participation, actinide chemistry, and open up to special topics, as appropriate.

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APPENDIX A: AGENDA

5th US/German Workshop on Salt Repository Research, Design, and Operation

La Fonda Hotel
Santa Fe, New Mexico

September 7 – 11, 2014

Please join us Sunday September 7, 2014 for a welcome and reception at the La Fonda Hotel hosted by Sandia National Laboratories beginning at 6:00 PM.

Day 1

Technical Agenda

September 8 - Monday

08:00-08:45	Sign-in and distribution of meeting materials	
08:45-09:45	Welcome addresses	H.C. Pape (BMWi) US-DOE Offices
	Highlights of US/German Collaboration	F. Hansen (SNL) W. Steininger (PTKA)
Repository Operational Safety		
09:45-10:45	Welcome and keynote on operational safety	S. Rottler, Vice President (SNL)
10:45-11:00	**Break**	
11:00-11:20	Operational safety activities in Germany	T. v. Berlepsch (DBE TEC)
11:20-11:40	Operational safety at US repositories	E. Hardin (SNL)
11:40-12:00	Case Study: Recent WIPP Experience	A. Van Luik (CBFO)
12:00-13:30	**Workshop Group Photo and Lunch**	
13:30-14:00	WIPP Recovery Plan	T. Reynolds (NWP)
14:00-14:30	Panel Discussion	E. Hardin - Lead
Retrievability and Repository Design		
14:30-14:50	U.S. Perspective on retrievability, retrieval, and reversibiltiy	S. Wagner (SNL)
14:50-15:10	Retrievability as design requirement for a repository for HLW and SF	W. Bollingerfehr (DBE TEC)
15:10-15:30	Salt Disposal RD&D	R. MacKinnon (SNL)
15:30-15:50	Natural Analogues	N. Rempe US
15:50-16:10	Dutch Salt Safety Case and Research Program	J. Hart (NRG) TBD
16:10-16:30	**Break**	
16:30	Depart for Los Alamos Bradbury Museum Tour and Dinner	J. Icenhower (SNL)

Day 1 Companion Event - Walking Tour of Downtown Santa Fe. Begins 10 AM. Map will be provided

Day 2

September 9 – Tuesday

TM-behavior of salt		
08:30-08:50	Update on the "Joint Project on Constitutive Laws benchmark"	A. Hampel (Scientific Consultant)
08:50-09:10	Modeling WIPP rooms B/D	L. Argüello (SNL)
09:10-09:30	Laboratory tests on WIPP salt (update)	U. Düsterloh (TU Clausthal)
09:30-09:50	Laboratory tests on WIPP salt (update)	T. Popp (IfG)
09:50-10:10	Complementary laboratory tests on WIPP salt at higher temperatures	I. Plischke (BGR)
10:10-10:30	Characterization of halite from WIPP and Gorleben	M. Pusch (BGR)
10:30-10:50	**Break**	
Plugging and Sealing		
10:50-11:10	Shaft Seal System of VSG	N. Müller-Hoeppe (DBE TEC)
11:10-11:30	ELSA shaft seal project	U. Glaubach (TU BAF)
11:30-11:50	Salt reconsolidation principles and application	F. Hansen (SNL)
11:50-12:10	Discrepancy between modeling and measurement in the realization of real seals	N. Müller-Hoeppe (DBE TEC)
12:10-13:30	**Lunch**	
Safety Case and Performance Assessment		
13:30-13:50	Summary /Synopsis and open questions of the VSG	J. Mönig (GRS)
13:50-14:10	US response on the methodological approach (Interim report ISIBEL-project)	C. Camphouse (SNL)
14:10-14:30	PA development (PFLOTRAN) and the Safety Case	G. Hammond (SNL)
14:30-14:50	Visualization tool VIRTUS: possibilities and limits of application	K. Wieczorek (GRS)
14:50-15:20	**Break**	
15:20-15:35	FEPs development activities	G. Freeze (SNL)
15:35-15:50	FEPs development activities	J. Wolf (GRS)
15:50-16:10	IGD-TP Joint Activity: Handling of uncertainties	D-A. Becker (GRS)
16:10-16:30	Feedback Session	G. Freeze (SNL)
16:30	Optional – Restaurant reservations for those interested at. Omira Bar & Grill	Brazilian Buffet 1005 S. St. Francis Drive

Day 2 Companion Event - Folk Art Museum of Santa Fe
Begins 10 AM. Transportation will be provided

Day 3

Technical Agenda

September 10 – Wednesday

08:30-09:00	Uncertainty analysis	C. Sallaberry (SNL), D-A. Becker (GRS)

Special Topics

09:00-9:30	HM-modeling and two-phase flow	R. Wolters (TUCl) J. Rutquist (LBNL)
9:30-10:00	P&T in the context of waste management	W. Bollingerfehr (DBE TEC) J. Mönig (GRS)
10:00-10:30	Report on discussion results of the hydrology group (separate micromeeting)	J. Wolf (GRS) K. Kuhlman (SNL)
10:30-10:45	**Break**	
10:45-11:15	NEA-Salt Club update	J. Mönig, Chairman (GRS)
11:15-12:00	Proposals for future joint collaboration: German Perspective	W. Steininger (PTKA), W. Bollingerfehr (DBE TEC)
	Proposals for future joint collaboration: US Perspective	C. Leigh (SNL)
12:00-13:00	**Lunch**	

Specially Scheduled Breakout Sessions

13:00-17:00	To be selected	C. Leigh (SNL)

Day 3 Companion Event
Nothing in particular is scheduled

Day 4 Participant and Companion Event

Field Trip – Geology of Note in the Santa Fe Area

Thursday September 11, 2014

Departs La Fonda Hotel at 7:00 AM

Returns to La Fonda Hotel at 7:00 PM

Transportation and Box Lunch Provided

(Tour Includes busing to locations of interest and walking around those locations. Please wear shoes suitable for walking)

APPENDIX B: WELCOME ADDRESS:

Dr. Pape—Welcome Address

Ladies and Gentlemen,

On behalf of the Federal Ministry for Economic Affairs and Energy – the German ministry responsible for non-site specific project-funded research into nuclear waste disposal – I would like to extend my warmest greetings to you at the start of the fifth US-German workshop on Salt Repository Research, Design and Operation organized by Sandia National Laboratories, DBE-Technology, and Project Management Agency Karlsruhe. I would particularly like to thank Sandia for the excellent preparations in Santa Fe.

I am looking forward to this event, attended by fifty international participants, which will give us an overview of topics reflecting the current status of salt repository research, design, and operation, in particular addressing the thermomechanical behaviour of salt, plugging and sealing, and the safety case.

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

This annual workshop is a poster child of our cooperation. There is a long tradition of co-operation between the US and Germany dating back to the 1970s. Some of our American colleagues were part of the research being done then, especially in the underground laboratory in the Asse research mine in Germany. We well remember the famous "BAMBUS" project, the world's first long-term demonstration experiment.

Changes in political priorities in both countries repeatedly led to the joint research work being put on hold. However, in the scientific community the view prevailed that it is indeed technically feasible to construct, operate, and safely close final repositories within salt rock formations.

Starting in 2009, both countries have again been more open-minded about rock salt to host final repositories and thus reverted back to the long-standing tradition of German-US co-operation in this area. So far, four workshops have been held as part of the effort to share scientific experience and resume our fruitful co-operation.

We owe these workshops to four people in particular, namely Frank Hansen of Sandia National Laboratories, Walter Steininger from the Project Management Agency in Karlsruhe, and Enrique Biurrun and Wilhelm Bollingerfehr of DBE Technology. A very special thanks to these three men for their dedicated work over many years and for preparing and organising the event.

2011 marks another important milestone in US-German co-operation: this was the year of the signing of the agreement between the Federal Ministry for Economic Affairs and the two Offices of the U.S. Department of Energy – Environmental Management and Nuclear Energy. I would like to thank the two representatives of the US-DOE for their support and for their active commitment to our co-operation.

The fact that both countries had resumed their exploratory work on rock salt was highlighted by the establishment of the Salt Club, an expert group within the OECD/NEA. Both the US and Germany were founding members of this group, which was set up in 2012 and is chaired by Germany's Jörg Mönig. We are of course also delighted that Michael Siemann has been appointed Head of Division for Radiological Protection and Radioactive Waste Management in the Secretariat of the NEA (Nuclear Energy Agency) in Paris.

I think that this brief overview of the history of our co-operation in research on rock salt disposal has already given us an idea of how influential politics and changes in the political situation in both our countries have always been in the context of the issues we are dealing with at this workshop.

This brings me to my next point, namely the changes that have come about in Germany with regard to the final disposal of nuclear waste.

The legal framework for this is given by the European Directive on spent fuel and radioactive waste adopted in 2011, which has to be implemented at a national level, and the German Site Selection Act at the national level which entered into force in 2013. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety has the lead responsibility for both areas. It shares areas of common interest with the Federal Ministry for Economic Affairs and Energy regarding the final disposal of radioactive waste since the latter is mainly responsible for site-independent applied research into nuclear waste disposal. In this role, the Federal Ministry for Economic Affairs and Energy determines together with the Project Management Agency Karlsruhe the strategic and technical orientation of the research activities.

Based on the European spent fuel and radioactive waste directive, Germany like all other EU Member States is called upon to set up a National Waste Management Program for all radioactive waste by summer 2015. Draft programs so far include two repository sites for Germany, one waste with negligible heat generation and one for heat-generating high-level radioactive waste.

Specific cases are on the one hand the ERAM at Morsleben. This final repository for low and medium-level radioactive waste was established in a former potash and rock salt mine. The storage in Morsleben was halted in 1998. Currently, the mine areas are being stabilised and the closure procedure is underway.

Dr. Pape—Welcome Address
(Continued)

On the other hand, there is the Asse II mine, a former salt mine. I will address it later.

The Shaft Konrad has been proposed as a final repository for low and medium-level radioactive waste and the planning approval has been granted. The work on converting Konrad into a final repository has been ongoing since 2007, and completion of the work is currently scheduled for 2022. The Konrad repository is crucial for the storage of non-heat generating low and medium-level radioactive waste resulting from the decommissioning of Germany's nuclear power plants. A speedy completion of the Konrad repository without any further delay is necessary to provide planning certainty for nuclear power plant operators and the institutions involved.

According to the Site Selection Act, a storage site and/or alternative methods of disposal are being sought. The content of the Site Selection Act was covered in detail at the last workshop in Berlin in 2013. An essential aspect of the Act is that it prescribes an open-ended and unbiased site selection process, starting with a "white map" of Germany. As a result, potential sites in rock salt will have to compete with sites in alternative rock formations.

At the same time, the implementation of the Act means that, in addition to consideration of alternative means of disposal and rock formations, further work has to be done on the science and technology of the suitability of rock salt for the disposal of radioactive waste. Here, we particularly need to draw on international networks and experience.

The Commission "Storing High-Level Radioactive Waste" is responsible for the actual site selection process as part of the implementation of the Site Selection Act. It has taken up its work this summer and is made up of scientists, representatives of society, members of the German Bundestag and members of the Länder governments. The Commission's task is to address fundamental aspects of the disposal of high-level radioactive waste and to review the existing requirements of the Site Selection Act. In seeking to fulfil this task, the Commission will draw on the work of expert institutions. In this context, major importance will be placed on international experiences. In addition to the analysis of expert reports and expert opinions and judgments, the Commission will also address international projects and visit them. The Commission is required to submit its findings in a report to the German Bundestag by mid-2016.

This report will be decisive for the long-term orientation of the disposal strategy for high-level radioactive waste in Germany.

In addition to these future tasks, and in the context of the search for a site for a High Level Waste repository and the completion of the Konrad final repository, the low and medium-level radioactive waste stored in the Asse II mine takes on special importance. There is the political will to retrieve this waste and store it in an appropriate final repository.

As you know, the Asse mine is a former salt mine which the Federal Government used as a research mine and a pilot final storage facility from 1967 to 1978. Approx. 126,000 barrels of low and medium-level radioactive waste were stored there for research purposes. During the preparations for the closure of the mine according to mining law, the rules were changed in 2009 in favour of a closure under nuclear law. Also, the operator of the mine changed. Since 2009, the Federal Office for Radiation Protection has been the new operator of the mine and after comparing various options in January 2010 it presented the recovery of the stored waste as the favoured option. First drillings have since been made both underground in the storage chambers for fact-finding purposes and above ground for the exploration of a new shaft which is necessary for the retrieval of nuclear waste. However, it continues to be unclear whether the retrieval is technically feasible, especially with regard to the radiation protection measures, and how or where the retrieved waste will be stored. According to the operator, the Federal Office for Radiation Protection, a retrieval of the waste is not to be expected before 2033.

After this digression on the three final storage projects for low and medium-level radioactive waste, I would now like to speak about the Gorleben project and address the implications resulting from the implementation of the Site Selection Act.

In the 1980s, the Gorleben salt dome was selected for exploration to see if it would be suitable as a final repository. As a result of political changes, non-saline rock formations and alternative options have increasingly been considered, particularly in recent times. The Site Selection Act stipulates that such alternative options must be considered, which ultimately led to the exploration work in Gorleben being abandoned in November 2012. The Site Selection Act, which entered into force in summer 2013, also sets out the requirement for Gorleben to be included in the selection procedure and to be treated the same as any other possible site, that is in line with the rules and criteria set in out in the Act. For the Gorleben salt mine this means that operations there are to be brought down to what is "absolutely necessary". Only parts of the infrastructure are to remain operational whereas the area in which explorations have so far been taken place is to be closed and visits stopped. The security fence above the ground is to be reduced to reflect the "normal industrial standard".

I'm giving you this information on the Asse and Konrad projects for final repositories in Germany, on the Gorleben explorations and on the new initiative for searching a site for a final repository for High-Level Waste in Germany, to make it clear to you just how much we need additional support from science, particularly for the process of disposing of highly radioactive waste.

Dr. Pape—Welcome Address
(Continued)

The work that is being done as part of our US-German co-operation is important for us to gain detailed insights into the qualities of rock salt as a host rock and to bring older findings in line with the current state-of-the-art of science and technology. Our countries have similar salt formations, i.e. salt domes and bedded salt, and could use them in similar ways. This geological fact makes the US our most important international research partner on salt rock – and the fact, of course, that your country has excellent expertise in this area. As we address the challenges in hand, Germany will continue to add to its own long-standing expertise on salt rock and share it. Our co-operation makes it possible for both partners to create synergies in our work and thus advance our programmes. We can reap joint scientific and economic benefits and continue our joint research based on what we have already achieved. This of course includes the successful joint project on constitutive laws benchmark, the joint work on the FEP-catalogue (FEP = Features, Events, Processes) and on natural analogues. Safety in the operational phase will be another focal area for research. We will of course go more into detail on this on Wednesday, when we discuss our future plans.

Please take note that the fact that Germany is exploring other possible ways of disposing nuclear waste does not mean that we are turning our backs on salt as a host rock. Salt remains very much on the table as an option, as do non-saline rocks (clay and granite). We need more research in all these areas. This fact is reflected in the work that is currently being done by our ministry and the Project Management Agency in Karlsruhe to update our joint funding strategy.

Ladies and Gentlemen,

All that remains for me to say is that I very much hope that the fruitful co-operation that already exists between our countries will be continued with the same degree of intensity and commitment.

On this note, I wish us all a very successful event.

APPENDIX C: LIST OF PARTICIPANTS AND OBSERVERS FROM 5th WORKSHOP

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APPENDIX D: PRESENTATIONS

Highlights of US German Salt Repository Collaborations

5th US/German Workshop on
Salt Repository Research, Design and Operations

Santa Fe, New Mexico, USA

September 7-11, 2014

Frank Hansen--Sandia National Laboratories, Albuquerque New Mexico USA

Walter Steininger-- Karlsruhe Institute of Technology, Project Management Agency

Abstract

This presentation summarizes some of the highlights from more than 40 years of collaboration between Germany and the United States (US) involving salt repository science and engineering. The US/German collaborations have never before been as productive over such a wide range of topics as they have been over that last five years. The excellent collaborations are due in part to historical developments in the US and Germany and in part to long-standing collaborations of a few key researchers. Today German rock salt repository activities and US waste management programs face challenges that may adversely affect current and future core capabilities in rock salt repository science and technology. We are using these annual workshops on salt repository research, design and operation to address this recognized need.

Topics addressed by the US/German salt repository collaborations align well with the findings and recommendations summarized by the US Blue Ribbon Commission on America's Nuclear Future and are consistent with the aspirations of the key topics of the Strategic Research Agenda of the Implementing Geological Disposal of Radioactive Waste Technology Platform, and BMWi´s R&D concept as well. These workshops revived joint efforts in salt repository investigations after some years of hibernation by leveraging collective efforts for the benefit of respective programs. These efforts form a basis for providing attractive, cost-effective insurance against the premature loss of virtually irreplaceable scientific expertise and institutional memory.

During the last 40-50 years extensive research, development and demonstration activities have contributed to the profound knowledge available concerning rock salt. These achievements were manifested in laboratory and in situ experiments, as well as in large-scale demonstration activities. In recent years noteworthy progress was made in the US and Germany on safety assessment exercises, geomechanical benchmark modeling, and technological developments, such as waste emplacement techniques. Because of this work, comprehensive knowledge and sound expertise in various fields of salt repository science and engineering have been developed.

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Highlights of US German Salt Repository Collaborations
Walter Steininger--PTKA
Frank Hansen--Sandia National Labs
5th US/German Workshop on
Salt Repository Research, Design and Operation
Santa Fe, New Mexico, USA
September 7-11, 2014
September 2014
5th INTERNATIONAL US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Santa. Fe, NM
Sandia National Laboratories
PTKA
DBETEC
DBE TECHNOLOGY GmbH
ENERGY
NNSA
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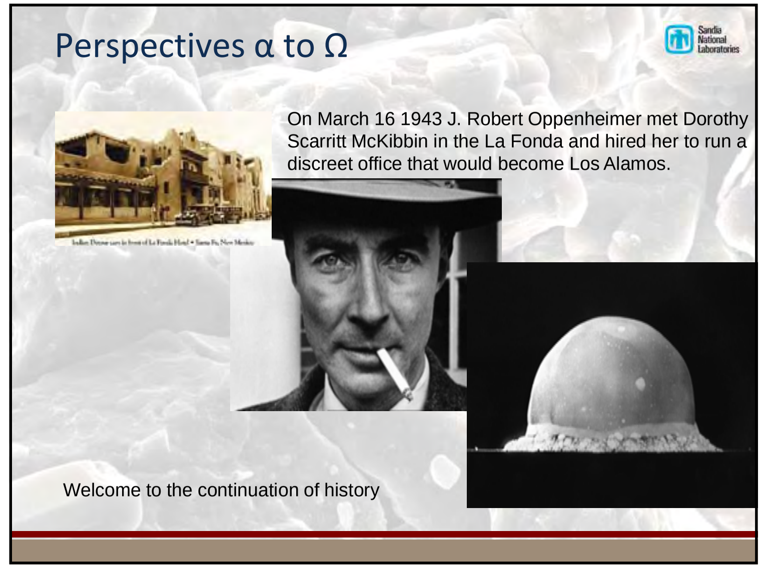
Perspectives α to Ω
Sandia National Laboratories
On March 16 1943 J. Robert Oppenheimer met Dorothy Scarritt McKibbin in the La Fonda and hired her to run a discreet office that would become Los Alamos.
Welcome to the continuation of history


General Chronology of Salt Repository Research
Sandia National Laboratories
Project Salt Vault
WIPP Underground Research Laboratory
1960
2014
BMT
ASSE
TSDE /BAMBUS
US/German Collaboration Salt Repository Science
September 2014
US/GERMAN WORKSHOP


German Accumulation of Expertise in the Past Decades
Sandia National Laboratories
• Techniques for waste emplacement were developed (Direct Disposal = reference repository concept)
• Feasibility of vertical borehole emplacement of spent fuel & HLW (BSK-3 canister) was shown
• Instruments, tools, and methodologies for modeling and safety analysis were substantially further developed and have been applied in several exercises (e.g. vSG)
• In Germany underground disposal facilities for chemical-toxic wastes are licensed and are operational for years
• A lot of experience in rock salt available from practical application and excellent RD&D
4

USA Accumulation of Expertise in the Past Decades

- **Sandia, as Science Advisor, developed much of the salt expertise for the Waste Isolation Pilot Plant.**
- **WIPP was a successful operation 1999-2014.**
- **Solution Mining Research, Strategic Petroleum Reserve, American Rock Mechanics Assoc., Salt Mechanics Symposia**
- **Salt mining is a world-wide, proven and reliable technology**
- **Rock salt is highly suitable for hosting a repository for heat-generating nuclear waste**

Hansen, F.D. and C.D. Leigh. 2011. *Salt Disposal of Heat-Generating Nuclear Waste*. SAND2011-0161, Sandia National Laboratories Albuquerque New Mexico.

5

Benefits of the Strategic Partnership in National and International Cooperation

- Collaboration hibernated for more than 10 years (different priorities in Germany and US)
- Re-start of collaboration in 2010 with a common US-German Workshop in Mississippi (organized by PT-KA, Sandia NL, DBE TEC)
- Benefits
  - To exchange experiences and know-how, get external expertise and feedback
  - Expertise and knowledge to make science-based recommendations on the pros and cons of different host rocks
  - Mutual added value, the appropriate investment of money, cost sharing and the gain of confidence
  - Internationally accepted is the opinion to cooperate with foreign partners because of the importance for any national program
  - Topics emphasized
  - Safety Case
  - Salt repository concepts & designs
  - Modeling of groundwater flow and radionuclide transport
  - Geotechnical barriers
  - Site characterization & host rock characterization

6

US/German Salt Repository Research

- Collaborations between the US and West Germany began in the 1970's (Asse: Temp.Tests)
- Technical evaluations for salt disposal of heat-generating waste experienced a rather long hiatus because of "priority changes" in both countries
- Salt repository research in Germany slowed down somewhat since 2000 (political decisions, moratorium), but increased in 2010.
- Representatives of institutions in both countries wished to renew collaborations and cooperation on overall salt repository science, to coordinate a potential research agenda of mutual interest, and to leverage collective efforts for the benefit of their respective programs.
- By the first US/German Workshops on Salt Repository Research, Design and Operation collaboration was re-initiated.
- A coordinated research agenda has been pursued to maximize mutual benefit.
- The fifth workshop will highlight ***Repository Design and Operations*** and this topic will be the focus of the first day. The focus of the second day will be the ***Thermomechanical Behavior Of Salt, Plugging And Sealing, And The Safety Case.*** Special topics will be addressed on the third day.

Accomplishments and Ongoing Activities

- Five consecutive workshops (information: http://energy.sandia.gov/page_id=17258, includes workshop proceedings and all presentations)
- Memorandum of Understanding between the German Ministry of Economic Affairs and Energy and the US-Department of Energy [Environment Management (EM) and Nuclear Energy (NE)]
- Founding of the OECD/NEA "Salt Club" (Participants: Germany, US, The Netherlands, Poland)
  - Natural analogues workshop for rock salt
  - Features, Events, and Procedures (FEP) catalogue for rock salt
  - State-of-the-art report on salt reconsolidation
  - Salt knowledge archive
- Workshops on actinide brine chemistry (ABC) with Los Alamos National Laboratory

Kuhlman, K. L., S. Wagner, D. Kicker, R. Kirkes, C. Herrick, D. Guerin. 2012. Review and Evaluation of Salt R&D Data for Disposal of Nuclear Waste in Salt. Fuel Cycle Research & Development. FCRD-UFD-2012-000380. SAND2012-8808P

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Accomplishments and Ongoing Activities

- Collaboration in the Joint Project on "benchmarking constitutive models for rock salt" (Sandia & German organizations) (funding by BMWi and US-DOE)
- Contributions to conferences and workshops (American Rock Mechanics Association, Mechanical Behavior of Salt Symposia, Waste Management)
- Notably the ARMA conference had five sessions on "salt" with many contributions made by US/German collaborators
- Collaborative efforts were also completed in the EC (Euratom)-Project (7th Framework Program) "Monitoring Developments for Safe Repository Operation and Staged Closure" (MoDeRn)
- Collaboration/information exchange in the area of safety case
- Common "joint activity on Handling of Uncertainties" in the framework of the IGD-TP (Implementing Geological Disposal - Technology Platform)

Steininger, W., F.D. Hansen, E. Biurrun and W. Bollingerfehr. 2013. *US/German Collaboration in Salt Repository Research, Design and Operation*. WM2013 Conference, February 24-28, 2013, Phoenix, Arizona, USA.

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Activity Overview 5th US/German Workshop

- **Ongoing collaborations**
- Operational Safety—Key Note Rottler/Kennedy/v. Berlepsch/Hardin presentations
- Retrievability and Repository Design—Wagner/Bollingerfehr/URL
- Benchmark modeling (Joint Project III)—Hampel/Arguello presentations
- Laboratory testing of WIPP salt—Düsterloh/Popp/Plischke/Pusch presentations
- Plugging and sealing--Müller-Hoeppe/Glaubach/Hansen Presentations
- Safety case and performance assessment—Mönig/Hammond/Wieczorek/Freeze/Wolf/Becker/Sallaberry/Rempe presentations
- Nuclear Energy Agency Salt Club—Mönig presentation
- Special topics--Researcher-to-researcher collaborations

- **Next steps**
- Proposals for joint collaboration—wrap-up session
- SALT MECH VIII
- Field-scale natural analogue observations
- Underground laboratory in the context of salt research and development

German Testing of WIPP Salt

Perceptions--Future Work

- **US and German proposals/ideas for future collaboration**
- **Reconsolidation of granular salt**
  - Final porosity
  - Additives for construction and sealing properties
  - Numerical modeling verification
  - Further analogue experience

- **Underground research lab in the context of salt R&D**
  - Viability of salt formations for repository is established
  - Need a Framework for URL implementation
  - Justification required in context of all salt repository R&D

- **The SALT Primer**
  - Reference for college classroom
  - Basics, experimental techniques, isochoric deformation, damage and healing
  - Modeling
  - Applications, cavities, boreholes, repository

Exceptional service in the national interest

Sandia National Laboratories

Engineered Safety at Sandia National Laboratories

September 8, 2014

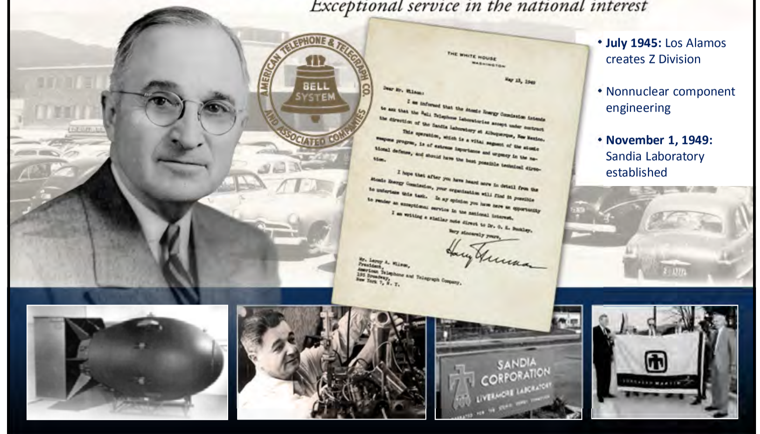
J. Stephen Rottler
Vice President, California Laboratory
Vice President, Energy & Climate Programs

U.S. DEPARTMENT OF ENERGY NNSA

SAND 2014-17166 PE

Sandia's History

Exceptional service in the national interest



- **July 1945:** Los Alamos creates Z Division
- Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established

2

Sandia's Sites

3

Sandia's Role at the Waste Isolation Power Plant (WIPP)

- **Nuclear waste disposal is a long-term challenge of great national importance**
- **Sandia has been the Science Advisor on WIPP since its inception**
  - **Sandia was lead laboratory for the Yucca Mountain Repository license application**
- **Geologic disposal has direct ties to Sandia's National Security mission**
- **Sandia has a long history, and continues to lead the way, in salt repository research**

4

Vision and Mission Statements

- On behalf of our nation, we anticipate and solve the most challenging problems that threaten security in the 21st century
- Our unique mission responsibilities in the nuclear weapons program create a foundation from which we leverage capabilities enabling us to solve complex national security problems

5

Sandia's Mission Work Reflects National Security Challenges

1950s	1960s	1970s	1980s	1990s	2000s	2010s
NW production engineering & manufacturing engineering	Development engineering	Multiprogram laboratory	Missile defense work	Post–Cold War transition	Expanded national security role post 9/11	LEPs Cyber, Biosecurity Proliferation
	Vietnam conflict	Energy crisis	Cold War	Stockpile stewardship		Evolving national security challenges

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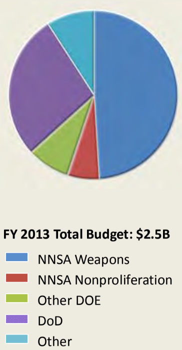
Sandia's National Security Mission Areas



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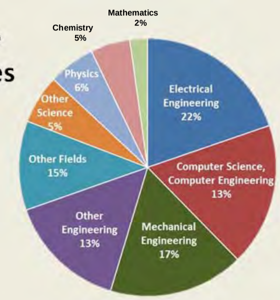
Sandia's Foundation

8

Sandia's People

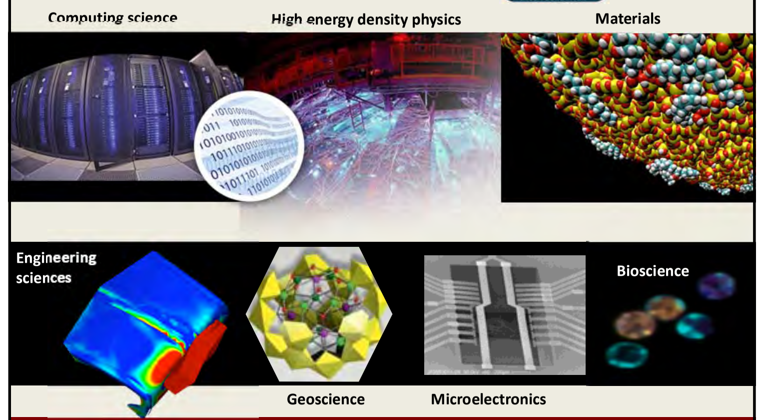
- Highly educated workforce
- Strategically managed workforce of diverse skills and competencies
- Modern business practices and operations in support of our missions



R&D staff by discipline

9

Sandia's Discipline-Based Research Foundations



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Sandia's Capabilities

- High-reliability engineering
- Sensors and sensing systems
- Cyber technology
- Reverse engineering
- Micro- & nano- electronics and systems
- Modeling & simulation and experiment
- Natural and engineered materials
- Pathfinders
- Safety, risk, and vulnerability analysis

11

Major Facilities and Tools

- Inertial Test Lab
- Abnormal Thermal Environment Lab
- Climatic Lab
- Annular Core Research Reactor (ACRR)
- Blast Tube
- Inertial Test Lab
- Centrifuge Complex
- Weapons Evaluation Test
- Cross-Flow Test Fire Facility
- Aerial Cable Facility
- Drop Tower Facility
- Light Initiated High Explosive Facility
- Electromagnetics Test Facility (TEMPEST)
- Climatic Lab (TEMPEST)
- Environmental Lab (TEMPEST)
- Explosive Machining Facility (TEMPEST)
- FARM (Facility for Antenna and RCS Measurements)
- Thermal Test Complex Burn Facility
- Tonopah Test Range Flight
- Tonopah Test Range Ground Penetration
- Weapons Evaluation Test
- Flight Test Assembly
- Gamma Irradiation Facility
- Mobile Gun Complex
- Shock Thermodynamics Applied Research Lab
- Modal/Vibe/Shock Vibration Lab
- Water Impact Facility
- Normal Thermal Environment Lab
- Aerospace laboratories (High Altitude Chamber, Ion Beam Lab, Lightning Effects Facility, Mass Properties Lab, Modal and Structural Dynamics, Structural Mechanics Lab …)
- Radiant Heat Test Cell
- Radiation Metrology
- Non Destructive Evaluation Lab
- RF and Optics Microsystem
- Z Pulsed Power Facility
- Hermes-III Gamma-Ray Facility
- Saturn
- SPHINX
- Solid Mechanics Lab
- Mechanics of Materials
- Terminal Ballistic Facility
- Centrifuge Complex Vibration Lab
- …

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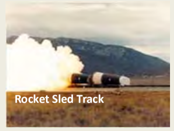
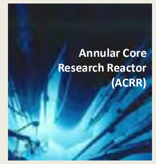
Operations at Sandia

- Operations span research, design, development, prototype, qualification and production activities
- Breadth of work encompasses micro- to macro-scale efforts
- Varying levels of complexity
- Typically involves multiple hazards in combination





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Operations "by the Numbers"

- There are 45 major test facilities at Sandia
- We have 2,718 labs (NM and CA only), utilizing 1,827,151 sf (39% of Sandia's Net Square Feet)
- We have 1,958 light labs (NM and CA only) utilizing 1,038,248 sf

14

Types of Hazards

- Mechanical
- Electrical
- Chemicals
- Fire Protection/Thermal Hazards
- Pressure/Vacuum
- Radioactive/Fissile/ Nuclear
- Biological
- Ozone Depletion
- Drinking Water
- Beryllium
- Noise
- Lasers/Non-Ionizing Radiation
- X-Ray Devices
- Explosives & Ammunition
- Confined Space
- Working at Heights
- Heavy Object Ergonomics & Lifting
- …

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Why Engineered Safety at Sandia?

- Previous work planning and control (WP&C) practices were driving a focus on effective conduct of operations
- The underlying technical basis for "design safety features" of an activity could be taken for granted or receive inadequate technical review
- WP&C practices may not have detected technical design flaws affecting the safety of an activity
- Safety needed to be considered in a system engineering context appropriate for an R&D laboratory
- WP&C program was modified to incorporate engineered safety principles

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What is Engineered Safety?

- A principle-based approach for designing safe "operational systems"
- Safety is an attribute of an operational system achieved by intent
- Operational systems are systematically and critically analyzed to identify ways in which they can fail to perform as intended
- Operational systems are designed and validated to prevent identified failure modes and to mitigate the consequences of a failure should one occur

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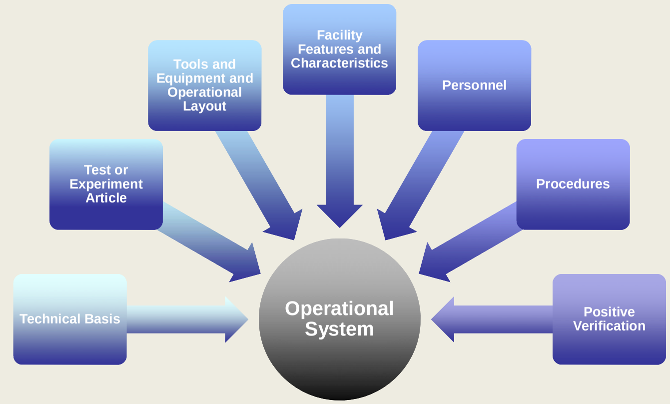
The "Operational System"



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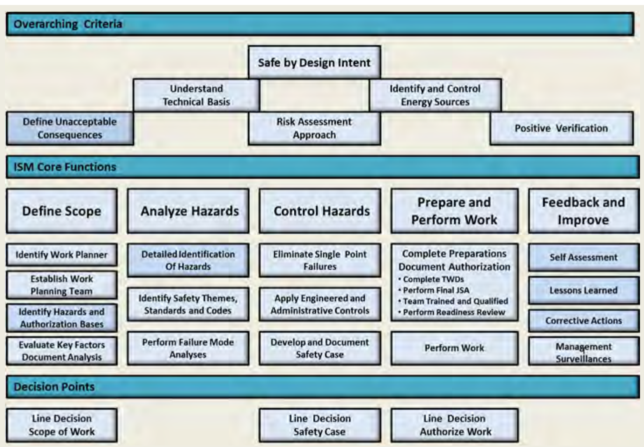
SNL Engineered Safety Framework



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Engineered Safety in Six Questions

- What is the system?
- Who is the decision maker?
- What are the unacceptable outcomes?
- How can the system fail to perform as intended and how can I prevent such failures?
- What if the system fails anyway?
- How do you know it will work as intended?

20

Safety Case: A Management Narrative Explaining how the Criteria are Addressed

- Clearly explains the critical thinking and reasoning in regard to managing the safety risk
- Includes planning for off-normal events
- Demonstrates technical "due diligence" apparent to others technically knowledgeable and familiar with the hazards involved
- Always comes down to a judgment as to whether the controls actually implemented are commensurate with the safety risk
- Is approved at management levels appropriate to the real or perceived risk of the hazardous activity

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Engineered Safety: Examples

- Bioremediation project
- Polymer R&D laboratory
- Z accelerator containment system

22

Engineered Safety Model Applied to Bioremediation Project

- Objective: Characterize degradation of environmental contaminants (both energetic and inert), using microbial processes
- Description of work
  - Small quantities of energetic materials dissolved in acetone forming a "stock solution"
  - Samples created, stored and analyzed in biology laboratory
- Major hazards
  - Energetic materials
  - Microorganisms and/or biological toxins
  - Mechanical hazards (centrifuges)
  - Thermal/pressure hazards (autoclave)
  - Chemicals

23

Elimination of a Hazard through Application of Critical Thinking

- Determined maximum credible event: Inadvertent initiation of energetic compounds during handling, mixing, or testing
- Identified unacceptable consequences
  - Individual illness, injury
  - Mission impact greater than 6 weeks
  - Adverse effect on the community
- Identified and implemented solutions
  - Required explosives training for lab workers, consulted with SME
  - Weighed/pre-mixed energetic materials in separate laboratory
  - Reduced volume of material samples

"By applying **critical thinking**, we redesigned our experiments such that through dilution, we **eliminated the hazard** associated with the procedure in a manner that still **enabled us to meet our experimental objectives**."

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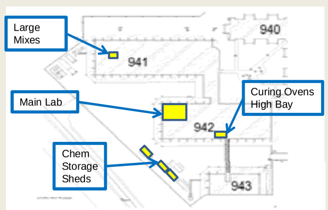
Engineered Safety Model Applied to Polymer R&D Laboratories

- **Applied materials research and prototyping laboratories perform activities including surface preparation, coating, encapsulation, casting, bonding, curing and polymer formulation in multiple laboratories**
  - **Multiple laboratories located in several buildings support breadth of work**



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Critical Review of Multiple Operations Enhanced Lab Safety

- **Identified unacceptable consequences**
  - **Acute or chronic injury/illness from exposure to toxic chemicals**
  - **Injury from mechanical hazards (machine tools, hand tools, lifting heavy objects)**
- **Reviewed possible sources of concern**
  - **Chemical spills (pouring, transport or storage)**
  - **Spill or splatter during mixing**
  - **Underestimation of exotherms**
  - **Uncertain equipment failure modes**
- **Implemented solutions**
  - **Verified that equipment "fails safe"**
  - **Incorporated secondary containment systems**
  - **Used modeling to determine proper quantities**

Moving and pouring tools

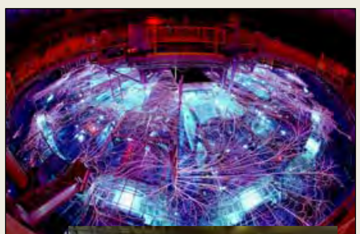
Beaker 1st & prototype LAST

Assure proper ventilation & storage

26

Engineered Safety Model Applied to Plutonium Experiments in the Z facility

- **Earth's most powerful pulsed-power facility and X-ray generator (26MA)**
- **Essential to nuclear weapon stockpile stewardship**
- **Used to measure properties of plutonium at extreme pressures and temperatures**



27

System Designed and Fielded to Assure Safe and Successful Experiments

- **Identified unacceptable consequences**
  - **Radiation dose to a worker**
  - **Environmental contamination**
  - **> 6 month pause in operation**
- **Conducted failure mode effects and fault tree analyses**
- **Identified and implemented solutions**
  - **Eliminated failure modes**
  - **Provided positive assurance through 18 formal approvals for critical subsystems prior to key activities in the shot setup timeline**
  - **Designed a secondary system to manage a containment breach safely**

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"Every Day Safe" with a Critical Thinking Mindset

- Broadens application of engineered safety principles to beyond the laboratory or test facility, i.e., in "everyday life"
- Based on three simple questions:
  - What could go wrong?
  - How can I prevent it?
  - How can I prepare for the unexpected?
- By using these three questions routinely to think critically about day-to-day activities, we can eliminate conditions or situations that lead to accidents
  - With a little practice, this critical thinking mindset will become a habit

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Closing Remarks About Engineered Safety at Sandia

- Integrates safe designs with effective conduct of operations
- Establishes a credible technical basis for safety in work
- Easier to understand and use by an R&D organization
- Creates increased and more effective management engagement
- Further matures and improves the Laboratories' safety culture
- Expands to encourage critical thinking in daily life

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Exceptional service in the national interest

Sandia National Laboratories

Operational Safety Activities in Germany

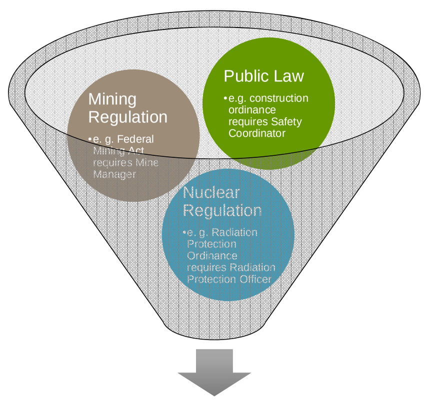
Thilo v. Berlepsch
DBE TECHNOLOGY GmbH
Eschenstraße 55, D31224 Peine/Germany

Outline

Leading Question:
How is operational safety ensured in practice?

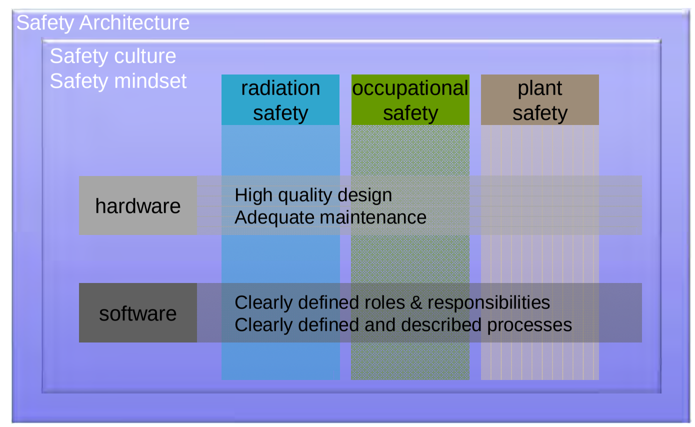
- Managing Operational Safety
  - Basis for Operational Safety
  - Architecture for Operational Safety
- Managing Pre-closure Hazards
  - Mitigating the Consequences of Hazards
  - Protecting People in Case of Hazards
- Summary

Managing Operational Safety: Legal Basis

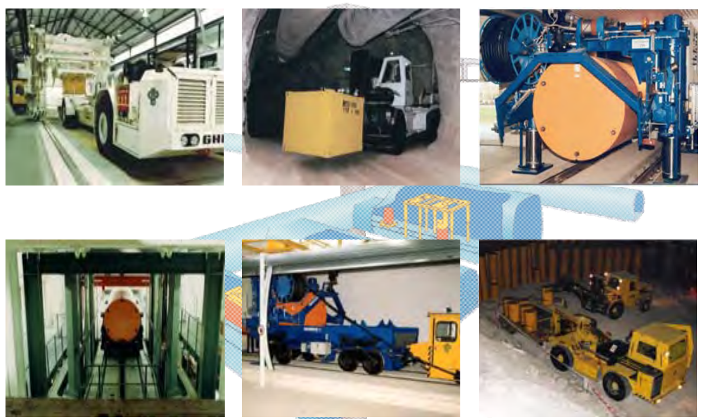


Technical and Operational Requirements for the Operation of a Repository

Basic Considerations for Repository Operation

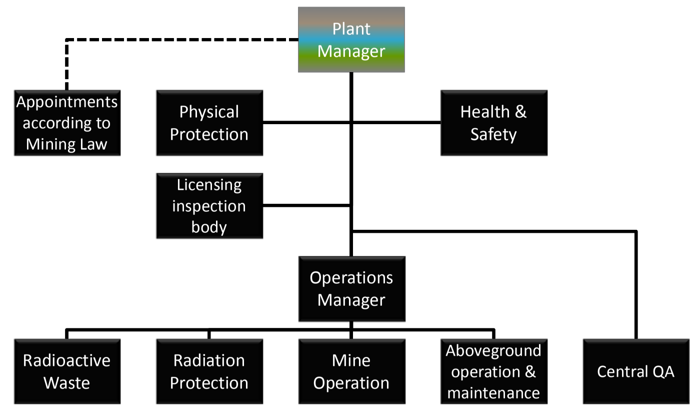


Safety Hardware



T. v. Berlepsch
US/German Workshop 2014

Safety Software: Organisation



(extract from ERAM organisational chart)

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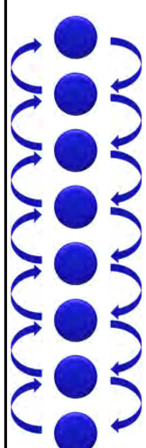
US/German Workshop 2014

Safety Software: Delegation



- Delegation of tasks and (to a certain extent) responsibilities
- Delegator has to ensure that Delegatee has:
  - Adequate physical capability;
  - Obtained adequate training;
  - Sufficient resources and equipment; and
  - Adequate empowerment.
- Delegator has to ensure that task is performed properly by:
  - Reporting requirements; and
  - Sufficiently frequent controlling of Delegatee.
- In case of incidents authorities investigate at first if obligatory supervision by Delegator was sufficient.

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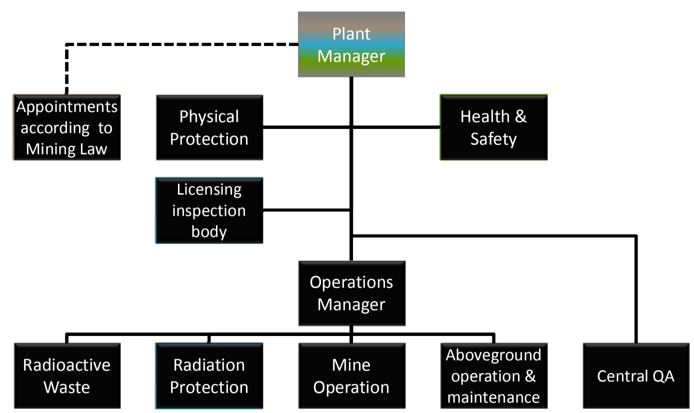
Safety Software: Organisation



(extract from ERAM organisational chart)

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Safety Housing: Ensuring Safety Culture and Mindset

Adequate information on all levels by jour fixes, eg.:

- 05.30 am: Sub-foremen from all divisions
- 07.00 am: Foremen, Plant manager, Geologist, Surveyor
- 01.00 pm: All divisions (incl. eg. PR)

Delegators visit all workplaces in her/his responsibility adequately frequently

- Learning about issues, needs, …
- Caring about staff
- Assuring performance of delegees

Staff and management at eye level

→ Equality and trust
ensures identification with company
ensures safety culture and mindset

Regular instructions in tools and personal safety equipment:

- necessary abilities to perform work
- necessary abilities to use emergency equipment
- adequate risk awareness

Training to obtain and maintain necessary skills
Training plan is submitted to (but neither approved nor checked by) authorities

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DBE TEC

Managing Pre-closure Hazards

- **Despite planning for and realisation of a safe operation (even when proofed with an outstanding safety record), hazards can't be excluded**
- **Dominating hazards to consider:**
  - **Radiological events;**
  - **Fire hazards.**
- **Fundamental mitigating means**
  - **Protecting people;**
  - **Mitigating the consequences of hazards.**

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DBE TEC

Protecting People in Case of Hazards

- **Adequate training and instruction**
- **Adequate design of emergency plans and measures**
  - **Limited time to rescue people;**
  - **If necessary, provision of refuge chambers;**
  - **Regular testing and maintenance of equipment.**

- **Ensuring fast intervention rescue brigade**
  - **Leader is assigned according to mining law;**
  - **Reports directly to plant manager;**
  - **Voluntary brigade receiving specific training;**
  - **Surveyed and trained by Mining Association.**

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DBE TEC

Mitigating the Consequences of Hazards

- **Enable early detection of hazards**
  - **eg. use of sniffers.**
- **Early mitigation of risks**
  - **eg. mobile fire extinguishers.**
- **Keep hazards locally confined**
  - **Electronic on-time ventilation guiding system for mapping flow rates, pressures, and temperatures in the entire mine;**
  - **Placement of ventilation barriers at precalculated positions;**
  - **Reduction of fresh air supply.**
- **Prevention of access to hazard source**
  - **In case of radiological hazard risk of contamination;**
  - **In case of fire danger to suffocate or 'boil'.**

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DBE TEC

Summary

- Safe operation of a plant has to be considered holistically
  - High quality equipment as ‘hardware’;
  - Sufficient processes as ‘software’; and
  - Right mindset as ‘housing’ for safety.

- However, hazards can’t be excluded, but mitigated by
  - Ensuring the safety of people;
  - Enabling Means to mitigate the consequences of hazards.

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**Thank You
for Your Attention!**

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Operational Safety at U.S. Repositories

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Gerald Nieder-Westermann
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Abstract

Operational safety analysis for geologic repositories has been in transition over the past decade, with respect to the assessment of hazards and initiating events, to rely more on probabilistic methods. Nuclear power plants have traditionally been analyzed and licensed by compiling hazards and initiating events, analyzing the hazards and consequences of events, and emphasizing feedback into the "safety basis" including design, operation, and administrative controls. Efforts have been made to consider event likelihood and consequences together in a risk context, but without probabilistic aggregation for direct comparison to regulatory dose standards. A shift to a probabilistic approach is incorporated in the U.S. safety regulation specific to a Yucca Mountain repository (10 CFR Part 63). The approach is evolutionary in that event compilation, sequence development, and hazard analysis are performed using traditional methods, combined with probability estimation under uncertainty, and explicit simulation of dose consequences for comparison to quantitative, regulatory screening criteria. The different approaches are compared using examples from U.S. Department of Energy nuclear facility safety analysis (e.g., WIPP Documented Safety Analysis) and the Yucca Mountain License Application. In Germany deterministic methods also have a long history in safety case scenario analysis, but probabilistic methods are increasingly used as a complementary tool for screening events and hazards. This review with examples shows that operational safety analysis is changing, at the same time that safety experience is accumulating at existing facilities. There are significant opportunities to benefit from international cooperation in methodology development and demonstration, and in safety analysis implementation with feedback to system design and operational controls.

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.
SAND2014-17181A

Exceptional service in the national interest

Operational Safety at US Repositories

Probabilistic and deterministic approaches, and technical vulnerabilities

E.L. Hardin, Sandia National Laboratories
G.-H. Nieder-Westermann, DBE TEC GmbH

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Operational Safety at U.S. Repositories

Outline

- Deterministic vs. Probabilistic (finding balance)
- Deterministic Safety Analysis at U.S. Department of Energy (DOE) Facilities (e.g., Waste Isolation Pilot Plant, WIPP)
- Overview of Yucca Mountain Preclosure Safety Analysis (PCSA)
- Current German Approach for Licensing of Repositories
- Technical/Regulatory Vulnerabilities
- Summary and Outlook

Probabilistic vs. Deterministic

Finding Balance for Operational Safety Analaysis

- U.S. Repositories for HLW/SNF (deterministic ↔ probabilistic)
  - Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada (10 CFR Part 63, U.S. Nuclear Regulatory Commission)
    - Aggregated repository worker dose (10 CFR Part 20, U.S. NRC)
    - Dose at or beyond site boundary (10 CFR Part 63, U.S. NRC)
- German Repositories (deterministic ↔ probabilistic)
  - Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste (Sicherheitsanforderungen)
    - Requires both deterministic and probabilistic assessment
    - Requires implementation of nuclear power plant requirements for operational safety

Deterministic Safety Analysis U.S. DOE Nuclear Facilities (1/4)

- Hazards to workers, the public, and the environment
- Transuranic Waste (DOE, not NRC regulated)
- Deterministic (DOE Order 5480.23 - SAR)
  - Similar to civilian power plant licensing (NRC 10CFR Part 50)
  - Design basis (normal, accidents, events)
- Facility Nuclear Hazard Category (complexity and inventory)
  - Risk Category 1: Potentially significant off-site consequences (e.g., reactor)
  - Risk Category 2: Potentially significant on-site consequences (e.g., WIPP with >80 Ci Pu-239 per container)
  - Risk Category 3: Localized (facility) consequences (e.g., accelerator)

Deterministic Safety Analysis
U.S. DOE Nuclear Facilities (2/4)

- Graded Approach for Each Credible Hazard Identified (DOE STD 5506-2007)
  - Magnitude of hazards, complexity of facilities, life-cycle state
  - Example: WIPP Documented Safety Analysis

ACCIDENT/EVENT DOSE CONSEQUENCE GUIDELINES*

Consequence Level	Maximally Exposed Offsite Individual	Co-Located Worker (at 100 m)	Facility Worker
High	Approaching 25 rem	>100 rem	Safety Significant (DOE STD 3009)
Moderate	≥1 rem	≥25 rem	Qualitative; no threshold
Low	<1 rem	<25 rem	Qualitative; no threshold

ACCIDENT/EVENT RISK CLASS*

Consequence Level	Beyond Extremely Unlikely $<10^{-6}$/yr [A]	Extremely Unlikely 10^{-4} to 10^{-6}/yr	Unlikely 10^{-2} to 10^{-4}/yr	Anticipated 10^{-1} to 10^{-2}/yr
High	III	II	I	I
Moderate	IV	III	II	II
Low	IV	IV	III	III

[A] Probability of 10^{-6} calculated conservatively, or 10^{-7} calculated realistically.

* Not to be construed as regulatory acceptance criteria, per DOE STD 5506-2007.

Deterministic Safety Analysis
U.S. DOE Nuclear Facilities (3/4)

- Hazard/Accident Analysis → Material-at-Risk →
  Hazard Evaluation (prevention, mitigation) → Design Basis
- "Hazard Evaluation" → Technical Safety Requirements
  - Identify Safety-Significant systems, structures and components
  - Administrative controls
- Develop Prevention/Mitigation Controls
  - Examples: waste loading, waste transport, etc.
- Identify Representative Hazards for Further Analysis as Design Basis Events (DBEs)
- Analyze Beyond-Design-Basis Events
  - Low-probability, high consequence

Deterministic Safety Analysis
U.S. DOE Nuclear Facilities (4/4)

- Example: WIPP Risk Ranking
  - Contact-handled waste, underground events

Event #	Description	Frequency (mitigated)	Consequence (mitigated)			Risk Class		
			MOI [A]	Co-Located Worker	Facility Worker	MOI [A]	Co-Located Worker	Facility Worker
CH-UG-1-001a	Single-vehicle fire underground during waste transport	10^{-4} to 10^{-6}/yr	M	M	L	III	III	IV
CH-UG-1-002a	Collision of 2 vehicles and fire underground during waste transport	10^{-4} to 10^{-6}/yr	L	M	L	IV	III	IV
CH-UG-1-003a	Single-vehicle collision, fire under-ground at waste face	10^{-4} to 10^{-6}/yr	H	H	L	II [B]	II	IV
CH-UG-6-001a	Internal deflagration in CH waste container underground	10^{-2} to 10^{-4}/yr	L	L	H	III	III	I

[A] MOI = Maximally Exposed Off-Site Individual [B] Risk class of I may be unacceptable and II may be marginally acceptable, for the MOI. Source: *WIPP Documented Safety Analysis*, DOE/WIPP 07-3372 Rev. 4

Overview of YM PCSA (1/4)
Probabilistic Approach (YM, Part 63)

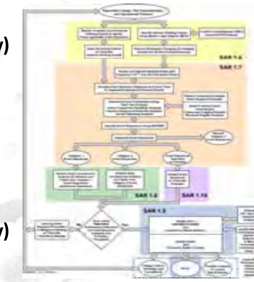
- "What can go wrong?"
  - A set of scenarios or event sequences
- "How likely is it?"
  - Compile available evidence including historical records, engineering analysis (e.g. fragility, reliability) and expert judgment
  - ➡ Use event sequence diagrams to estimate the probability of unlikely scenarios, with uncertainty
- "What are the consequences?"
  - ➡ PCSA Consequences: Directly calculate dose to off-site public, dose to on-site workers and public, criticality
  - ➡ Explicit dose limits are defined by decision-makers (e.g., U.S. NRC regulations: 10 CFR Part 63 for YM)

Overview of YM PCSA (2/4)

Some Differences Using 10 CFR 63 Compared to Previous, Deterministic Nuclear Power Plant Licensing:

- Category 1 (expect ≥ 1 over ~100 years) dose limits for public
  - Aggregated over normal operations and all Category 1 events*
  - Onsite dose: 100 mrem/yr (5 rem/yr for workers; see 10 CFR Part 20)
  - At site boundary: 15 mrem/yr* or 2 mrem/hr
  - Beyond site boundary: 100 mrem/yr or 2 mrem/hr
- Category 2 (expect < 1 but ≥ 10^{-4} over ~100 years)
  - Event sequences categorized <u>individually</u> on probability only, not risk*
  - At or beyond site boundary, for each sequence: 5 rem (workers or public*)
  - Onsite dose: Not regulated*
- No criticality allowable for Category 1 and 2 event sequences
- No consequence analysis needed for "Beyond Category 2"

Overview of YM PCSA (3/4)



- Initiating Events
  - Internal (process diagrams, hazard/operability)
  - External (experiential)
- Event Sequences
  - Screen on probability of initiating events
  - Logic diagrams, hazard analysis, fault trees
  - Simulate hazards, fragilities, etc.
  - Quantify event sequences (SAPHIRE)
  - Categorize (1, 2 and/or Important to Criticality)
- Dose Consequence Analysis
  - Normal + Category 1, aggregated (workers and public)
  - Category 2, individual events $p > 10^{-4}$ in ~100 years (public)
- Design Interface
  - Identify items "Important to Safety" ("Q-List")
  - Develop as-low-as-reasonably achievable (ALARA) requirements for normal operations and Category 1
  - Develop design basis (iterate on design)

Overview of YM PCSA (4/4)

- Preclosure Dose Summary for YM PCSA
  - Aggregated for normal operations + Category 1 (expect ≥1 in ~100 years)
  - Each Category 2 event sequence analyzed individually

Category	Standard	Limits	Results
Public onsite	Normal operations + Category 1	100 mrem/yr TED[A]	78 mrem/yr
Public at site boundary	Normal operations + Category 1	15 mrem/yr TED	0.05 mrem/yr
Public beyond site boundary	Normal operations + Category 1	100 mrem/yr TED	0.11 mrem/yr
Radiation workers	Normal operations + Category 1	5 rem/yr TED	1.3 rem/yr
Public at site boundary	Any Category 2 event sequence	5 rem TED	0.01 rem
Public beyond site boundary	Any Category 2 event sequence	5 rem TED	0.03 rem

[A] TED = Total Effective Dose Equivalent (see Parts 20 and 63 for individual organs. Peak dose rate limits or results, and airborne emissions of radioactive material to the environment, are not shown.
Source: *Yucca Mountain Repository Safety Analysis Report*, DOE/RW 0573 Rev. 1. Table 1.8-36.

Current German Approach to Repository Operational Safety Analysis

- Probabilistic Safety Analysis is Used in Germany to Identify/ Quantify Event Sequences
  - Initiating events that cannot be controlled by design
  - Supplement deterministic safety assessments
  - Analyze high-consequence events
  - Sensitivity analysis; effectiveness of prevention/mitigation measures
- PSA is Required for Repository Licensing to Supplement Deterministic Assessments, But Limits Have Not Been Defined
- Guidelines for Implementing PSA in Nuclear Power Plant Operational Reviews Were Developed in 2005 (BfS)
- Similar PSA Provisions Specific to a HLW Repository Will Likely Be Incorporated After Codification of the Site Selection Decision (by 2031, per the Site Selection Act of July, 2013).

Regulatory Vulnerablities

- Larger Repositories
  - Factor of 2 to 3 range in waste inventory is possible
- Longer-Operating Repositories
  - 50 years operation vs. → 150 years
- More Waste Packages
  - YM (~11,000) vs. all U.S. SNF (up to 90,000)
- Completeness of Initiating Events/Sequences
- Feedback to Design & Operations
- Methodological
  - Disaggregation
  - Representational Accuracy

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Disaggregation Dilemma Caused by Probabilistic Approach (10 CFR 63)

- Level of Aggregation (resolution) of Initiating and Pivotal Events Represented in a Sequence Can Determine Categorization Probability, esp. Internal Events
- More Aggregation → Higher Probability Event Sequence
- More Resolution (less aggregation) → Lower Probabilities → More Analysis/Licensing Effort
- Example: Impact and Breach of Canister
  - Should a single event sequence include all drops of all types of canisters from all possible sources in all facilities?
- Important for Risk Management (feedback into design & operations):
  - Hardware reliability requirements
  - Operations/procedures

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U.S.-German Workshop on Salt Repositories — Operational Safety (SAND2014-17182PE)

Representational Accuracy

- Criterion for level of aggregation is representational accuracy
- Separation into different event sequences warranted because of variations of:
  - Facility configuration and operations (leading to different challenges, e.g. lift heights, number of lifts, residence time)
  - Equipment (although some equipment is similar across facilities,the complement of equipment is different for each facility)
  - Waste forms and containers (variation in robustness over different casks and canisters and variation in source terms because of different fuel/form of fuel)
- Disaggregation should represent different waste processing functions, waste forms, containers and facilities
  - For example: receipt, preparation, transfer, welding, load-out, transport, and emplacement

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U.S.-German Workshop on Salt Repositories — Operational Safety (SAND2014-17182PE)

Summary and Outlook

- Deterministic vs. Probabilistic, in Transition (finding balance)
- Accumulating Experience with Nuclear Safety Analyses
- Periodic Updates for Operating Facilities
- Regulatory Developments are Iminent in Germany & the U.S.
  - Siting process, conceptual design and suitability determination
  - Re-promulgation of generic repository regulations
- New Systems Important to Nuclear Safety, and Supporting Analyses
  - Conveyances, packaging, etc.
- International Cooperation is Vital to Confidence Building
  - Events/sequences
  - Feedback to design & effective operations
  - Methodology

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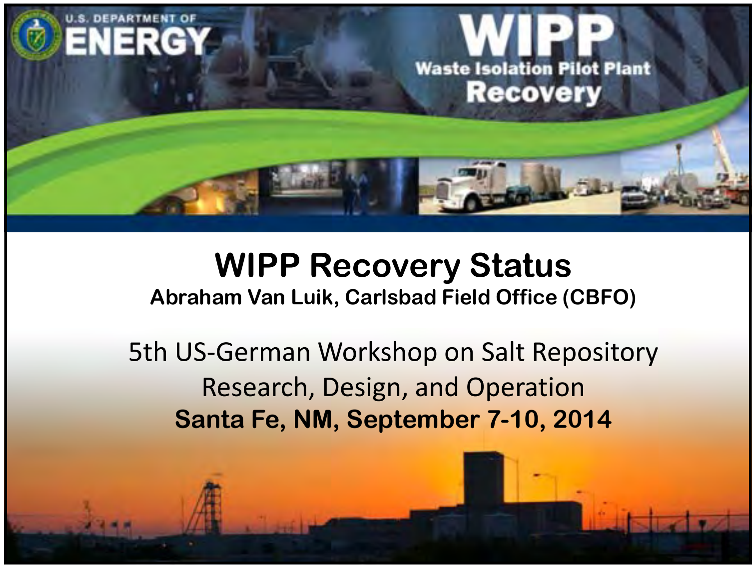
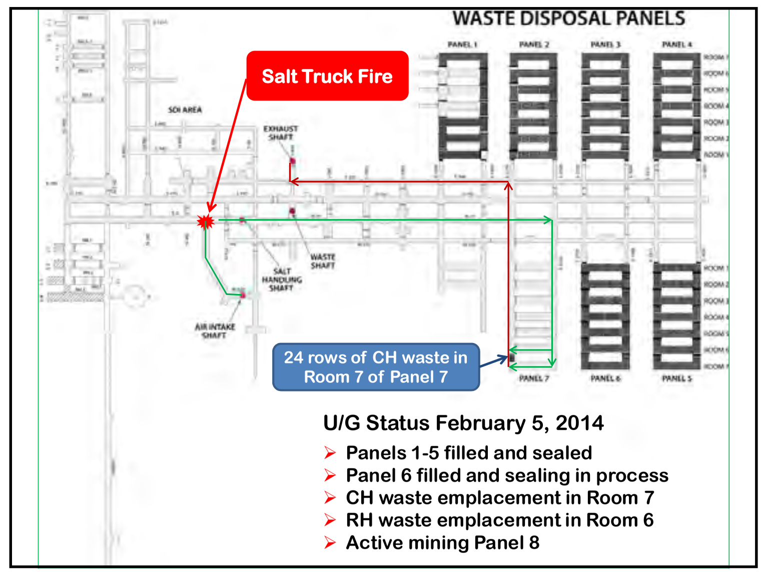
U.S.-German Workshop on Salt Repositories — Operational Safety (SAND2014-17182PE)

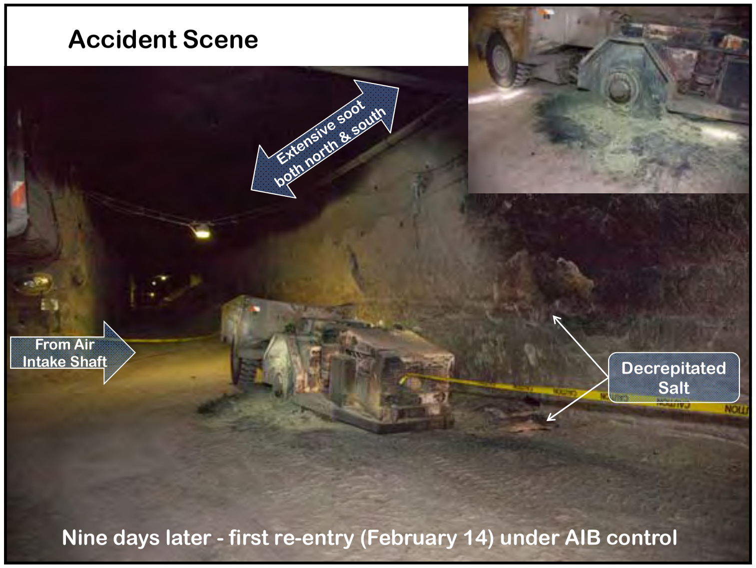

U.S. DEPARTMENT OF ENERGY
WIPP
Waste Isolation Pilot Plant
Recovery
WIPP Recovery Status
Abraham Van Luik, Carlsbad Field Office (CBFO)
5th US-German Workshop on Salt Repository Research, Design, and Operation
Santa Fe, NM, September 7-10, 2014


WIPP's 15-year History of Success
11,894 shipments received
33,000 type B packages unloaded
91,000 cubic meters of TRU waste disposed
14,200,000 loaded miles
22 storage sites de-inventoried of legacy TRU waste
Panel Status
Filled
Active disposal
Mining underway


February 5, 2014
ENERGY
WIPP Underground Fire Accident Investigation Summary
February 5, 2014
Ted Wyka
Chairman, Accident Investigation Board
March 2014
EM-1 Orders Type B Accident Investigation
Underground fire shuts WIPP
The Accident
On February 5, 2014, at approximately 11:00 AM, the Waste Isolation Pilot Plant in Carlsbad, New Mexico suffered an underground fire in a salt hauler vehicle. There were 86 people in the mine at the onset of the fire, all exited the mine safely. Six personnel were transported to the Carlsbad Medical Center for smoke inhalation and an additional seven personnel were treated on-site.
The EIMCO Model 985, 15 ton haul truck is a diesel powered vehicle used to haul salt from the mine. This is an aged piece of equipment, approximately 29 years old.


WASTE DISPOSAL PANELS
Salt Truck Fire
SOI AREA
EXHAUST SHAFT
WASTE SHAFT
SALT HANDLING SHAFT
AIR INTAKE SHAFT
PANEL 1
PANEL 2
PANEL 3
PANEL 4
PANEL 5
PANEL 6
PANEL 7
24 rows of CH waste in Room 7 of Panel 7
U/G Status February 5, 2014
Panels 1-5 filled and sealed
Panel 6 filled and sealing in process
CH waste emplacement in Room 7
RH waste emplacement in Room 6
Active mining Panel 8

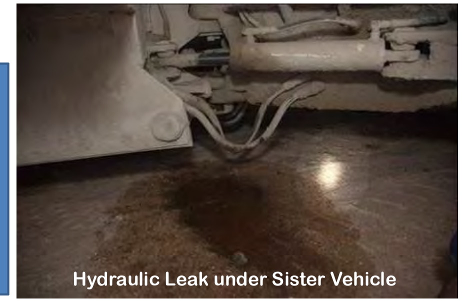
Accident Scene



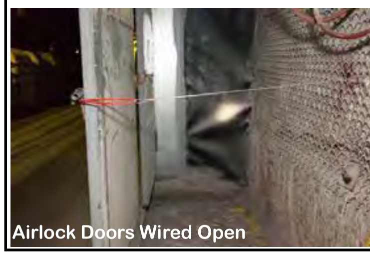
Nine days later - first re-entry (February 14) under AIB control

AIB Report Findings

- Maintenance program was ineffective
- Fire protection program was less than adequate
- Nuclear facility versus mine culture



Hydraulic Leak under Sister Vehicle

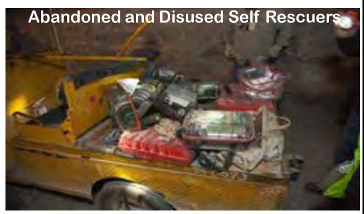


Airlock Doors Wired Open

Combustible Loading in U/G

AIB Report Findings

- Emergency management & preparedness and response program were ineffective (several repeat issues from external reviews)
- CMR response (evaluation and protective actions) were less than adequate
- Different treatment of waste vs. non-waste handling equipment, e.g., combustible buildup, manual versus automatic fire suppression system, fire resistant hydraulic oil, etc.

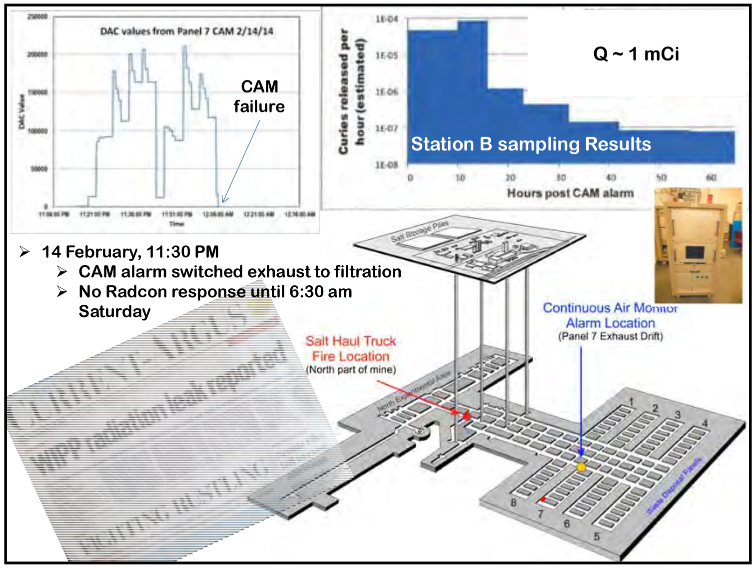


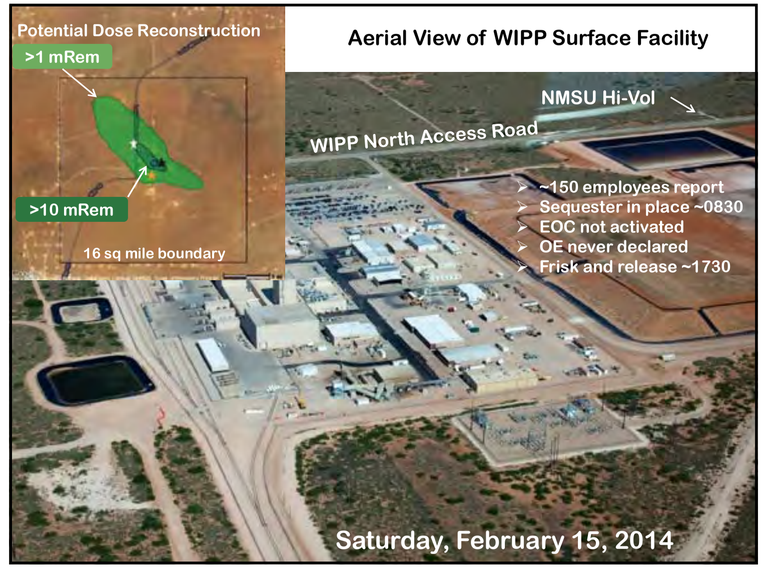
Abandoned and Disused Self Rescuers

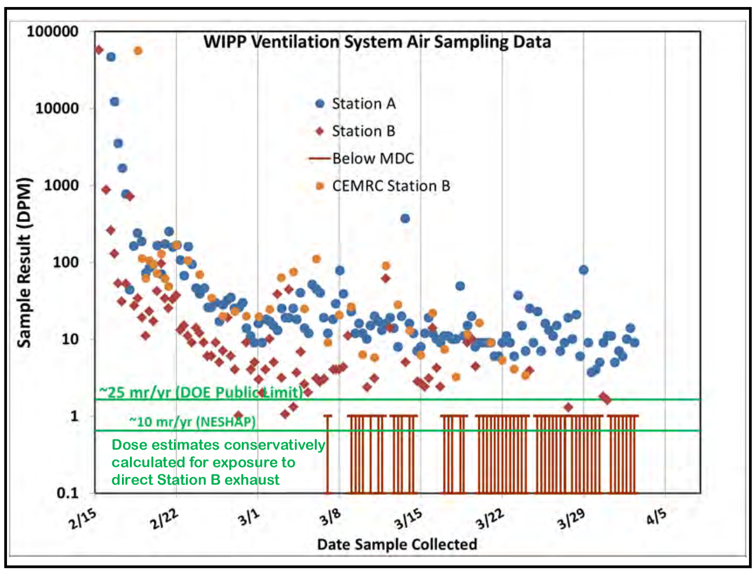
CH Waste Face: Room 7 of Panel 7, Mid-day February 14

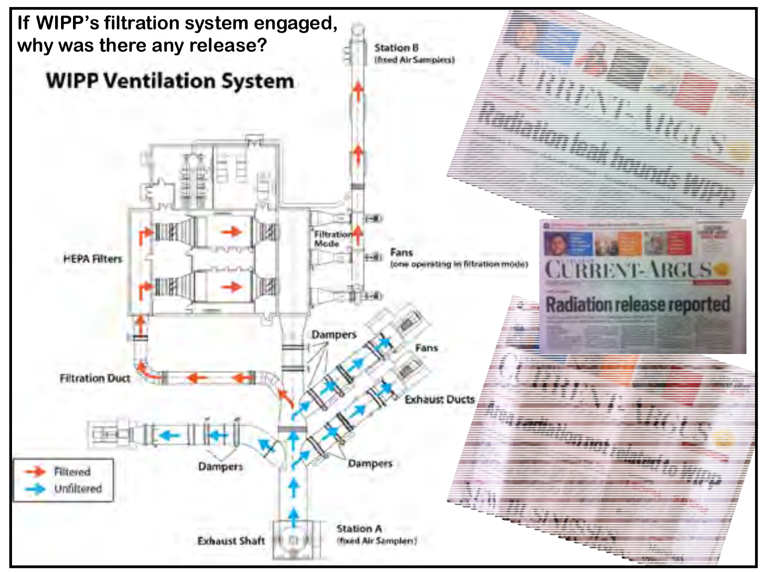
Ground conditions apparently nominal

Nine days after the fire -
Single re-entry on Feb. 14 under AIB control


DAC values from Panel 7 CAM 2/14/14
CAM failure
Q ~ 1 mCi
Curies released per hour (estimated)
Station B sampling Results
Hours post CAM alarm
14 February, 11:30 PM
CAM alarm switched exhaust to filtration
No Radcon response until 6:30 am Saturday
Salt Haul Truck Fire Location
(North part of mine)
Continuous Air Monitor Alarm Location
(Panel 7 Exhaust Drift)
Salt Storage Piles
WIPP radiation leak reported

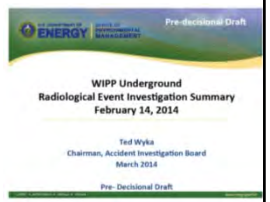

Potential Dose Reconstruction
>1 mRem
>10 mRem
16 sq mile boundary
Aerial View of WIPP Surface Facility
NMSU Hi-Vol
WIPP North Access Road
~150 employees report
Sequester in place ~0830
EOC not activated
OE never declared
Frisk and release ~1730
Saturday, February 15, 2014


WIPP Ventilation System Air Sampling Data
Sample Result (DPM)
100000
10000
1000
100
10
1
0.1
Station A
Station B
Below MDC
CEMRC Station B
~25 mr/yr (DOE Public Limit)
~10 mr/yr (NESHAP)
Dose estimates conservatively calculated for exposure to direct Station B exhaust
2/15
2/22
3/1
3/8
3/15
3/22
3/29
4/5
Date Sample Collected


If WIPP's filtration system engaged, why was there any release?
WIPP Ventilation System
Station B (fixed Air Samplers)
HEPA Filters
Filtration Mode
Fans (one operating in filtration mode)
Dampers
Fans
Filtration Duct
Exhaust Ducts
Dampers
Dampers
Filtered
Unfiltered
Exhaust Shaft
Station A (fixed Air Samplers)
CURRENT-ARGUS
Radiation leak hounds WIPP
Radiation release reported

AIB issues Phase 1 report on the radiation release event April 24,2014

- Phase 1 focused on the release of radioactive material from underground to the environment, and the follow-on response to the release:
  - ➢ Board reviewed the adequacies of the safety management programs and systems.
  - ➢ Important to report on Phase 1 to maintain transparency and move quickly on the corrective actions.



- Phase 2 will focus on the direct cause of the release of the material and the impact on worker protection in the underground.

Phase I AIB Report Conclusions

Nuclear Safety Program: Ineffective
- ➢ Misclassified safety class of the ventilation system and CAMs
- ➢ Non-conservative DSA and TSR controls

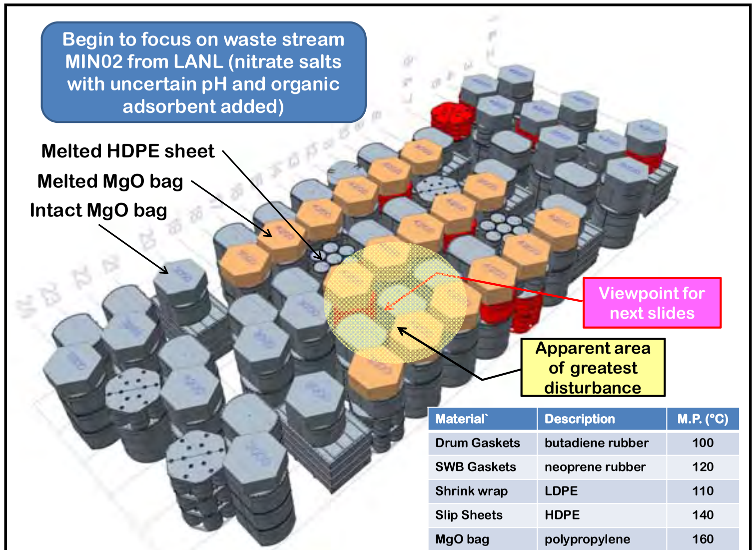
Maintenance Program: Ineffective
- ➢ Key components and systems inoperable or unreliable

Radiation Protection Program: Ineffective
- ➢ Delayed response, contamination control, surveys, and training

Emergency Management Program: Ineffective
- ➢ Not effective in prompt categorization, implementation, required notifications

Conduct of Operations: Key elements ineffective

Safety Culture and Oversight:
- ➢ Nuclear facility versus mining culture: Difference in expectations
- ➢ NWP safety culture does not embrace ISMS
- ➢ NWP contractor assurance system and CBFO oversight ineffective
- ➢ EM HQ line management ownership and oversight were ineffective



Material`	Description	M.P. (°C)
Drum Gaskets	butadiene rubber	100
SWB Gaskets	neoprene rubber	120
Shrink wrap	LDPE	110
Slip Sheets	HDPE	140
MgO bag	polypropylene	160

Release Cause Investigation Continues

- Phase 2 Accident Investigation Board report on cause of the release not yet completed
  - What is known from underground air particulate and swipe sample analyses:
    - The material that was released appears to be generated by a combustion (rapid chemical oxidation) process
    - Its chemical and radiological signatures are similar to the waste stream in the breached waste container that contained nitrate salts and organics in a very acidic matrix
    - Am to Pu ratios were about 10:1, which is a distinctly different ratio from the bulk of the waste in the repository
    - Suspect waste has been re-classified as ignitable

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Recovery is In Progress

- Each of the Accident Investigation Board conclusions and recommendations for cultural and technical changes is being implemented
- The underground facility is being rehabilitated:
  - Decontamination where needed and feasible to allow underground work to resume in stages
  - Additional clean air supply and exit air filtration capacity is being implemented
  - Areas with suspect waste are planned to be isolated from the working repository as soon as practicable
- A draft detailed Recovery Plan is under review

19

Activities Required for WIPP Restart

Near term:

- **Upgrade Documented Safety Analysis, fire and safety systems**
- **Uncontaminated and contaminated areas established;**
- **Ground control fully functioning (roof bolting catch-up);**
- **Procure temporary filtered ventilation capacity using skid HEPA filters;**
- **Design activity: permanent ventilation changes, new exhaust shaft;**
- **Mine characterization and decontamination;**

Mid term:

- **Install/operate skid fans/HEPA filters;**
- **Design/Permit permanent ventilation system and new exhaust shaft;**
- **Begin initial operations/emplacement using existing panels;**
  - **Supplemental ventilation on air intake shaft;**
  - **Three shifts to optimize use of available ventilation capacity;**
- **Further upgrade above and below ground utility/safety systems;**

Long term:

- **Construction of permanent ventilation system and new exhaust shaft;**
- **New salt shaft and ventilation system operational;**
- **Operational Readiness Reviews;**
- **Begin full operations/waste-emplacement;**
- **Potential shift to utilize some electric mining equipment**


Strong Headquarters
Support for Recovery
Secretary of Energy Ernest Moniz at a Town Hall meeting in Carlsbad, NM, August 12, 2014
"We are absolutely committed to this facility. We are, of course, committed to bringing it back to initial operations and then eventually to full operations, with safety fully in mind."
Waste Isolation Pilot Plant
WIPP
SNL • WTS • DOE • LANL • CTAC
21


Permanent Isolation in Deep Geologic Salt
A National Solution and International Model

Waste Isolation Pilot Plant
Road to Recovery

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

Tammy Reynolds, NWP Deputy Recovery Manager
September 8, 2014

1

WIPP

Quick Facts:
- Opened: March 26, 1999
- 11,894 shipments received
- 90,983 cubic meters of waste disposed
- 171,064 containers disposed in the underground

2

WIPP Haul Truck Fire Event

3

AIB Salt Haul Truck Fire Findings

Feb. 7, DOE EM Deputy Assistant Secretary appointed an Accident Investigation Board (AIB) to conduct an evaluation of event and response.

Positive Observations

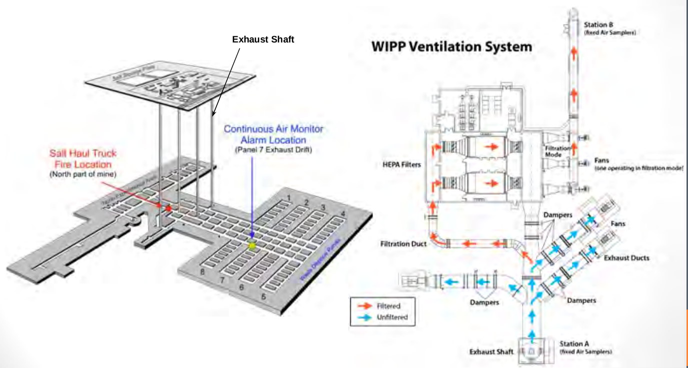
- Supervisors and employees in the underground proactively alerted other workers of the fire and need to evacuate before the evacuation alarm was sounded.
- Workers assisted each other during the evacuation, including helping them to don self-rescuers and SCSRs.
- Personnel in the underground exhibited detailed knowledge of the underground and ventilation splits.
- NWP on-site medical response was effective in treating personnel.

Report Findings

- Maintenance program was ineffective.
- Fire protection program was less than adequate.
- CMR response (evaluation and protective actions) was less than adequate.
- Emergency management/ preparedness and response programs were ineffective.
- Different treatment of waste versus non-waste handling equipment. (Nuclear facility versus mine culture)
- Inadequate oversight from government agencies

4

WIPP Underground and Ventilation System



5

AIB Radiological Release Findings

Feb. 27, Accident Investigation Board appointed to evaluate radiological release and response.

- Phase 1 of the AIB investigation focused on the radiological release and the follow-on response to the release:
  - Ineffective components of the following WIPP programs were identified:
    - Nuclear safety program
    - Maintenance program
    - Radiation protection program
    - Emergency management program
    - Conduct of operations
    - Safety culture and oversight
- Phase 2 is focused on determining the direct cause of the release of material

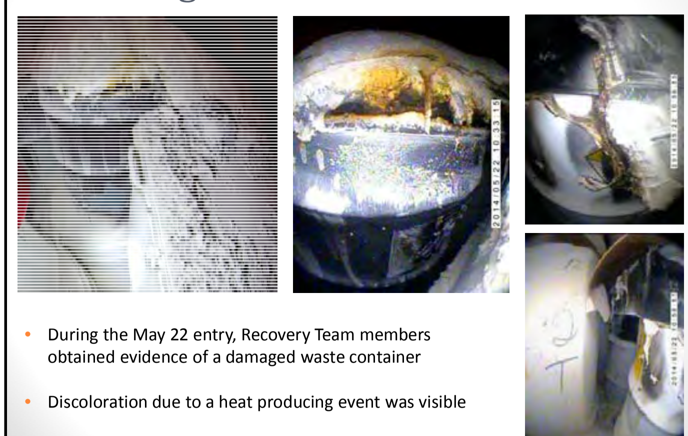
6

Initial Response: Plant is safe and stable

- Developed Nuclear Safety Documentation to support recovery activities
- Collection and analysis of environmental samples
- Completion of the event bioassay program
- Sealing of the bypass dampers
- Fans balanced and preventive maintenance completed to restore reliable operation
- Continuous Air Monitor installed at Station B
- Filters loaded with fire combustion products replaced and HEPA filters efficiency tested
- Cleaning of the Waste Hoist Tower and Waste Hoist components
- Safety Management Program compensatory measures implemented
- Significant nuclear operations experience added to NWP leadership team

7

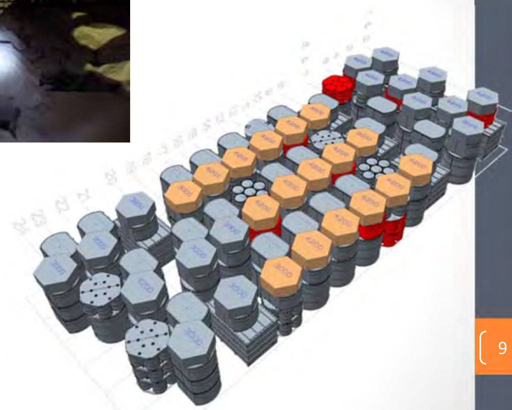
Phase 2 AIB Investigation – Radiological Release



- During the May 22 entry, Recovery Team members obtained evidence of a damaged waste container
- Discoloration due to a heat producing event was visible

8

Room 7, Panel 7



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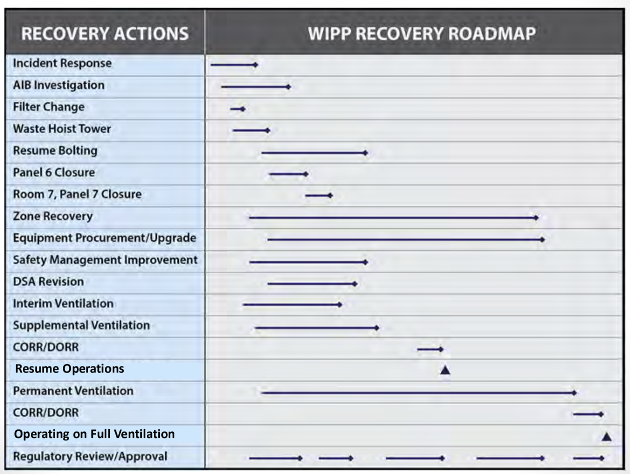
Support to the Accident Investigation Board

- Additional samples from Panel 7, Room 7 were taken on 8/15.
- Project REACH
  - Operator training
  - Shipment to WIPP
  - Install underground
  - Operation
  - Extendable composite 90-foot boom, suspended by moveable cradle atop a support structure

10

WIPP Recovery Roadmap



11

Resume Operations - Key Steps

- Nuclear Safety Document Revisions (continuing)
- Safety Management Program Revitalization (continuing)
- Underground restoration (initiated)
  - Radiological Roll-back, Re-Establish Safety Systems, Cleanup, Habitability, Fire Protection, Maintenance and Ground Control
- Expedited Panel 6 and Room 7, Panel 7 Closure
- Interim Ventilation Modifications (procurement underway)
- Expedite mine stability (resume bolting)
- Supplemental Ventilation Modifications (initiated)
- Readiness Activities
- Limited Operations
  - On-site waste
  - Off-site waste generators

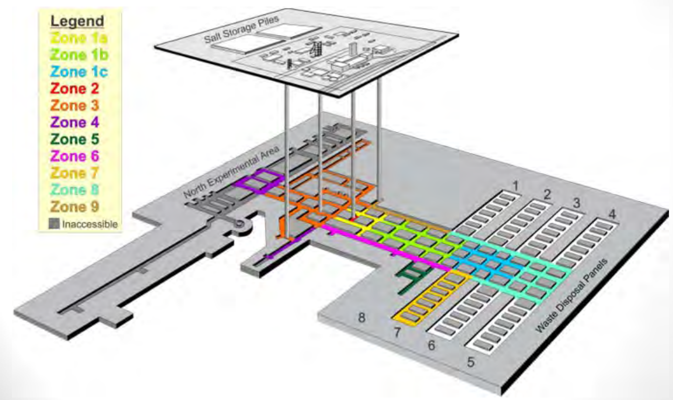
12

Operating on Full Ventilation - Key Steps

- Nuclear Safety Document revisions to support new ventilation system
- Continued ground control activities
- Replacement of outdated safety, mining and waste handling equipment
- New Ventilation System
  - Capital Project
  - New shaft and drifts (requires extensive mining)
  - New above ground ventilation system components (fans, filters)
- Readiness Activities

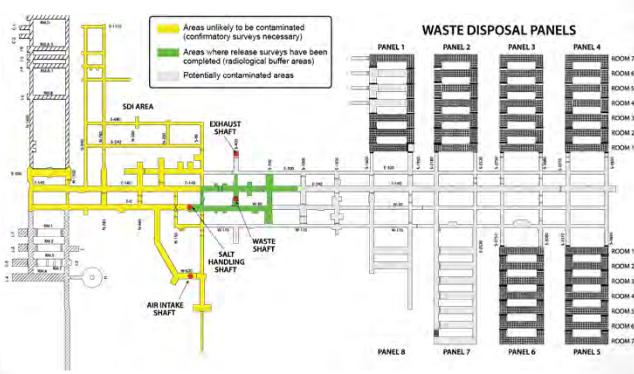
13

Recovering the Underground



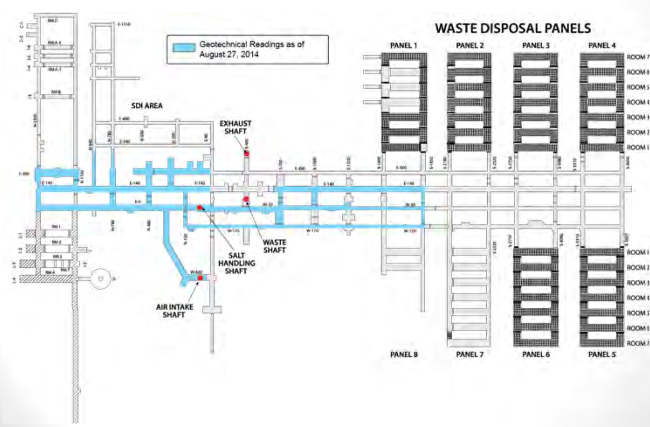
14

Radiological Area Rollback



15

Geotechnical Measurements



16

Nuclear Safety Culture – Driving WIPP's Future

- Immediate emphasis on stop work and verbatim procedure compliance
  - Good Catch recognition
  - Reinforcement by PM in All-Hands meetings and Straight Talk
- Continuing emphasis on Work Control
  - Interactive Team Reviews
  - SMRB Review
  - Frequent rework to establish new expectations
- Revitalization of NSC as foundation
  - Seasoned advisors
  - Improvement Plan
  - Leadership Workshops
- Management time in field
- Reporting of mistakes/errors
- WIPP NSC Worker Reference Guide

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18

A Perspective on Removal, Retrieval and Reversibility as they relate to the Waste Isolation Pilot Plant

Steve Wagner

Abstract

With respect to waste removal, retrieval or reversibility (RR&R) within the WIPP project, the overall concept can be addressed by answering general questions about what is required, what the project said they would do, and what was actually done. The following answer these and other questions as they apply to RR&R and the Waste Isolation Pilot Plant (WIPP) radioactive waste disposal project.

What is Required: The radioactive waste disposal concept in the United States (U.S.) included "retrieval" from the start. The U.S. Government is legally responsible for radioactive waste disposal. The first geologic disposal concepts were based on recommendations in a 1957 National Academy of Science report on radioactive waste disposal. All attempts at siting disposal facilities used the "Pilot Project" concept. Eventually the U.S. government started investigating the bedded salt formation in the Delaware Basin of New Mexico. To gain acceptance at that time from the State of New Mexico and Local Municipalities, the disposal concept would first have a "test period" where all waste would be retrievable should the concept not meet disposal objectives. In 1976, the Environmental Protection Agency (EPA) was given the responsibility to develop generic radioactive waste disposal regulations that eventually included waste retrieval and removal requirements. At that time the ability to retrieve or remove waste became necessary past the "test period". The EPA's rationale for waste removal was not to make recovery of the waste easy or cheap but to make it possible in case some future discovery or insight made it clear that the waste needed to be relocated. Additional requirements imposed on the WIPP by the U.S. Congress and the State of New Mexico required a retrieval demonstration prior to actual waste emplacement.

Additionally the WIPP project defines "disposal" as permanent isolation of radioactive waste from the accessible environment with no intent of recovery. Disposal occurs in a mined geologic repository when all of the shafts to the repository are backfilled and sealed. Where the WIPP project includes the concepts of waste removal and retrieval, the project does not intend to ever do so.

What they said they would do: As stated earlier, the WIPP is a pilot project that included the concept requiring the ability for waste retrieval before closure. The disposal regulations also required that it be feasible to remove waste after operations ceased and the repository was sealed. A waste removal after closure feasibility analysis was included in the Compliance Certification Application to the EPA and a remote retrieval demonstration was performed under conditions simulating a roof fall in the underground on simulated waste containers.

International Perspective: Most international disposal concepts are similar to what was developed in the U.S. in that most include the requirement for waste retrieval during the repositories operational period. Recent attention has been given to the concept of reversibility.

The intent is to include reversibility in the disposal system design. Whereas the U.S. concept only requires it to be feasible to remove waste after closure, reversibility requires a repository design that allows for waste retrieval during any phase of a disposal program.

What has been done – Actual retrieval: DOE has retrieved a few of the emplaced containers from the underground. The State of New Mexico required DOE to retrieve a waste container in August, 2007 when it was learned that the wrong container had been shipped to WIPP. The DOE decided to retrieve another waste container in June, 2008. These drums were returned to the generator sites for remediation because they did not fully meet the waste acceptance criteria, not for health and safety reasons.

Lessons Learned - Risk vs benefits: One element that has been overlooked by the WIPP regulators and stakeholders is risk. The regulations associated with waste retrieval/removal do not address risk or benefit and are silent as to the conditions that warrant retrieval/removal. The project therefore has no recourse when regulators require retrieval of waste containers that may be deficient but can be shown to not have any impact on overall repository performance. Lessons learned regarding removal/retrieval requirements recommend that other disposal program's regulations outline specific risk vs. benefit elements in decisions that lead to waste retrieval. The actual risk of retrieval, in many cases, have associated risks relating to occupational health, dose and transportation/accident risks that are real and may be greater than the risks associated with the newly discovered condition of the waste or repository.

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. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy.
SAND2014-16394A

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DBETEC DBE TECHNOLOGY GmbH

PTKA Project Management Agency Karlsruhe

U.S. DEPARTMENT OF ENERGY NNSA

A Perspective on Removal, Retrieval and Reversibility as they relate to the Waste Isolation Pilot Plant

Steve Wagner – John Hart and Associates

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. 2014-16571PE

This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy.

Outline

- With respect to waste removal, retrieval or reversibility within the WIPP project, the overall concept can be addressed by answering general questions:
  - What is required
  - What did the project said they would do
  - What has the project actually done
- This presentation will answer these and other questions as they apply to the Waste Isolation Pilot Plant (WIPP) radioactive waste disposal project.

2

Waste Isolation Pilot Plant Facts

- WIPP is geologic disposal facility designed to dispose ~176,000 m^3 of transuranic waste from defense-related activities
- Waste area is mined in a bedded salt formation, ~ 2,150 ft (655 m) Below the Ground Surface
- Plutonium & Americium are major radionuclides in the waste
- US Congress established the Environmental Protection Agency (EPA) as the radioactive waste disposal regulating authority; the Department of Energy is the site developer
- Early disposal concepts of "Pilot Project" included Retrievability Requirement (1970's)

3

RR&R – What is Required?

- US Government's first radioactive waste geologic disposal concept was a "Pilot Project" based on National Academy of Science recommendations (1957)
- Originally Self-Regulated – Atomic Energy Commission
- To gain acceptance from State and Local Municipalities, the disposal concept would first have a "test period" where all waste would be retrievable should the concept not meet disposal objectives

4

RR&R – What is Required?

- In 1976 the EPA was given the responsibility to develop general radioactive waste disposal regulations
- Retrieval requirements were included in the final regulation
- Retrieval concept became necessary past "test period"
- Additionally, the U.S. Congress and the State of New Mexico required test-phase Retrieval demonstrations (LWA, Consultation and Cooperation Agreement)

5

RR&R – What is Required?

EPA Regulations for WIPP

EPA 40 CFR 191
Generic Radioactive Waste Disposal Standards

- **Assurance Requirement 191.14(f): Disposal systems shall be selected so that removal of most of the waste is not precluded for a reasonable period of time after disposal**

↓

EPA 40 CFR 194
Site-Specific Certification Criteria

- **Removal of waste must be feasible using existing technology**
- **Waste must be retrieved to the extent practicable if EPA revokes certification**

6

RR&R – What is Required

- EPA RR&R Perspective
- EPA Certification Criteria (40 CFR 194.46)
  - "Any compliance application shall include documentation which demonstrates that removal of waste from the disposal system is feasible for a reasonable period of time after disposal. Such documentation shall include an analysis of the technological feasibility of mining the sealed disposal system, given technology levels at the time a compliance application is prepared"

7

What We Said We Would Do

- For US Congress and State of New Mexico Requirements
  - DOE documented a mock test waste retrieval demonstration on April 27, 1992 using remote controlled devices (video available)
- For EPA Disposal Requirements
  - DOE document the results of a feasibility of waste removal after closure in Appendix WRAC of the EPA compliance application
  - DOE acknowledges that EPA requires waste retrieval if the certification were to be revoked.
    - "If the Administrator revokes the certification, the Department shall retrieve, as soon as practicable and to the extent practicable, any waste emplaced in the disposal system." 40 CFR 194.4(b)(1)

8

What We Actually Have Done

- DOE has retrieved emplaced containers from the underground
  - The State of New Mexico required DOE to retrieve a waste container in August, 2007
  - DOE decided to retrieve a waste container in June, 2008
- Drums were returned to the generator sites for remediation because they did not fully meet the waste acceptance criteria, they were not returned for health/safety reasons

9

International Perspective

- Most international disposal concepts are similar to what was developed in the U.S.
  - most programs include the requirement for waste retrieval during the repositories operational period.
- Recent attention has been given to the concept of reversibility.
  - The intent is to include reversibility in the disposal system design. Whereas the U.S. concept only requires it to be feasible to remove waste after closure, reversibility requires a repository design that allows for waste removal during any phase of a disposal program.

10

Lessons Learned

- RISK
  - The WIPP regulations associated with waste retrieval/removal do not address risk or benefit and are silent as to the conditions that warrant retrieval/removal.
  - The project has no recourse when regulators require retrieval of waste containers that may be deficient but can be shown to not have any impact on overall repository performance, the environment or public safety.
- Recommendation
  - Recommend that disposal program's regulations outline specific risk vs. benefit elements in decisions that lead to waste retrieval.
  - The actual risk of retrieval, in many cases, have associated risks relating to occupational health, dose and transportation/accident risks that are real and may be greater than the risks associated with the newly discovered condition of the waste or repository.

11

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Retrievability as Design Requirement for a Repository for HLW and SF

Wilhelm Bollingerfehr
DBE TECHNOLOGY GmbH
Eschenstraße 55, D31224 Peine/Germany

Outline

- Why Retrievability?
- Definitions and legislation on retrievabiltiy
  - ➢ Definitions
  - ➢ Legislation
- Implications of retrievability requirements on repository designs
  - ➢ Drift disposal concept
  - ➢ Borehole disposal concept
- Summary and conclusions

Why Retrievability?

EC-Concerted Action on Retrievability (2000)

The most frequently used arguments listed are:

1. Safety and operational arguments

- Disposal should be reversible in case something goes wrong with the emplacement of a package
- Retrieval of a waste package may be necessary in case a waste package malfunctions during or after emplacement
- Retrieval of waste packages may be necessary if the repository appears to be malfunctioning at a later stage

2. Licensing arguments

- Retrievability should be included in order to facilitate a staged decision and licensing process

Why Retrievability?

3. Societal arguments

- Radioactive waste may contain potentially useful materials, which may become valuable in the future. It could be the wish of a future society to utilise such a resource.
- Disposal decisions should not be irrevocable, in order to provide future generations with the option to make their own decisions.
- From a sustainable society viewpoint, high priority is given to the reuse of materials and to a minimisation of the quantity of waste that needs to be disposed of. Views and/or technology for reuse of materials may be different in the future
- The precautionary approach and the recognition of uncertainty speak in favour of retrievability

Why Retrievability?

4. Waste management arguments

- Future new technology or scientific knowledge could – based on re-evaluation of the cost/benefit balance – motivate modifications in earlier disposal, or retrieval of disposed waste packages.
- A repository that includes design features to keep the waste packages retrievable could offer better possibilities for control and surveillance of the waste after disposal.

5. Public acceptance arguments

- A disposal concept may be better appreciated, when key decisions are reversible. Including retrievability may enhance the acceptance of geological disposal.

Definitions

Reversibility

➢ „Reversibility describes ***the ability in principle*** to change or reverse decisions taken during the progressive implementation of a disposal system" /NEA 2011/.

Retrievability

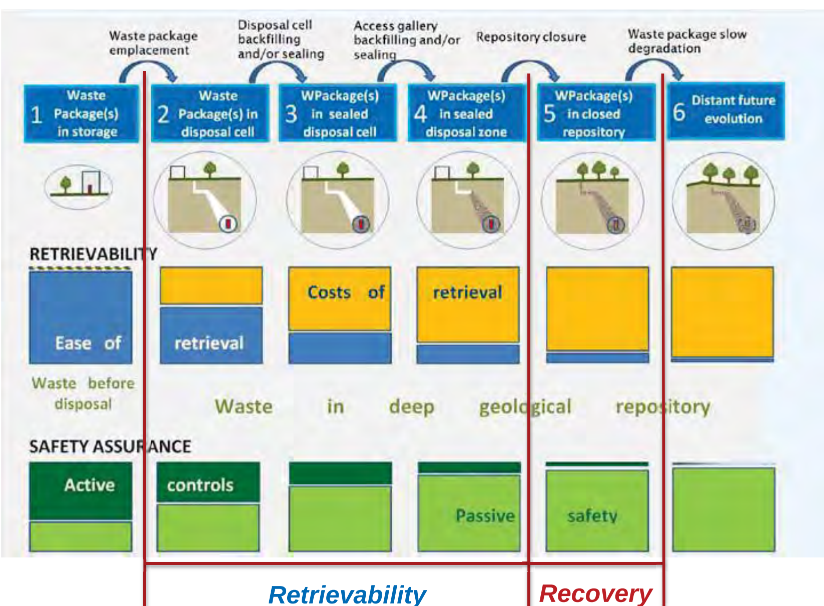
➢ „Retrievability, in waste disposal, is ***the ability in principle*** to recover waste or entire waste packages once they have been emplaced in a repository" /NEA 2011/.

➢ "Retrievability is the ***planned technical option*** for removing emplaced radioactive waste containers from the repository mine "/BMU 2010/.
  - ✓ operational phase of repository until closure of shafts and/or ramps

Recovery

➢ "Recovering is the retrieval of radioactive waste from a final repository as an ***emergency measure***" /BMU 2010/.
  - ✓ up to 500 years after repository closure

Retrievability-Scale (NEA 2011)



German Legislation

Retrieval requirements:

"8 .6 :

Waste containers ***must fulfil the following safety functions***, with due regard for the waste products packaged therein and the backfill surrounding them:

- For probable developments, ***handleability*** of the waste containers must be ***guaranteed for a period of 500 years*** in case of recovery from the decommissioned and sealed final repository. Care should be taken to avoid the release of radioactive aerosols.
- During the ***operating phase*** up until sealing of the shafts or ramps, ***retrieval*** of the waste containers ***must be possible***.

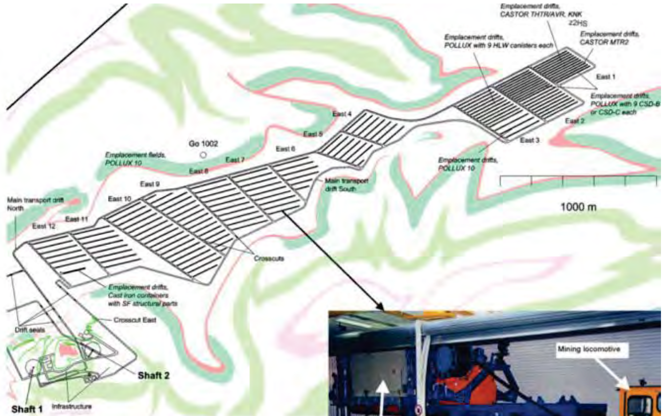
Measures taken to secure the options of recovering or retrieval must not impair the passive safety barriers and thus the long-term safety."

(according to: "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" as at 30 September 2010)

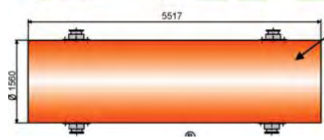
Implication on Repository Design

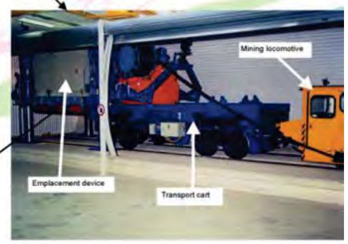
Drift Disposal Concept

site-specific design of repository



waste package for HLW and SF: POLLUX® cask



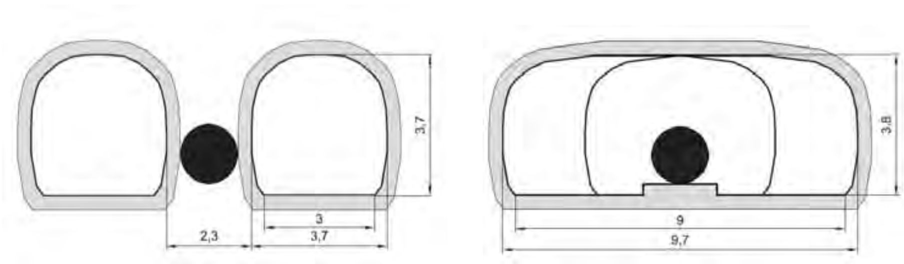


verification of safety and reliability of transport and emplacement technique by means of 1:1 scale demonstration tests

(Source: VSG)

Implication on Repository Design

Stepwise Process for Excavation of Drifts

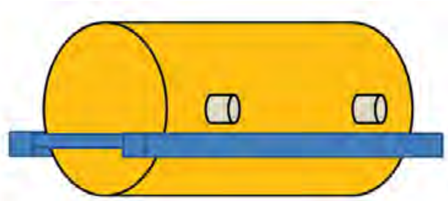


step 1 and step 2:
excavation of drifts parallel to the emplaced POLLUX® cask

final step:
excavation of remaining compacted backfill material surrounding POLLUX® cask

Implication on Repository Design

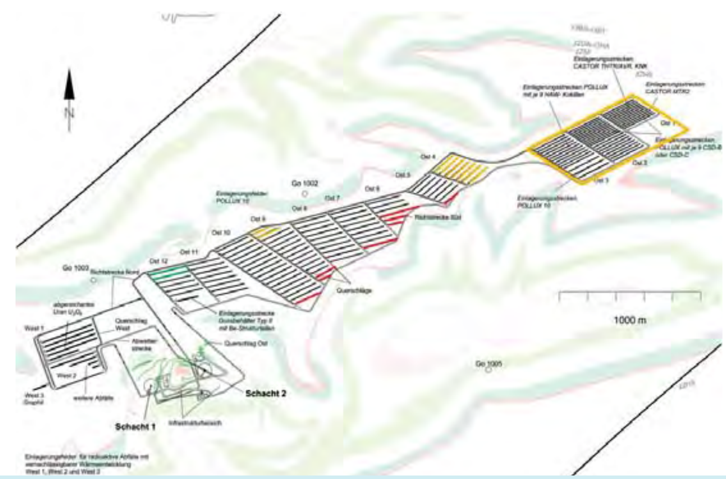
Modification for POLLUX® cask Lifting



Schematic view of a steel frame construction as a lifting device for POLLUX® casks

Emplacement device for POLLUX® casks

Implication on Repository Design



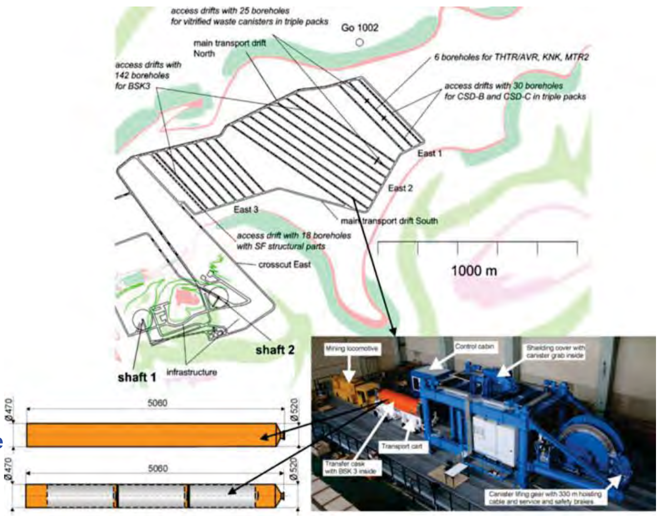
Detailled planning of retrieval actions (basis: VSG design)
- **green:** retrieval drifts,
- **red**: retrieval drifts not connected with a second crosscut,
- yellow retrieval drifts connected with main transport drift North,
- yellow frame: prior to excavation start need for geomechanical proof of pillar stability)

Implication on Repository Design

Borehole Disposal Concept

site-specific design of repository

waste package for HLW and SF:BSK 3

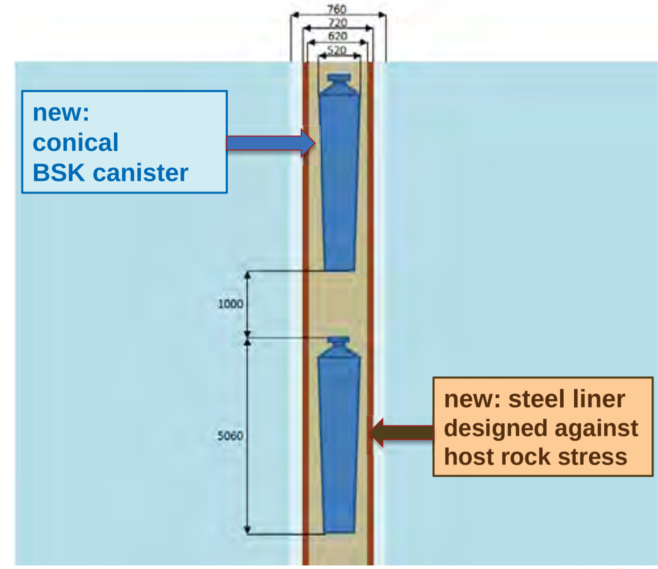


verification of safety and reliability of transport and emplacement technique by means of 1:1 scale demonstration tests

(Source: VSG)

Implication on Repository Design

Borehole Disposal Concept



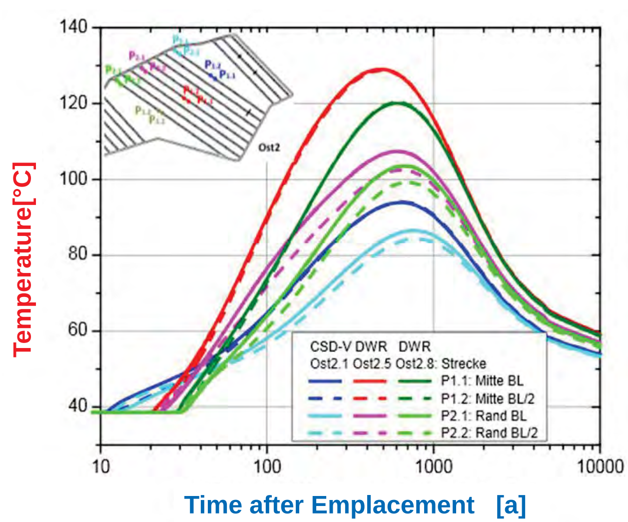
new: conical BSK canister

new: steel liner designed against host rock stress

Implication on Repository Design

Detailed planning of ventilation/cooling needed!

Example: Borehole Disposal Concept



Summary and conclusions

- **For drift disposal concept**
  - ✓ Retrieval of emplaced POLLUX ® casks is technically feasible during repository operational period (several decades)
- **For borehole disposal concept:**
  - ✓ Retrieval of emplaced BSK containers is technical feasible assuming:
    - the borehole is lined
    - the new BSK container meets design expectations
- **For both concepts**:
  - ✓ Detailled ventilation and cooling systems have to be designed
  - ✓ Interim storage facilities and casks are required (prior to repository licensing)
  - ✓ A conditioning plant may be required (depending on disposal concept)

Acknowledgements

Many thanks

- to my colleagues:
  - ✓ Wolfgang Filbert
  - ✓ Phillip Herold
  - ✓ Sabine Dörr

  for their contributions to the DBETEC report on retrievability

- to the Federal Ministry for Economic Affairs and Energy (BMWi) and the Project Management Agency Karlsruhe (PTKA) of the Karlsruhe Institut of Technology (KIT) for funding the R&D project on retrievability

Thank You
for Your Attention!

Salt Disposal Research, Development, and Demonstration

5th US/German Workshop on
Salt Repository Research, Design and Operations

Santa Fe, New Mexico, USA

September 7-11, 2014

Robert J. MacKinnon--Sandia National Laboratories, Albuquerque New Mexico USA

Abstract

The United States Department of Energy (US DOE) is conducting research and development (R&D) activities within the Used Fuel Disposition (UFD) Campaign to support disposal of used nuclear fuel (UNF) and wastes generated by existing and future nuclear fuel cycles. Disposal R&D focuses on identifying geologic disposal options and addressing technical challenges for generic disposal concepts in mined repositories in salt, clay/shale, and granitic rocks, and deep borehole disposal. This talk will first give an overview of the DOE UFD Campaign and its mission and then describe the R&D investigations that are being implemented to support a generic safety case for a geologic repository in salt host rock. These R&D investigations range from laboratory-scale investigations and modeling studies to the design of larger-scale field testing that would be beneficial for specific safety case objectives.

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 DEAC04-94AL85000. SAND2014-16796A.

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Salt Disposal Research, Development, and Demonstration (RD&D)

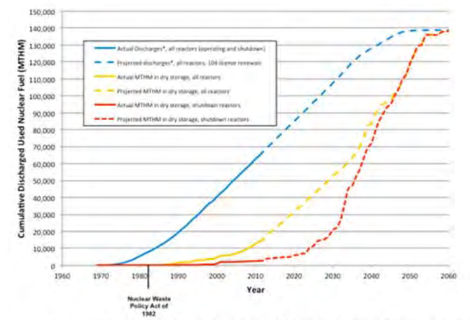
Robert J. MacKinnon
Sandia National Laboratories

5th US/German Workshop on
Salt Repository Research, Design and Operation

Santa Fe, New Mexico, USA

September 7-11, 2014

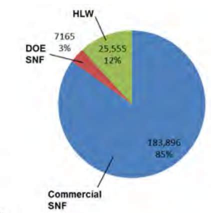
Projections of Future SNF and HLW



Source: *Based on actual discharge data as reported on RW-859s through 12/31/02, and projected discharges, in this case for 104 license renewals

Historical and Projected Commercial SNF Discharges in the United States

Projected Volumes of SNF and HLW in 2048



Volumes shown in m³, assuming constant rate of nuclear power generation

Summary of the Administration's Strategy for Used Nuclear Fuel and High-Level Radioactive Waste

Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste issued January 2013.

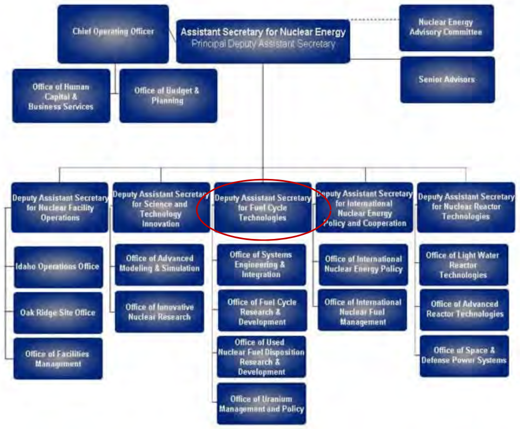
The Strategy outlines a 10-year program:

- Site, design, license, construct and begin operation of a pilot interim storage facility (operating 2021)
- Advance toward siting and licensing of a larger interim storage facility (operating 2025)
- Make demonstrable progress on siting and characterization for geologic disposal (sited 2026, operating 2048)

Disposal R&D within the DOE

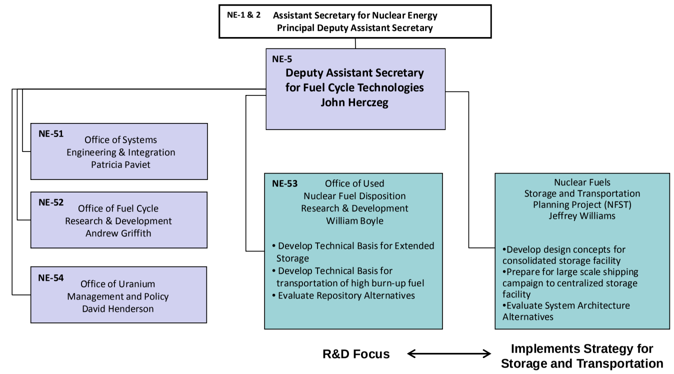
- **The Nuclear Waste Policy Act and Congressional Appropriations preclude site-specific repository investigations**
- **All disposal research must be generic at this stage**
- **What can generic R&D accomplish?**
  - Provide a sound technical basis for the assertion that the US has multiple viable disposal options that will be available when national policy is ready
  - Identify and research the generic sources of uncertainty that will challenge the viability of disposal concepts
  - Increase confidence in the robustness of generic disposal concepts to reduce the impact of unavoidable site-specific complexity
  - Develop the science and engineering tools required to address the goals above, through collaborations within NE and DOE, and with universities, industry, and international programs

DOE Office of Nuclear Energy Organization Chart



Source: http://energy.gov/ne/organization

DOE Office of Nuclear Energy Office of Fuel Cycle Technologies (NE-5)

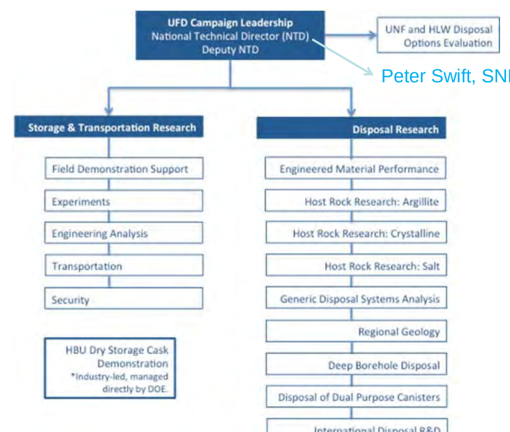


DOE's R&D Program for Used Nuclear Fuel Disposition

Nine national laboratories participate in the DOE Office of Nuclear Energy's "Used Fuel Disposition Campaign" (UFDC)

Campaign Mission: 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

Campaign Structure

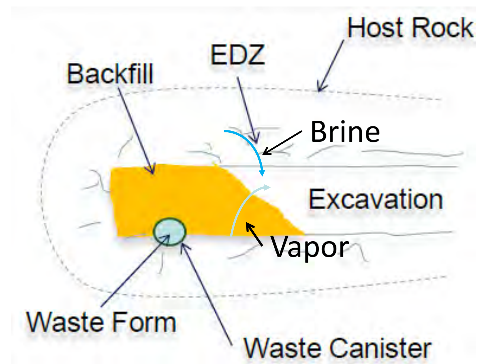


UFD R&D Campaign 2009-Present

- FY09 Planning meeting at Argonne National Laboratory, June 2009
- FY10 R&D funding at $7.1 M
  - Disposal R&D, modest level of effort on Storage R&D, no Transportation R&D
- FY11 R&D funding at $23.8 M
  - Nine national laboratories participating in UFD
  - Significant R&D program in Storage, including Transportation
  - Disposal R&D not site specific
- FY12 R&D budget baseline at $22.8 M, end-of-year actual ~$37 M (Salt R&D - $4.5 Mill)
  - Some elements of FY12 work scope not established until fourth quarter
- FY13 R&D $23.5 M (Salt R&D - $2.06 Mill)
  - Nuclear Fuel Storage and Transportation Planning Project initiated
  - Storage demonstration R&D initiated external to UFD R&D campaign
- FY14 R&D end-of-year baseline at $22.5 M (Salt R&D - $2.25 Mill)
  - Significant redirection of scope within campaign in initial planning
    - Storage and transportation at 54% of budget
    - Disposal research at 37% of budget
    - Management and integration at 8%
  - Work through February 2014 limited to annual total of $15.4 M
- FY15 Salt R&D projected to be $1.25 Mill ($750K lab, $500K Field)

Summary of UFD R&D Campaign 9

Schematic of Features of a Backfilled Repository Room



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Salt RD&D

Many of these activities are documented in technical reports and will be discussed in this 5th US/German Workshop

EXISTING SALT DATA COMPILATION AND ASSESSMENT

THERMAL, MECHANICAL, HYDROLOGIC, AND CHEMICAL LABORATORY STUDIES RELATED TO SALT

- ***Hot Granular Salt Consolidation, Constitutive Model and Micromechanics***
- ***Thermal Conductivity as a Function of Porosity and Temperature***
- ***Laboratory Thermomechanical Testing***
- ***Brine Migration Experimental Studies***
- ***Material Interactions In Heated Salt***
- ***Thermodynamic Properties of Brines, Minerals and Corrosion Products In High Temperature Systems***
- ***Radionuclide Solubility Measurements***

MODELING STUDIES RELATED TO SALT

- ***Safety Framework Development***
- ***Total System Performance Assessment (TSPA) Model Development***
- ***Generic Salt Repository Benchmarking***
- ***Thermomechanical-Hydrological and Chemical (TMHC) Model Development*/Brine *Migration***

INTERNATIONAL COLLABORATION

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Salt RD&D Deliverables

- Summary Results for Brine Migration Modeling Performed by LANL, LBNL and SNL for the Used Fuel Disposition Program (9/25/2014) – SNL, LBNL, LANL
- Salt R&D Brine migration experimental studies in salt 2014 (08/24/2014) - LANL
- Report on Modeling Coupled THMC Processes and Brine Migration in Salt at High Temperatures (9/13/2014) - LBNL
- Analysis of Data from Salt Reconsolidation Experiments at Sandia National Laboratories in FY12 and FY13 (3/13/2014) - SNL
- Thermal Conductivity of Salt as a Function of Porosity (3/12/2014) - SNL
- Modified Test Plan For Salt Reconsolidation Experiments at Sandia National Laboratories (6/26/2014) - SNL
- Thermomechanical Testing of Intact Salt Results for FY14 (6/16/2014) - SNL
- Thermodynamics of Brines, Minerals and Corrosion Products at High Temperatures: FY14 Results (9/30/2014) - SNL
- Results from the US-German Benchmark Initiative for FY14 (9/30/2014) - SNL
- Results from The 4th US German Workshop on Salt (12/23/2013) - SNL

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Salt RD&D: Field Studies

General Objectives

- *Develop technology and methodology for rock characterization and testing*
- *Better understand, model and test relevant processes*
- *Better understand various components of engineering barrier system*
- *Provide quantitative data for safety assessment calculations*
- *Test and optimize full-size repository components and operating procedures (demonstration)*
- *Optimize repository construction techniques*
- *Training and benchmarking*
- *Promote international co-operation*
- *Build confidence in scientific and technical community*
- *Contribute to public trust and confidence*

After IAEA-TECDOC-1243, 2001

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Salt RD&D: Field Studies

Upcoming Deliverables

- ***Framework for Underground Research—important protocol for URL activity evaluation***
- ***Draft report--Test Plan for Mechanical and Hydrological Behavior of the Near-field Host Rock Surrounding Excavations***
- ***Draft report--Test Plan for Phased Large-Scale Thermal Testing***

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Questions?

15

Practical Analogues for Postulated Releases from Geologic Repositories - Natural Background Radiation

N. Rempe

Abstract

Background radiation emanating from geologic and other natural sources is an obvious, yet routinely overlooked and neglected, analogue for theoretical, postulated, and calculated radiological releases from geologic repositories. Natural releases have varied through Earth's history and vary in terrestrial space by two orders of magnitude or more, with negligible to no deleterious effects (and significant indications of beneficial effects at low dose rates) on living organisms. Physical and geological evidence, rather than gratuitously imposed and enforced regulatory standards, should determine the outer bounds that scientists and engineers support and defend for hypothetical and real radiological releases from engineered geologic repositories.

Practical Analogues for Postulated Releases from Geologic Repositories – Natural Background Radiation

Norbert T. Rempe
Carlsbad, NM, USA

rempent@yahoo.com

While generations of students and scientists have learned about radioactive decay and the half-lives of various radioactive elements and isotopes, virtually **no one has turned the telescope around** and discussed or documented the reverse view: The same number of half-life years taken back into the past produces a double-life, a doubling of radioactivity for these elements, and an incremental terrestrial background level many times higher than today's levels.

Gerald L. Looney (2003) Radiation hormesis and the radiological imperative (http://www.sepp.org/Archive/NewSEPP/Hormesis-Looney.htm)

Annual Background Radiation Exposure vs. Annual Public Exposure Limits: U Mines and Mills

- Background Levels (from previous slide)
  - > Colorado average = 400 mrem
  - > Leadville, Colorado = 526 mrem
  - > U.S. average = 310 mrem
- Regulatory Limits
  - > EPA drinking water standard = 4 mrem[1]
  - > EPA limit for all exposure pathways = 25 mrem[2]
  - > NRC Limit with radon = 100 mrem; excluding radon = 25 mrem[3]

[1] U.S. Environmental Protection Agency. Radionuclides in drinking water. Available at:
[2] U.S. Environmental Protection Agency. Environmental radiation protection for nuclear power operations, 40 CFR 190.10, 2006
[3] U.S. Nuclear Regulatory Commission; Domestic Licensing of Source Material ; 10 CFR 40

SENES Consultants   SHB, Inc.

http://www.nma.org/pdf/urw/brown.pdf

Decrease in the natural radioactivity of Earth's crust from the decay of its most common radioactive isotopes

(Significant conclusion: All natural uranium is depleted uranium)

Million years ago	Relative decrease in radioactivity			
	U-238	U-235	Th-232	K-40
5000	2.14	128	1.29	14.3
2000	1.35	7.05	1.08	2.82
present	~1	~1	~1	~1

ng(o)₃

Simplified from L.A. Pertsov. The natural radioactivity of the biosphere. Israel Program for Scientific Translations, Jerusalem, 1967

Example Conclusions from Studies on Health Impacts on Populations Living Near Uranium Mines and Mills

"The absence of elevated mortality rates of cancer in Montrose County over a period of 51 years suggests that the historical milling and mining operations did not adversely affect the health of Montrose County residents."[1]

"No unusual patterns of cancer mortality could be seen in Kames County over a period of 50 years suggesting that the uranium mining and milling operation had not increased cancer rates among residents."[2]

[1] Cancer and Noncancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado, 1950-2000. Boice, JD, Mumma, MT et al. Journal of Radiation Research, 167:711-726, 2007

[2] Mortality in a Texas County with Prior Uranium Mining and Milling Activities, 1950 – 2001. Boice, JD, Mumma, M et al. Journal of Radiological Protection, 23:247 – 262, 2003

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http://www.nma.org/pdf/urw/brown.pdf

ng(o)₃

Radiation Background in Kerala India

- Unusually high natural radiation background has been known for many years due to natural thorium in the monazite sands of the region
- Annual outdoor exposure levels as high as 7000 mrem have been measured where people live
- Recent epidemiological studies have concluded no excess cancers in over 69,000 residents studied for 10 years[1]

[1] R Nair, B Rajan, et al; Background radiation and cancer incidence in Kerala, India—Karunagappally cohort study. Health Physics, 96,1, January, 2009

SENES Consultants

SHB, Inc.

http://www.nma.org/pdf/urw/brown.pdf

ng(o)₃

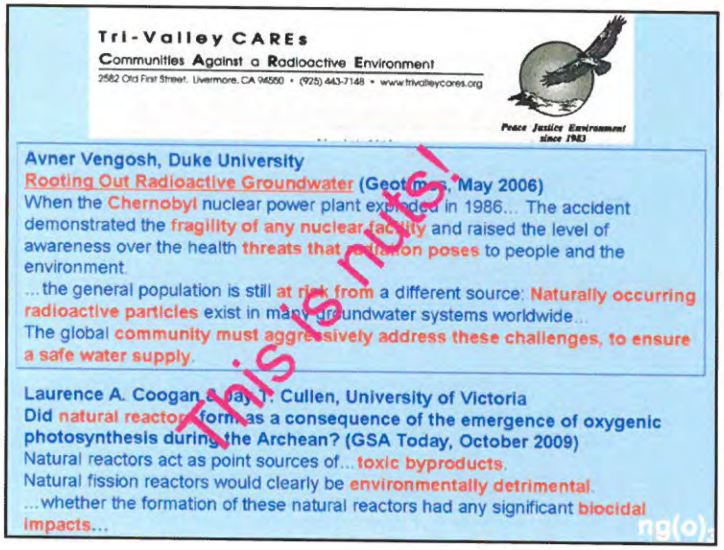
"Normal" or average v. highest known natural background radiation on Earth

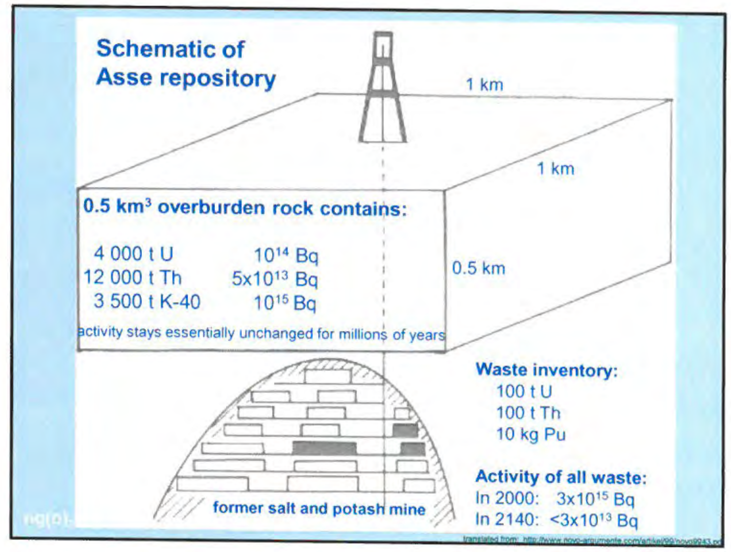
"normal"	Ramsar
Radium in groundwater (Bq/l)	
<10	~500
Radium in soil, rock, food (Bq/g)	
<0.5	~350
Radon inside homes (Bq/l)	
<0.5	>4
Population dose (mSv/yr)	
2-3	20-250

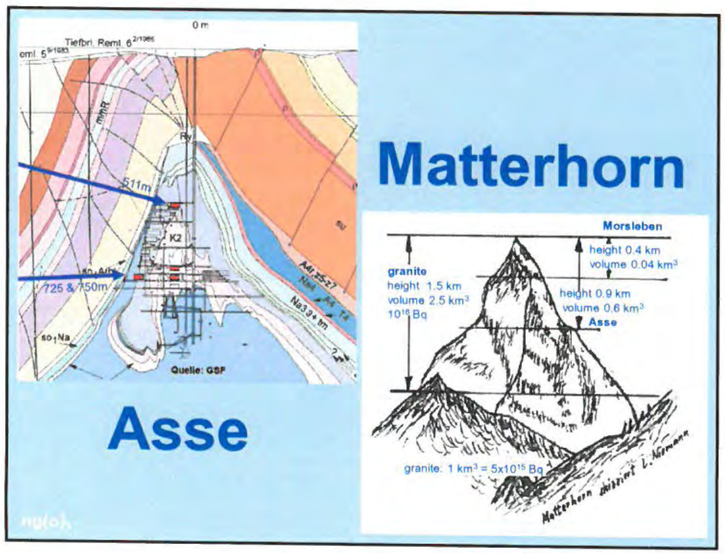
"no consistent detrimental effect has been detected so far"

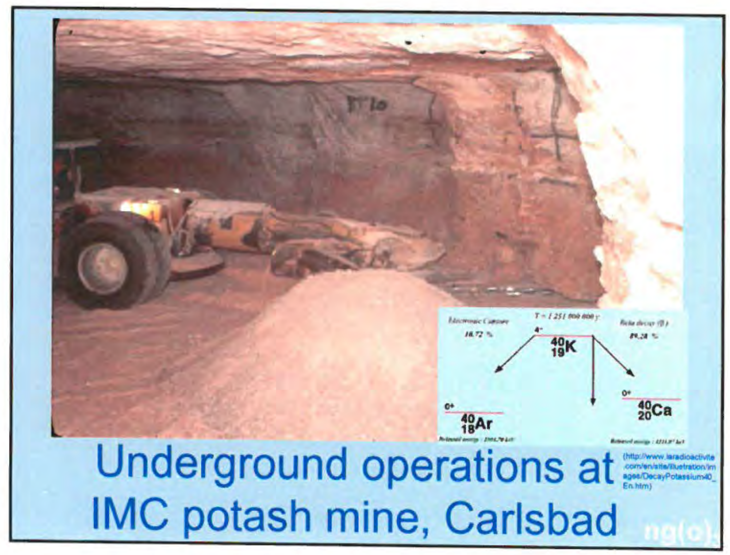
Source
The Very High Background Radiation Areas of Ramsar, Iran
Geology, Radiobiology, and Policy
Andrew Karam, Ph.D., CHP
University of Rochester
Presented to NO CHPS, Radiation Safety Without Borders
November 12, 2002

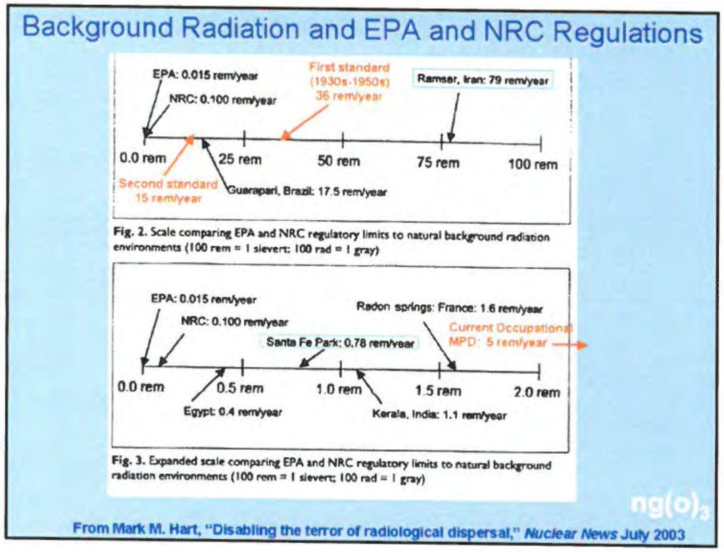
ng(o)₃

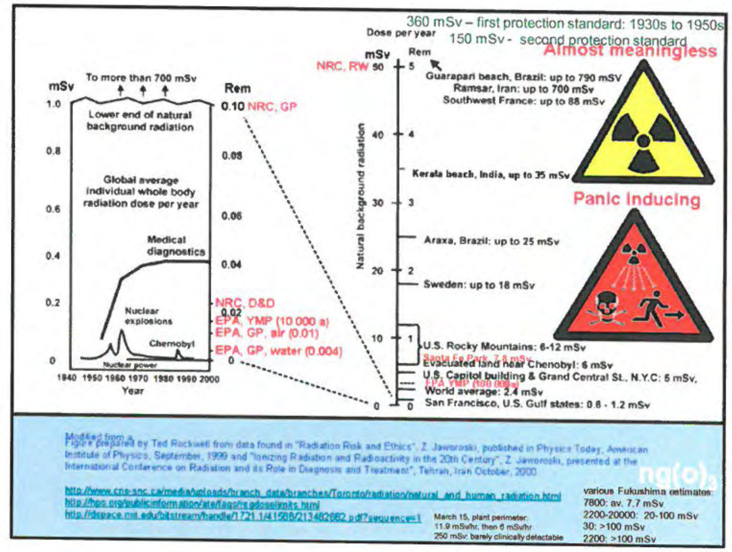

Tri-Valley CAREs
Communities Against a Radioactive Environment
2582 Old First Street, Livermore, CA 94550 • (925) 443-7148 • www.trivalleycares.org
Peace Justice Environment since 1983
Avner Vengosh, Duke University
Rooting Out Radioactive Groundwater (Geotimes, May 2006)
When the Chernobyl nuclear power plant exploded in 1986… The accident demonstrated the fragility of any nuclear facility and raised the level of awareness over the health threats that radiation poses to people and the environment.
…the general population is still at risk from a different source: Naturally occurring radioactive particles exist in many groundwater systems worldwide…
The global community must aggressively address these challenges, to ensure a safe water supply.
Laurence A. Coogan & Jay T. Cullen, University of Victoria
Did natural reactors form as a consequence of the emergence of oxygenic photosynthesis during the Archean? (GSA Today, October 2009)
Natural reactors act as point sources of… toxic byproducts.
Natural fission reactors would clearly be environmentally detrimental.
…whether the formation of these natural reactors had any significant biocidal impacts…
This is nuts!
ng(o)

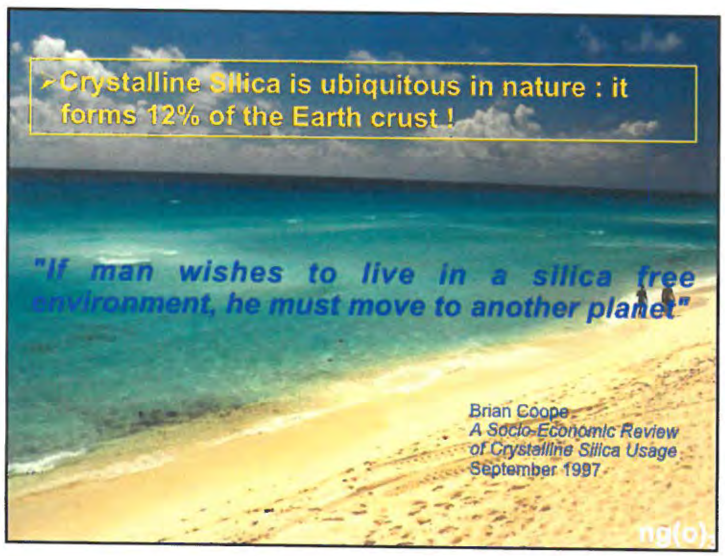

Schematic of
Asse repository
1 km
1 km
0.5 km
0.5 km³ overburden rock contains:
4 000 t U 10¹⁴ Bq
12 000 t Th 5x10¹³ Bq
3 500 t K-40 10¹⁵ Bq
activity stays essentially unchanged for millions of years
Waste inventory:
100 t U
100 t Th
10 kg Pu
Activity of all waste:
In 2000: 3x10¹⁵ Bq
In 2140: <3x10¹³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

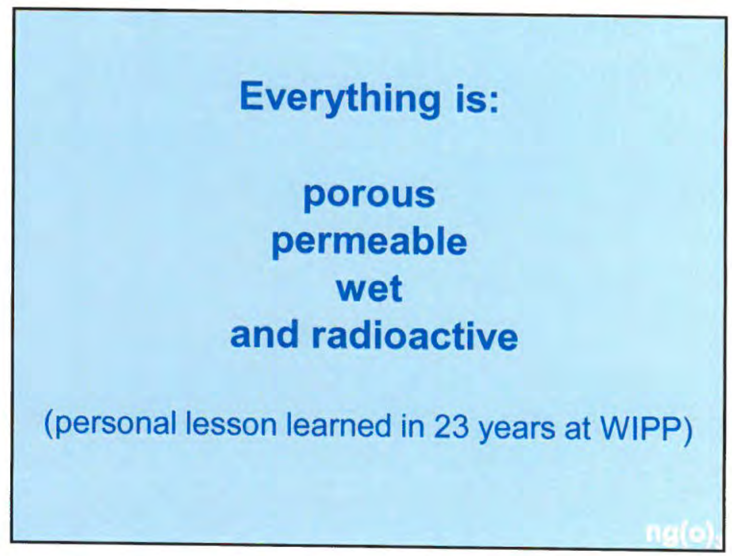

Asse
Matterhorn
Quelle: GSF
511m
725 & 750m
Morsleben
height 0.4 km
volume 0.04 km³
granite
height 1.5 km
volume 2.5 km³
10¹⁶ Bq
height 0.9 km
volume 0.6 km³
Asse
granite: 1 km³ = 5x10¹⁵ Bq
ng(o)


40 19 K
40 18 Ar
40 20 Ca
Underground operations at
IMC potash mine, Carlsbad
ng(o)


Background Radiation and EPA and NRC Regulations
EPA: 0.015 rem/year
NRC: 0.100 rem/year
First standard (1930s-1950s) 36 rem/year
Ramsar, Iran: 79 rem/year
0.0 rem
25 rem
50 rem
75 rem
100 rem
Second standard 15 rem/year
Guarapari, Brazil: 17.5 rem/year
Fig. 2. Scale comparing EPA and NRC regulatory limits to natural background radiation environments (100 rem = 1 sievert; 100 rad = 1 gray)
EPA: 0.015 rem/year
NRC: 0.100 rem/year
Radon springs: France: 1.6 rem/year
Santa Fe Park: 0.78 rem/year
Current Occupational MPD: 5 rem/year
0.0 rem
0.5 rem
1.0 rem
1.5 rem
2.0 rem
Egypt: 0.4 rem/year
Kerala, India: 1.1 rem/year
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
ng(o)3


360 mSv – first protection standard: 1930s to 1950s
150 mSv - second protection standard
Almost meaningless
Panic inducing
Dose per year
mSv
Rem
To more than 700 mSv
Lower end of natural background radiation
Global average individual whole body radiation dose per year
Medical diagnostics
Nuclear explosions
Chernobyl
Nuclear power
Year
0.10 NRC, GP
NRC, D&D
EPA, YMP (10 000 a)
EPA, GP, air (0.01)
EPA, GP, water (0.004)
NRC, RW 50
Natural background radiation
Guarapari beach, Brazil: up to 790 mSv
Ramsar, Iran: up to 700 mSv
Southwest France: up to 88 mSv
Kerala beach, India, up to 35 mSv
Araxa, Brazil: up to 25 mSv
Sweden: up to 18 mSv
U.S. Rocky Mountains: 6-12 mSv
Evacuated land near Chenobyl: 6 mSv
U.S. Capitol building & Grand Central St., N.Y.C: 5 mSv,
World average: 2.4 mSv
San Francisco, U.S. Gulf states: 0.8 - 1.2 mSv
various Fukushima estimates:
7800: av. 7.7 mSv
2200-20000: 20-100 mSv
30: >100 mSv
2200: >100 mSv
ng(o)3


➢Crystalline Silica is ubiquitous in nature : it forms 12% of the Earth crust !
"If man wishes to live in a silica free environment, he must move to another planet"
Brian Coope
A Socio-Economic Review of Crystalline Silica Usage
September 1997
ng(o)3


Everything is:
porous
permeable
wet
and radioactive
(personal lesson learned in 23 years at WIPP)
ng(o)3

Dutch Salt Safety Case and Research Program

Jaap Hart, Jan Prij
NRG Radiation & Environment
Petten, Netherlands

Acknowledged:
Dirk-Alexander Becker, Jens Wolf, Ullrich Noseck (GRS)
Geert-Jan Vis (TNO)

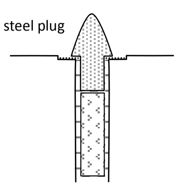
September 2014

Contents

- **Dutch National programs**
  - ICK (< 1979)
  - OPLA-1 (1984 – 1989)
  - OPLA-1A (1989-1993)
  - CORA (1995 – 2001)
- **Program Revatilisation**
  - OPERA
  - Safety Case
  - The “Salt Safety Case”
- **Concluding remarks**
- **Research performed at Utrecht University**

ICK Interdepartementale Commissie Kernenergie
Interdepartmental Commission Nuclear Energy

- Before 1979
- Types and amounts of radioactive waste
- Waste management methods
- Design considerations for deep disposal
- Temperature calculations - TASTE
- Criteria for site selection



TASTE: Three-dimensional Analysis of Salt Dome Temperatures

OPLA-1 Commissie Opberging te Land
Commission Disposal on Land

Central theme: radiation safety
- 1984-1989
- Geology / geohydrology
- Host rock mechanics
- Radiation damage in rock salt
- Mining engineering
- In situ experiments in Asse salt mine
- 26 Reports - Final Report (1989) available at www.covra.nl

OPLA-1A

Follow-up of OPLA-1

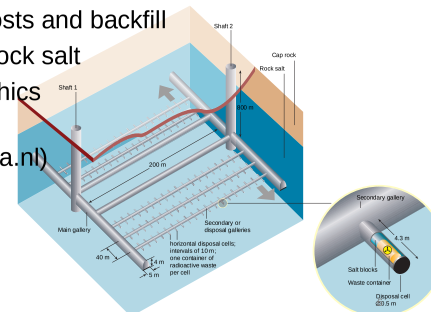
- 1989-1993
- Systematic scenario development
- Development and application of probabilistic methods for consequence analysis (**PROSA**)
- In situ research in Asse (demonstration techniques, heater experiments)
- Radiation damage in rock salt
- Final PROSA Report: 1993

Jan Prij, et al., PRObabilistic Safety Assessment, Final Report, 1993

NRG 5

CORA Commissie Opberging Radioactief Afval
Commission on Radioactive Waste Disposal

- 1996-2001
- Retrievable disposal in salt and clay
- Geology/geohydrology; additional research
- Mining engineering: costs and backfill
- Radiation damage in rock salt
- Societal effects and ethics
- 21 Reports
  (available at www.covra.nl)



NRG

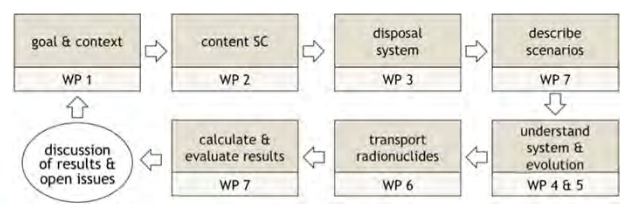
OPERA
Onderzoeks Programma Eindberging Radioactief Afval
Research Programme into Geological Disposal of Radioactive Waste

- 2011-2016
- Revitalization of the Dutch research on geological disposal
- Resolving outstanding issues from previous programmes
- Develop and preserve expertise and knowledge
- Focus on Boom Clay (but rock salt is not forgotten)
- **Result of OPERA:**
  Detailing a first roadmap for the long-term research on geological disposal of radioactive waste in the Netherlands

NRG 7

OPERA Programme Organization

- ❖ Organization of the OPERA research programme
- ❖ 7 Work Packages
- ❖ Programme is financed by the government (Ministry of Economic Affairs) and the energy sector, and coordinated by COVRA, the Dutch WM organization



NRG 8

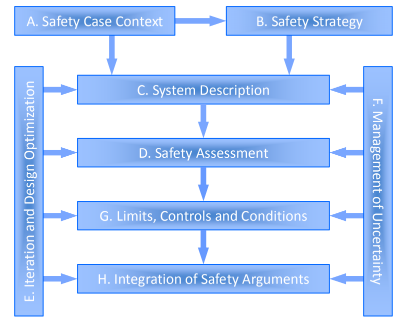
OPERA WP2: *Safety Case*

- **WP2**: Set-up and definition of Safety Cases for disposal in Zechstein rock salt and Boom Clay
  - Project **OSSC** – OPERA Salt Safety Case
- Evaluate the present knowledge about the safety and feasibility of a final disposal facility in rock salt in the Netherlands
- Available national (ICK, OPLA, CORA), and international (German and US) information about the final disposal in rock salt
- Put the information in the framework of a Safety Case
- Project Partners: GRS, TNO, NRG

9

Structuring the Information

- Methodology adopted from IAEA SSG-23 (2012), as further developed in IAEA project PRISM
- *Components* of the Safety Case



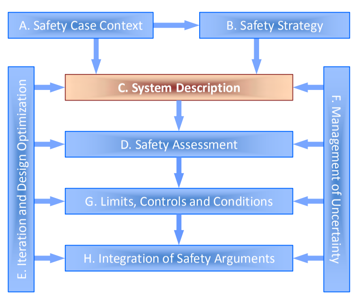
PRISM: ***PR****actical* ***I****mplementation of* ***S****afety assessment* ***M****ethodologies in a context of Safety Case (IAEA, 2009-2012)*

10

Structuring the Information - Example

Safety Case Component: **System Description**

- Objective and Scope
- Waste Characteristics
  - Current inventory of the OPERA reference database
  - Inventory for alternative waste scenarios in NL
- Facility Designs
  - Early design studies
  - Designs considered in OPLA
  - Designs considered in CORA
  - Designs considered in Germany
  - Designs considered in USA
- Salt formations in the Netherlands
  - General information
  - Maps
  - Salt domes
  - Aquifers surrounding rock salt
  - Knowledge gaps
- Biosphere Characteristics
- Evaluation



OSSC - Evaluation of FEPs

Example - Convergence

Convergence (2.1.07.01)		
Short description	FEP relates to the cross-sectional reduction of underground cavities and openings, starting after the excavation due to stress redistribution	
Index	VSG	45 Konvergenz
	WIPP	W20 Salt Creep W21 Change in the Stress Field
	PROSA	3.3.3 Convergence of Openings
Judgement	• Convergence leads to re-sealing of excavation-induced openings, and thereby to isolation of the waste • Convergence and compaction are important processes because convergence is the driving force for any (contaminated) brine extrusion from a flooded repository • Convergence is well understood	
Open questions	• The process of healing and sealing is yet not well understood, especially the effects of moisture-induced processes (moisture creep, fluid pressure)	

Conclusions (Preliminary)

- ❖ OSSC provides an evaluation of current knowledge for building the Safety Case for salt based repositories in the Dutch context
- ❖ For structuring the abundant information the methodology has been adopted as outlined in IAEA SSG-23 (2012), as further developed in IAEA project PRISM
- ❖ The main recommendation to proceed further with the development of the Salt Safety Case in the Netherlands is to establish and fix a final disposal facility in rocksalt. Subsequently, all Safety Case related aspects need to be revisited
  - ➢ After approval by COVRA, the reports will made available at www.covra.nl

NRG 13

Research performed at Utrecht University

- ❖ Long term mechanical and transport properties of salt rocks – experiments and model development
- ❖ Nawaz Muhammad (PhD), Chris Spiers
  - ➢ Microphysical mechanisms governing plastic flow of natural rocksalt
  - ➢ Pressure solution creep occuring in natural salt under in-situ conditions
  - ➢ Competition between microcrack growth and healing affecting the evolution of porosity and permeability
  - ➢ Feedback effects of brine penetration on mechanical behaviour and on-going dilatation and permeability evolution

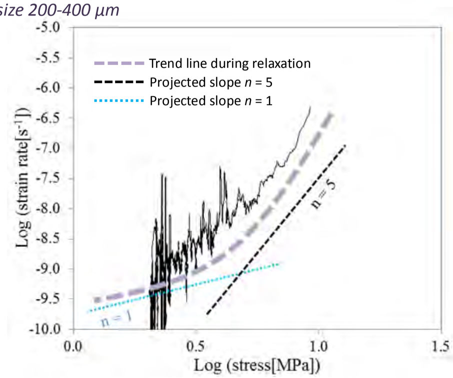
NRG 14

Utrecht University – Some Results
Relaxation test shows change in behaviour of wet salt

- *Wet synthetic salt (29 ppm), grain size 200-400 μm*
- *Triaxial deformation*
- *Confining pressure 50 MPa*
- *Temperature (125 °C)*
- *Deformation strain rate 5×10^{-7} s^{-1}*

Dislocation creep to pressure solution creep??

- *Power law stress exponent n-value decreases during relaxation, from > 5 to 1*
- *Rate controlling mechanism for wet salt at low stress and strain rate is pressure solution creep close o real in-sity conditions)*



NRG

Acknowlegdement

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

NRG 16

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

5th US-German Workshop on Salt Repository Research, Design and Operation

September 7-11, 2014, Santa Fe, NM, USA

Andreas Hampel, Scientific Consultant, Mainz, Germany

Abstract

In 2004, six German institutions started a joint project series on the comparison of constitutive models for the thermo-mechanical behavior of rock salt. General aims are 1) to investigate and check the abilities of the advanced models of the participants to describe correctly and reliably the relevant thermo-mechanical deformation phenomena in rock salt and their dependencies on boundary conditions, 2) to check and compare their procedures for the determination of salt type-specific model parameter values, and 3) to compare their procedures for the performance of numerical calculations of rock salt around underground openings. Reliable and well-tested models and procedures are required for numerical simulations performed e.g. for the design, stability analysis, and evaluation of the long-term behavior of underground repositories for radioactive wastes in rock salt.

The current third project (2010-2016) is a US-German collaboration of the following partners:

From Germany:

- Dr. Andreas Hampel (AH), Scientific Consultant, Mainz
- Institut für Gebirgsmechanik GmbH (IfG), Leipzig
- Karlsruher Institut für Technologie (KIT), Karlsruhe
- Leibniz Universität Hannover (LUH), Hannover
- Technische Universität Braunschweig (TUBS), Braunschweig
- Technische Universität Clausthal (TUC), Clausthal-Zellerfeld

From the United States:

- Sandia National Laboratories (SNL), Albuquerque, NM

In this project, selected benchmark calculations are carried out in order to check the ability of the involved models to describe correctly 1) the temperature influence on deformation and 2) the damage and dilatancy reduction and healing of rock salt. This contribution focuses on the second part.

At first, a unique set of model parameter values for the salt type around the subsequently calculated in-situ structure was determined with back-calculations of an extensive and systematic series of laboratory creep, strength, and healing tests. Then, several 3-D simulations of an old bulkhead structure in the Asse II salt mine in Germany were performed. The corresponding drift was excavated in 1911. After three years, a 25 m long section was lined with a cast steel tube, the residual gap between the tube and the salt contour was filled with concrete. Each partner calculated the structure with his constitutive model for a period of 88 years after the excavation. For comparison, he also calculated the open drift without the bulkhead for the same period of time.

In the presentation, a brief general overview of the project series, a summary of the calculations, some comparisons of results of the partners, and proposals for future collaborations are given.

5th US-German Workshop
on Salt Repository Research, Design and Operation
Santa Fe, New Mexico, USA – September 7-11, 2014

Update on the "Joint Project on the Comparison of Constitutive Models for Rock Salt"

Dr. Andreas Hampel

Sponsored by Federal Ministry of Economics and Technology (BMWi)

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

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

Project Partners

From Germany (since 2004):

Dr. Andreas Hampel, Scientific Consultant, Mainz
Institut für Gebirgsmechanik (IfG), Leipzig
Karlsruher Institut für Technologie (KIT), Karlsruhe
Leibniz Universität Hannover (LUH), Hannover
Technische Universität Clausthal (TUC), Clausthal-Zellerfeld
Technische Universität Braunschweig (TUBS), Braunschweig (since 2010)

From the United States (since 2010):

Sandia National Laboratories, Albuquerque & Carlsbad, New Mexico

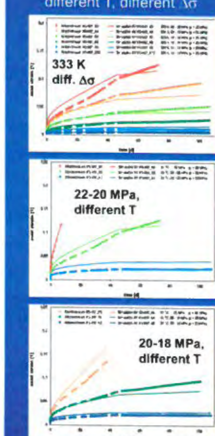
Three Joint Projects on the Comparison of Constitutive Models for Rock Salt

Project	Period	Main Objectives: Document, check and compare ...
I	2004 – 2006	... capabilities of the models to describe reliably the relevant deformation phenomena in rock salt
II	2007 – 2010	... the suitability of the models to perform 3-D simulations, predictions of the future behavior, calculations of permeability
III	2010 – 2016	... the modeling of temperature influence on deformation (part I): • performance of many creep & strength tests with Asse-Speisesalz (IfG) ➢ back-calculations of the lab tests, determination of parameter values • simulations of in-situ borehole tests IFC (isothermal) & HFCP (heated) ... the modeling of damage reduction & healing of rock salt • performance of high-precision healing tests with Asse-Speisesalz (TUC) ➢ back-calculations of the healing tests, determination of par. values ➢ simulation of the "Dammjoch" (bulkhead) in the Asse mine ... the modeling of temperature influence on deformation (part II): ○ performance & back-calculations of many creep & strength tests with clean salt & argillaceous salt from WIPP (IfG & TUC) ○ simulations of Rooms D (isothermal) & B (heated) at WIPP

Back-Calculations of Laboratory Deformation Tests with one Salt Type

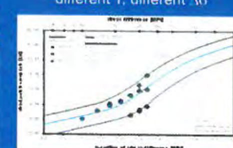
1. Check the ability of the models to describe the relevant deformation phenomena & dependencies.
2. Determine a unique salt-type-specific set of parameter values for each constitutive model.

transient creep
different T, different $\Delta\sigma$



Creep tests and strength tests with Asse-Speisesalz (IfG)

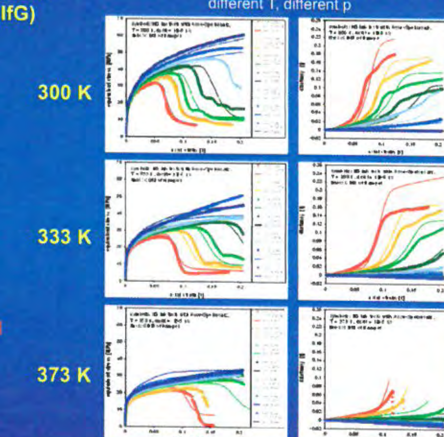
steady-state creep rates
different T, different $\Delta\sigma$

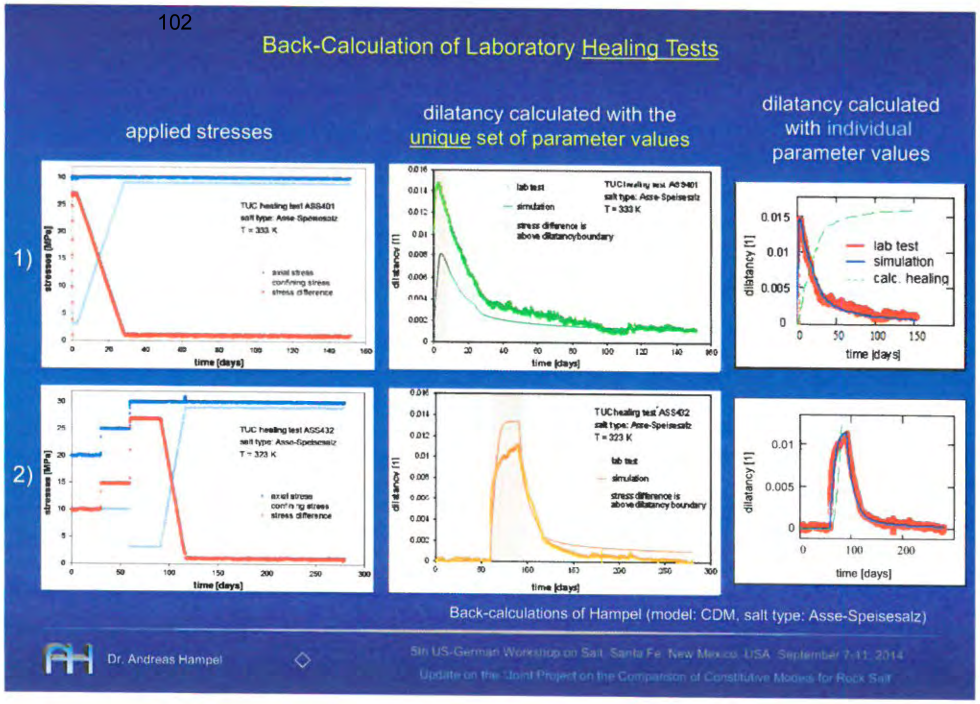


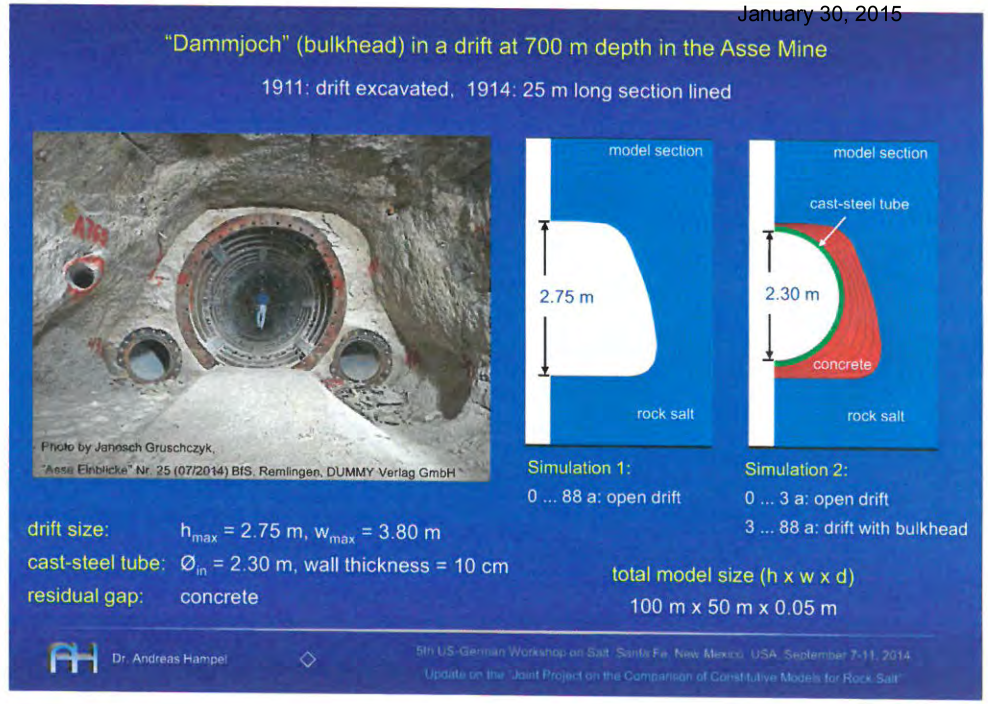
All tests were calculated with the same parameter values

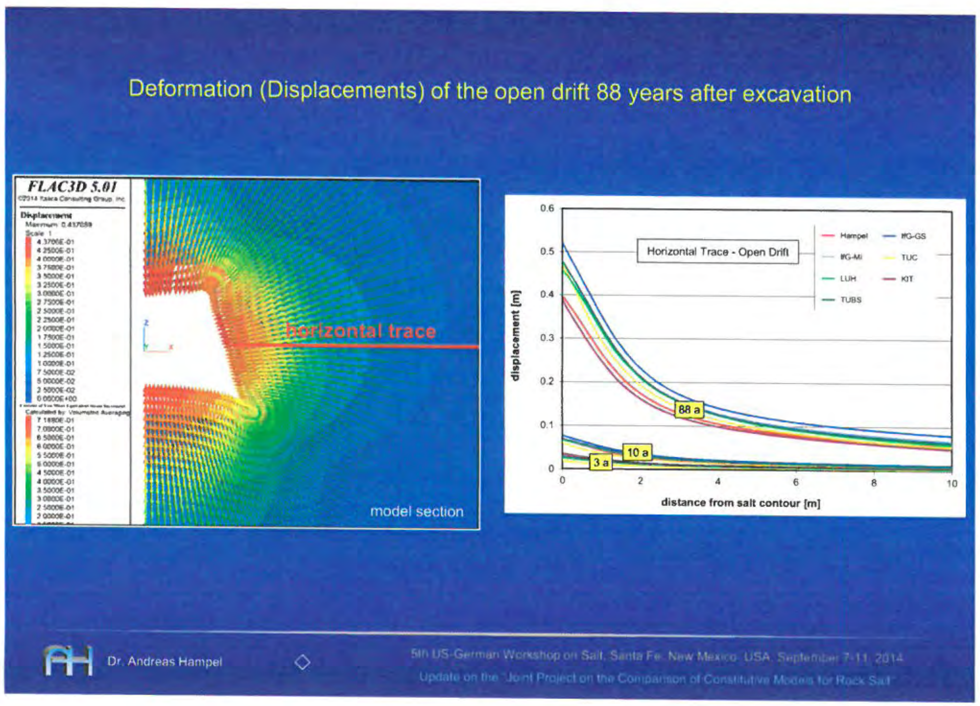
(this example: CDM of Hampel)

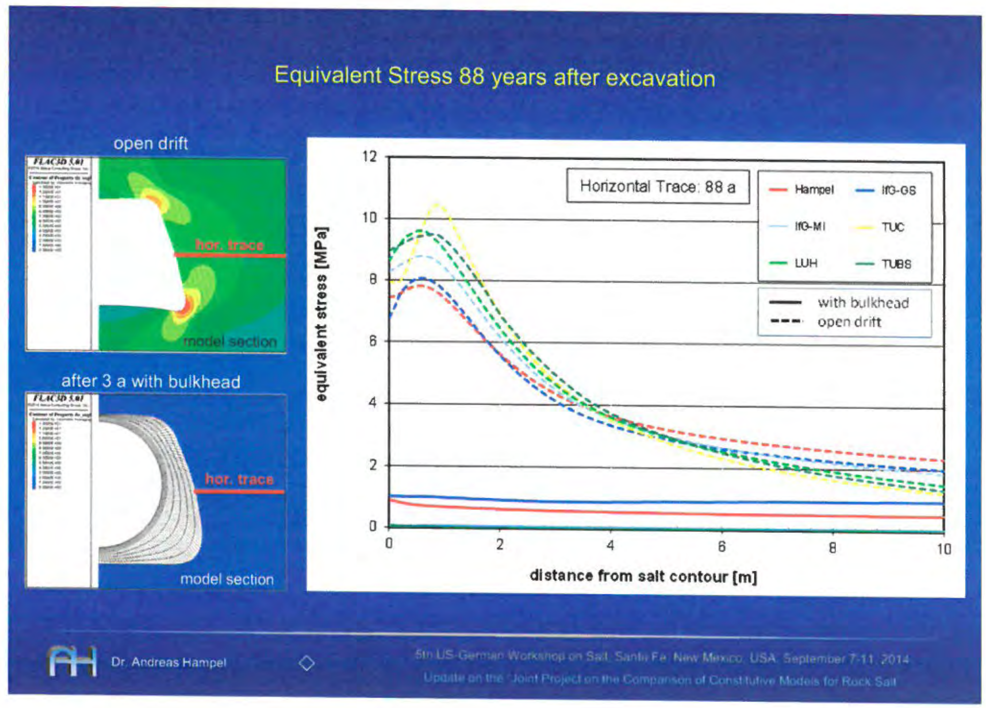
stress – strain   dilatancy – strain
different T, different p



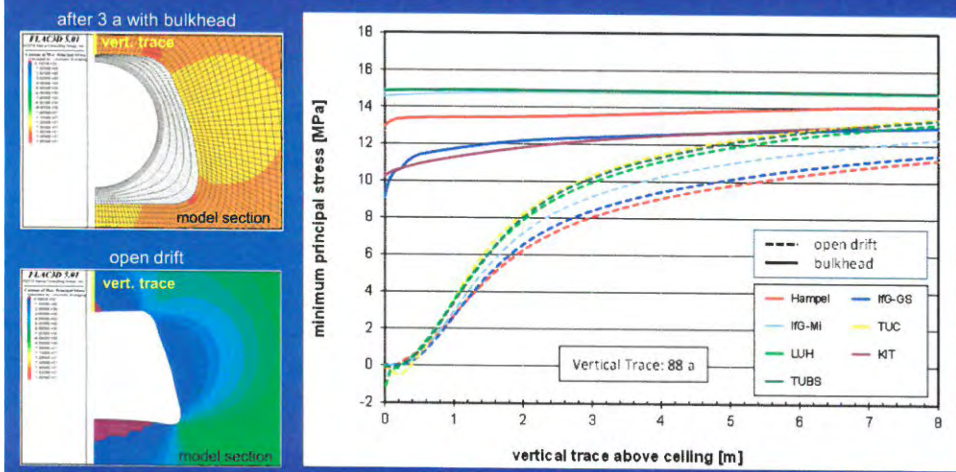

Back-Calculation of Laboratory Healing Tests
applied stresses
dilatancy calculated with the unique set of parameter values
dilatancy calculated with individual parameter values
1)
2)
TUC healing test AS5401
salt type: Asse-Speisesalz
T = 333 K
axial stress
confining stress
stress difference
TUC healing test AS5432
salt type: Asse-Speisesalz
T = 323 K
lab test
simulation
stress difference is above dilatancy boundary
TUC healing test AS5402
salt type: Asse-Speisesalz
T = 323 K
lab test
simulation
calc. healing
stresses [MPa]
dilatancy [1]
time [days]
Back-calculations of Hampel (model: CDM, salt type: Asse-Speisesalz)
Dr. Andreas Hampel
5th US-German Workshop on Salt, Santa Fe, New Mexico, USA, September 7-11, 2014
Update on the "Joint Project on the Comparison of Constitutive Models for Rock Salt"


"Dammjoch" (bulkhead) in a drift at 700 m depth in the Asse Mine
1911: drift excavated, 1914: 25 m long section lined
Photo by Janosch Gruschczyk,
"Asse Einblicke" Nr. 25 (07/2014) BfS, Remlingen, DUMMY Verlag GmbH
model section
2.75 m
rock salt
model section
cast-steel tube
2.30 m
concrete
rock salt
Simulation 1:
0 ... 88 a: open drift
Simulation 2:
0 ... 3 a: open drift
3 ... 88 a: drift with bulkhead
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
Dr. Andreas Hampel
5th US-German Workshop on Salt, Santa Fe, New Mexico, USA, September 7-11, 2014
Update on the "Joint Project on the Comparison of Constitutive Models for Rock Salt"


Deformation (Displacements) of the open drift 88 years after excavation
FLAC3D 5.01
horizontal trace
model section
Horizontal Trace - Open Drift
Hampel
IfG-GS
IfG-MI
TUC
LUH
KIT
TUBS
88 a
10 a
3 a
displacement [m]
distance from salt contour [m]
Dr. Andreas Hampel
5th US-German Workshop on Salt, Santa Fe, New Mexico, USA, September 7-11, 2014
Update on the "Joint Project on the Comparison of Constitutive Models for Rock Salt"


Equivalent Stress 88 years after excavation
open drift
hor. trace
model section
after 3 a with bulkhead
hor. trace
model section
Horizontal Trace: 88 a
Hampel
IfG-GS
IfG-MI
TUC
LUH
TUBS
with bulkhead
open drift
equivalent stress [MPa]
distance from salt contour [m]
Dr. Andreas Hampel
5th US-German Workshop on Salt, Santa Fe, New Mexico, USA, September 7-11, 2014
Update on the "Joint Project on the Comparison of Constitutive Models for Rock Salt"

Minimum Principal Stress 88 years after excavation

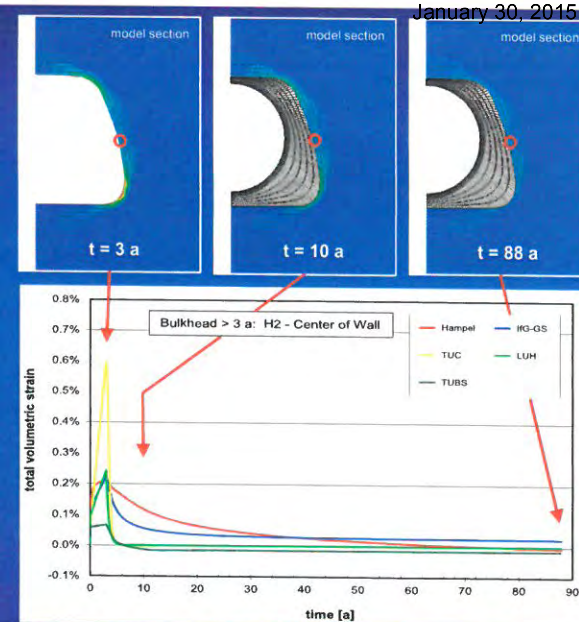


Volumetric Strains (Dilatancy)

Simulation 2:

0...3 a: open drift

3...85 a: with bulkhead



Summary

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

Part 2: Modeling of damage reduction and healing of rock salt

Investigations: High-precision laboratory creep & strength tests (IfG Leipzig)

High-precision laboratory healing tests (TU Clausthal)

Benchmarking:

1. Back-calculations of laboratory creep, strength, and healing tests, determination of a unique set of model parameter values
2. Simulations of the "Dammjoch" (bulkhead) in the Asse Mine (88 a)
   1) open drift, 2) drift with bulkhead after 3 years

→ Considered constitutive models are appropriate to model the healing of rock salt.

→ More high-precision experiments and further developments of the models are required.

Open Questions – Subjects for Future Collaborations

~> Joint Project IV on the Thermo-Mechanical Behavior of Rock Salt

- Investigation and modeling of the deformation at small stress differences
- Investigation and further development of the modeling of healing
- Investigation and modeling of the humidity influence on deformation
- Treatment of tensile stresses in model calculations
- Investigation and modeling of contact surfaces (e.g. salt/clay)
- Deeper and more detailed analysis of the bandwidth of modeling results

→ More high-precision laboratory tests and new in-situ underground experiments

→ Joint collaboration on the further development of constitutive modeling

Modeling WIPP Rooms B/D
5th International US-German Workshop on Salt Repository Research, Design and Operation to be held in Santa Fe, NM
Sept. 7-12, 2014

J. Guadalupe Argüello
Sandia National Laboratories
Albuquerque, NM, USA

Abstract

The US-German "Joint Project on 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 known as "Joint Project III," has been extended from its original scope to include two additional benchmarking problems based on full-scale in-situ 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, and the heated "Overtest for Simulated Defense High-Level Waste," WIPP Room B are the two test rooms that are being modeled. Both of these rooms are among a series of excavations at the WIPP that have been modeled in the past by Sandia, prior to WIPP licensing, using legacy numerical codes and techniques of the time [1].

Approximately thirty years of hardware and software advances have occurred since that time and those advancements have yielded a new generation of massively parallel multi-physics computational capabilities, embodied in the SIERRA Mechanics code suite, to support the Sandia engineering sciences mission. With SIERRA Mechanics, an unprecedented level of fidelity can be incorporated into the models of the room. Heretofore Sandia's recent efforts on WIPP Rooms D & B [2, 3] had been aimed at duplicating the legacy calculations of those rooms using roughly the same level of mesh discretization that was available at the time, and we were able to show that comparable results to the legacy ones could be obtained with SIERRA Mechanics for the thermo-mechanical response of the rooms. In this work we extend the previous work and show some of the results from Sandia's latest efforts as we have attempted to model these rooms, exercising the SIERRA code suite on models at levels of fidelity unobtainable in the 1980's, and compare simulation results to the data obtained from these full-scale tests. This has been done in an effort to arrive at an updated definition of the two benchmark problems that will be exercised under the US-German Joint Project III. The results from these efforts are important and pertinent to arriving at a set of agreed-to benchmark problems that will be analyzed by all participants.

References

1. Munson, D. E. 1997. Constitutive Model of Creep in Rock Salt Applied to Underground Room Closure. *Int. J. Rock Mech. Min. Sci.* 34:2 233-247.
2. Argüello, J.G. and J.S. Rath. 2012. SIERRA Mechanics for Coupled Multi-Physics Modeling of Salt Repositories. In Proceedings of the 7th Conference on the Mechanical Behavior of Salt, Paris, France, 16-19, April 2012, eds. P. Bérest et al, 413-423. London: Taylor & Francis Group.
3. Argüello, J.G. and J.S. Rath. 2013. Revisiting the 1980's WIPP Room D and B In-Situ Experiments: Performing Thermo-Mechanical Simulations of Rock Salt Using a State-of-the-Art Code Suite. In Proceedings of the 47th US Rock Mechanics/ Geomechanics Symposium, San Francisco, June 23-26 2013, ARMA 13-370. :ARMA.

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PTKA Project Management Agency Karlsruhe

ENERGY NNSA

Modeling WIPP Rooms D and B

J. Guadalupe Argüello

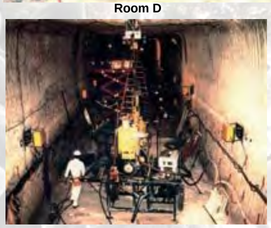
5th International US-German Workshop on Salt Repository Research, Design and Operation

Santa Fe, NM September 2014

Benchmarking WIPP Rooms for JPIII

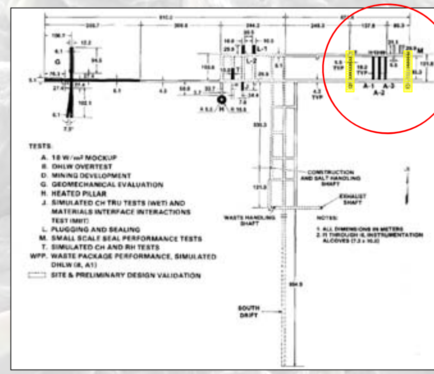
- "Joint Project III" was extended to include two additional benchmarking problems based on in-situ full-scale tests conducted in the early 1980's at the Waste Isolation Pilot Plant (WIPP), located in Southeastern New Mexico, USA
  - The isothermal Mining Development Test – WIPP Room D
  - The heated 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



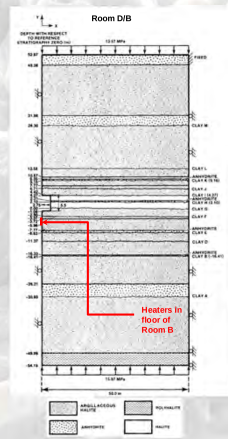
WIPP Experiments of Early 80's

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



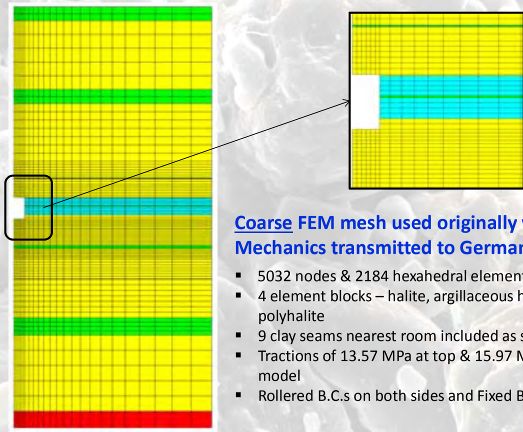
Experimental WIPP Rooms D & B are of special interest & well-suited for benchmarking

Why are WIPP Rooms D & B Well-Suited for Benchmarking?



- **Except for the heat load in Room B, both rooms are essentially identical**
  - Located in the same general area of WIPP
  - Relatively "isolated" from other workings
  - 5.5 X 5.5 m in cross-section (~100 m long)
  - At the same horizon and thus in the same vertical stratigraphic location
  - Tests conducted under rigorous Quality Assurance
  - Gages calibrated to NIST standards
  - Were extensively instrumented and data were taken for approximately 3.5 years (1300-1400 days) after excavation
  - Comprehensive datasets archived and available for benchmarking efforts

WIPP Room D Coarse Mesh



Coarse FEM mesh used originally with Sierra Mechanics transmitted to German partners:

- 5032 nodes & 2184 hexahedral elements
- 4 element blocks – halite, argillaceous halite, anhydrite, & polyhalite
- 9 clay seams nearest room included as sliding surfaces
- Tractions of 13.57 MPa at top & 15.97 MPa at bottom of model
- Rollered B.C.s on both sides and Fixed B.C. near top right

5

Mechanical Modeling Parameters for Use in WIPP Room D/B Calculations

Note: Models based on details provided in Munson, 1997, *Int. J. Rock Mech. Min. Sci.* 34:2 233-247 (& supplemental information not provided there)

- Clean salt and Argillaceous Salt modeled with MD creep model with parameters shown here

	Parameters		Units	Salt
Salt Elastic Properties	Shear modulus	G	MPa	12,400
	Young's modulus	E	MPa	31,000
	Poisson's ratio	ν	–	0.25
Salt Creep Properties	Structure Factors	A_1	s^{-1}	8.386×10^{22} (1.407×10^{23})
		B_1		6.086×10^{6} (8.998×10^{6})
		A_2		9.672×10^{12} (1.314×10^{13})
		B_2		3.034×10^{-2} (4.289×10^{-2})
	Activation energies	Q_1	cal/mole	25,000
		Q_2	cal/mole	10,000
	Universal gas constant	R	cal/mol-°K	1.987
	Absolute temperature	T	°K	300
	Stress exponents	n_1	–	5.5
		n_2		5.0
	Stress limit of the dislocation slip mechanism	σ_0	MPa	20.57
	Stress constant	q	–	5,335
	Transient strain limit constants	M	–	3.0
		K_0	–	6.275×10^{5} (1.783×10^{6})
		c	$°K^{-1}$	9.198×10^{-3}
	Constants for work-hardening parameter	α	–	-17.37 (-14.96)
		β	–	-7.738
	Recovery parameter	δ	–	0.58

6

Mechanical Modeling Parameters (Cont'd)

- Anhydrite and Polyhalite modeled with an elastic/perfectly-plastic Drucker-Prager criterion: $F = \sqrt{J_2} + aI_1 - C$

  where

  $I_1 = \sigma_{kk}$
  $J_2 = \frac{1}{2}s_{ij}s_{ji}$
  $a, C =$ material constants

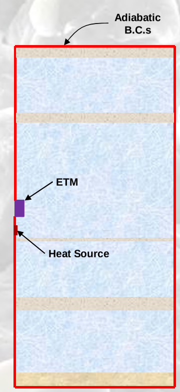
  with parameters as shown in table below.

Material	E (MPa)	ν	a	C (MPa)
Anhydrite	75,100	0.35	0.450	1.35
Polyhalite	55,300	0.36	0.473	1.42

- Clay seams modeled as sliding surfaces with M-C behavior: $\tau = \mu\sigma_n$ with μ=0.2
- Initial stress set to lithostatic stress varying linearly with depth

7

Thermal Modeling Parameters for Use in WIPP Room B Calculations



- All boundaries in "red" assumed to be adiabatic
- Boundaries sufficiently remote to preclude affecting room response for duration of simulation
- Entire formation prescribed to have an initial temperature of 300 K
- The drift area (in "purple") assumed to consist of an "equivalent thermal material" (ETM)
- ETM has a constant high conductivity of 50 W/(m-K) & a high thermal diffusivity [C_P of 1,000 J/(kg-K) and a density of 1 kg/m³]
- This presumably simulates radiative heat transfer in the room by an equivalent conduction
- Clay seams to be neglected in thermal analyses

8

Thermal Modeling Parameters (Cont'd.)

Heat transfer through salt, anhydrite, and polyhalite modeled with a nonlinear thermal conductivity of the form:

$$\lambda = \lambda_{300}(300/T)^{\gamma}$$

where λ is the thermal conductivity, T is the absolute temperature in Kelvin, and λ_{300} & γ are material constants.

The various parameters are given in table below and include:

C_P – the specific heat;
α – the coefficient of linear thermal expansion; and
ρ – the material density.

Material	C_P J/(kg-K)	α K^{-1}	λ_{300} W/(m-K)	γ	ρ kg/m^3
Salt	862	45×10^{-6}	5.4	1.14	2,300
Anhydrite	733	20×10^{-6}	4.7	1.15	2,300
Polyhalite	890	24×10^{-6}	1.4	0.35	2,300

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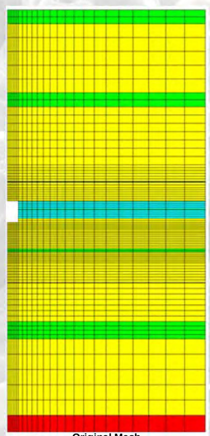
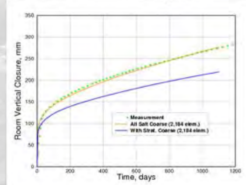
Room D Model Matching Capability Available in Mid-80s to early 90s



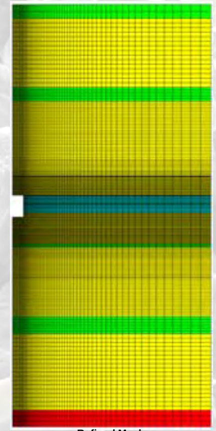
Original Mesh



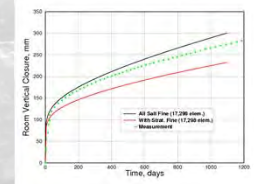
- Original mesh coarse by today's standards, but similar to what was possible in the mid-1980s to early 1990s, in terms of computational capability
- With this mesh, computed vertical closure comparable to measured values (using all-salt stratigraphy, as apparently done in past)
- With this mesh and the complete stratigraphy, computed vertical closure is less than the measured closure

10

Refining the Room D Model in Line with Current Generation Capability



Refined Mesh



- New generation of computational tools allows more refined mesh, in line with current practice/ standards, to better-capture stress gradients
- Mesh shown here includes ~8X the number of elements as the coarse mesh (not possible with machines of mid-80s to early 90s)
- With refined mesh, computed vertical closure is greater than that computed with coarse mesh, for either the all-salt or with complete stratigraphy cases
- Computed results bracket the measurements

11

Summary & Conclusions

- Initial efforts on WIPP Room D underway
- Original coarse mesh with various details transmitted to German partners
- Additional information needed for the benchmarking effort has been identified and will be transmitted
- Using original mesh with all-salt idealization, the computed Room D vertical closure with SIERRA Mechanics agrees reasonably well with the measurements
- Refinement of Room D model to conform with modern standards/ practice leads to greater vertical closure than measurements for the all-salt idealization but less than measurements for the full stratigraphy
- Appears that in legacy model, MD parameters (& other features, e.g., μ for clay seams) were calibrated to match the tests using a relatively coarse mesh acceptable at the time
- This remains an open question that we hope to answer under JPIII
- Implies that a common refinement of the room model among the partners may be needed to make appropriate comparisons among the results of the various partners participating in the benchmark

12

Laboratory Tests on WIPP Salt

Argillaceous Salt update

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Lehrstuhl für Deponietechnik und Geomechanik, TU Clausthal, 38678 Clausthal, Germany

In cooperation with T. Popp, K. Salzer

Institut für Gebirgsmechanik GmbH (IfG), 02479 Leipzig, Germany

1. Objective

A joint project on the comparison of constitutive models for rock salt funded by BMWi started in 2004. The joint project includes procedures for the determination of characteristic salt type-specific model parameter values and for the performance of numerical calculations of underground openings in rock salt. Within the current project selected benchmark calculations for room D and room B of WIPP site are planed in order to check the ability of the involved models to describe correctly the in situ load bearing behavior.

Based on investigations in the 80´s to 90´s a comprehensive data base regarding the stress-strain and creep behavior of WIPP salt exists. But, due to the development of new constitutive laws considering damage processes, specific material parameters are missing. Therefore a laboratory program was planed and realized to determine the load bearing capacity of rock salt from WIPP taken into account demands from different constitutive laws used by the partners of the joint project. To realize the laboratory program 5.5 tons of core material from WIPP was drilled and shipped by Sandia to Germany. Based on this core material IfG has prepared more than 150 cylindrical samples of clean salt as well as argillaceous salt. Clean salt in general was investigated by IfG, argillaceous salt in general was investigated by TUC. The test program, the test procedure and the results observed from triaxial short term tests to determine failure and dilation strength and triaxial long term tests to determine damage free and damage induced creep parameters are summarized in the following chapters.

2. Overview test program argillaceous salt

To enable a determination of strength, creep and damage parameter for argillaceous salt from WIPP taken into account different constitutive laws a lab program was evaluated by the project partners. The laboratory program planed for argillaceous salt from WIPP consists of 61 triaxial short term tests to determine failure strength as well as dilation strength depending on minimum principal stress, temperature and strain rate.

3. Test procedure and physical parameter

Prior to the lab tests in each case

(a) sample length and sample diameter were measured half way up the height of the specimen and along the central axis of the confining specimen using a slide calliper gauge,

(b) sample mass were measured using a balance,

(c) the rock densities were calculated from the masses and volumes of the specimens using Eq. (3.1):

$$\gamma = \frac{4 \cdot m}{\pi \cdot d_0^2 \cdot h_0} \cdot g \tag{3.1}$$

γ rock density (N/m^3)

m specimen mass (kg)

d_0 diameter of unstressed specimen (m)

h_0 height of unstressed specimen (m)

g gravity (m/s^2)

(d) an unloaded ultrasonic wave velocity measurement was done using a dilational wave analyser. The measured ultrasonic wave velocities of the P or longitudinal waves (vp) and the S or transverse waves (vs) were entered into Eqs. (3.2) and (3.3) to calculate the dynamic elasticity modulus E_{dyn} and the dynamic Poisson's number ν_{dyn}:

$$E_{dyn} = \frac{vs^2 \cdot \rho \cdot \left(3vp^2 - 4vs^2\right)}{vp^2 - vs^2} \quad (3.2)$$

$$\nu_{dyn} = \frac{vp^2 - 2vs^2}{2 \cdot \left(vp^2 - vs^2\right)} \quad (3.3)$$

where

E_{dyn} dynamic elasticity modulus (kPa)

ν_{dyn} dynamic Poisson's number (-)

ρ rock density(t/m^3)

vp longitudinal wave velocity (m/s)

vs transverse wave velocity (m/s)

(e) a digital photography was taken.

(f) At the end of the procedure characterized by (a) to (e) the specimens have been positioned in the triaxial cell and undergoes in each case an approx. 24-hour recompaction and tempering phase under an isotropic stress level of σ_{iso} = 20MPa and a preset temperature level of 27°C, 60°C, 100°C respectively.

At the end of the recompaction phase, the specimens were subjected to an axial stress σ_1 at constant confining pressure $\sigma_2 = \sigma_3$ under a constant strain rate of $\dot{\varepsilon}_1$. The next phase of the test involves maintaining constant confining load during a stress-controlled stress release and stress build-up cycle to determine the Young´s modulus. The axial stress was then increased under constant compression rate until the failure load is reached or above. Measurement contains recordings of

a) axial deformation by inductive transducers,
b) the hydraulic pressure measured in the test cylinder by an absolute pressure transducer which has to been converted to determine the axial pressure acting on the specimen,
c) the confining pressure by an absolute pressure transducer,
d) the oil temperature within the annulus of the triaxial cell,
e) the volume change of the specimen and
f) the change in ultrasonic wave velocity.

The volume change was determined from the inductive readings of axial specimen deformation Δl and the volumetric change in the oil volume in the triaxial cell. The oil volume $\pm\Delta V$ displaced from the triaxial cell during the test was fed into a twin-chamber cylinder.
The damage strength $\beta_{1dil\text{-}vol}$ was determined on the basis of the volume change characterises. The axial stress which is corresponding to a minimum volumetric specimen deformation was identified as damage strength $\beta_{1dil\text{-}vol}$ (primarily damage deformation after exceeding minε_{vol}).
Ultrasonic transmitter and receiver are integrated within the cover and base pressure plates to determine the damage strength more precisely. The continuous transmission of the samples during the test to record the ultrasonic velocity enables the damage strength to be determined independently of the volume measurement on the basis of the stress level observed. This is done by detecting a reduction in ultrasonic travel times as a result of the development of physical damage (microfissures). Damage strength $\beta_{1dil\text{-}vp}$ was defined as the axial stress at which the ratio v_p/v_{p0} reaches a maximum.
Based on test results it could be stated, that argillaceous salt from WIPP is characterized by typical average values of $\overline{E}_{dyn} \approx \overline{E}_{EW} \approx 28000 MPa$ and $\overline{\nu}_{dyn} = 0{,}278$. A dependency between density and Young´s modulus respectively Poisson´s ratio is not observed. It must be pointed out, that core material excavated in 2010 obviously is different from core material excavated in 2013. A reduced density can be observed for core material taken in 2010 in comparison to core material taken in 2013. May be this is caused by a drying effect during storage.

4. Results of short term tests to determine failure and dilation strength

Short term tests were performed at different temperatures of 27°C, 60°C, 100°C respectively and at different strain rates of $\dot{\varepsilon}_1$ = 0,6%/min, $\dot{\varepsilon}_1$ = 0,06%/min, $\dot{\varepsilon}_1$ = 0,006%/min respectively.
Depending on the preset strain rate and the total strain realized during the tests, the duration of the short term tests varied between some 170 minutes at minimum and 4.6d at maximum adding 1 day recompaction and tempering phase. In case of a testing temperature of 100°C additionally 1 day cooling phase must be considered prior to a dismounting of the sample.
The failure and dilation strength taken from tests is evaluated separately with respect to minimum principle stress, strain rate and temperature.
As a result a different between failure strength determined at core material excavated in 2010 and core material excavated in 2013 was observed. As mentioned above, the significant scattering of core material excavated in 2010 is assumed to be caused by drying during storage.
Referring to the observed dilation strength it must be pointed out, that due to the different between core material excavated in 2010 and core material excavated in 2013 some additionally tests are needed to evaluate an acceptably correlation between dilation strength and minimum principle stress.

5. Results of long term tests to determine damage free and damage induced creep rate

Lab tests to determine the damage free and damage induced creep behaviour are in general similar to classical creep tests. Simply the additionally online measurement of volume change and ultrasonic wave velocity enables to differ between damage free and damage induced parts of the observed total creep rate. The idea to differ between damage free and damage induced parts of the total creep rate is based on the knowledge of damage strength. Multi-level creep tests taken into account two load levels below damage strength to determine the damage free creep behaviour and one or two load levels above damage strength to determine the damage induced creep behaviour have been conducted. The damage induced part of the total creep rate at least can be calculated by a subtraction of the calculated damage free part of the total creep rate regarding to stress level three from the observed total creep rate during stress level three. Because the quantity of the damage induced creep rate

depends on the intensity of exceeding damage strength and - due to a time dependent accumulation of damage - additionally to the duration of exceeding damage strength, an online measuring of the damage process is required. In case the preset stress level is below dilation strength, no damage occurs and therefore no measure of dilatancy and ultrasonic wave velocity is needed.
Based on these measurements a first raw estimation of stationary and transient creep parameters corresponding to the constitutive model *Lux/Wolters* has been done. A typical correlation between creep rate and equivalent stress can be observed for argillaceous salt from WIPP. Determination of parameter to determine the damage induced creep rate is in progress.

6. Summary

A comprehensive data set for argillaceous salt from WIPP site has been prepared which in general allows determination of constitutive model parameters to carry out the planned benchmark calculations for room D and B. At now it is estimated that merely a few future tests will be needed to clarify questions regarding determination of model parameter.

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Laboratory Tests on WIPP Salt argillaceous salt

funded by federal ministry of economic affairs and energy

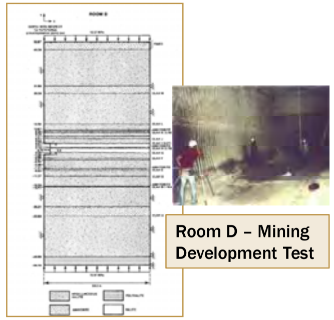
1. Objective
2. Overview test program
3. Results of short term tests to determine failure and dilation strength
4. Results of long term tests to determine damage free and damage induced creep behavior
5. Characterization of material properties based on lab tests

5th US/German Workshop on Salt Repository Research, Design and Operations
Santa Fe – 9th September 2014
apl. Prof. Dr.-Ing. habil. U. Düsterloh – Clausthal University of Technology - Chair for Waste Disposal Technologies and Geomechanics

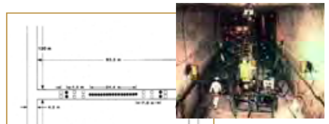
Objective

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



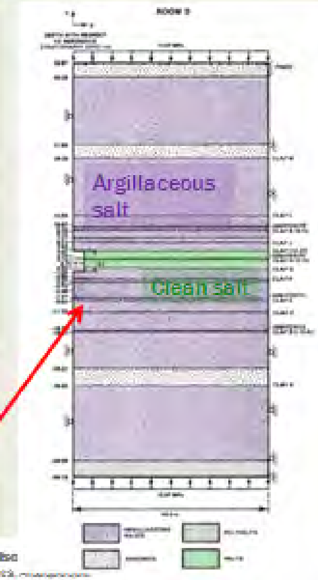
Room D – Mining Development Test



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.



Drilling and wrapping of cores at WIPP - site

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Preparation of a test specimen on a lathe

Institut für Gebirgsmechanik GmbH Leipzig

13. Workshop "Joint Project III: Comparison of Constitutive Models"
May 28.-29. 2014 - Sandia National Laboratories, Albuquerque

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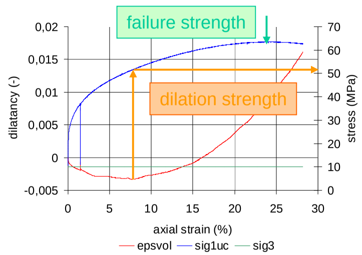
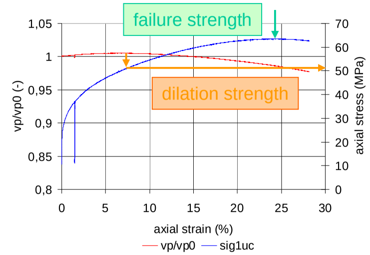
Laboratory program on argillaceous salt from WIPP to determine failure strength and dilation strength -

σ_3 MPa	strain rate 1/s	T °C	planned -	carried out -	in progress -
0,2 - 20	1,00E-05	27	14	10	0
0,2 - 20	1,00E-05	60	14	19	0
0,2 - 20	1,00E-05	100	14	14	0
0,2 - 20	1,00E-04	27	5	0	5
0,2 - 20	1,00E-06	27	14	14	0
Σ			**61**	**57**	**5**





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testing procedure and determination of physical parameters

(1) measure of length, diameter, mass in each case

(2) measure of unloaded ultrasonic wave velocity in each case

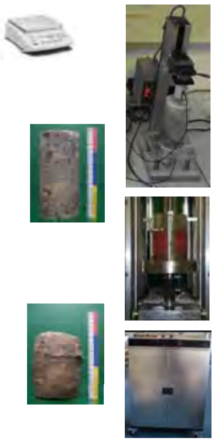
(3) digital photography of each sample prior to test

(4) one day isotropic recompaction at σ_{iso} = 20MPa and heating at 27°C, 60°C, 100°C respectively prior to each test

(5) including an unload-reload cycle to each test by reaching ε_1 = 1,5% (in case of $\sigma_3 \geq$ 1MPa) respectively ε_1 = 1,0% (in case of σ_3 < 1MPa)

(6) digital photography of each sample after test was finished

(7) oven drying of selected samples



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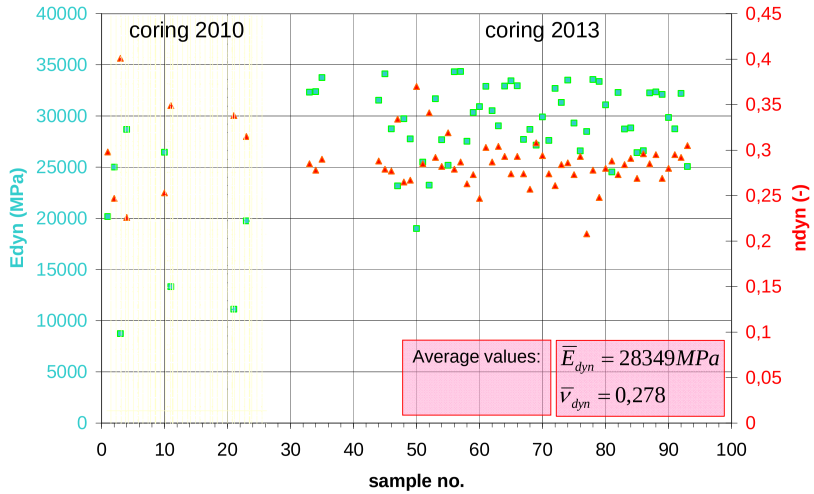
$$E_{dyn} = \frac{vs^2 \cdot \rho \cdot (3vp^2 - 4vs^2)}{vp^2 - vs^2}$$

$$\nu_{dyn} = \frac{vp^2 - 2vs^2}{2 \cdot (vp^2 - vs^2)}$$

physical parameter argillaceous salt WIPP



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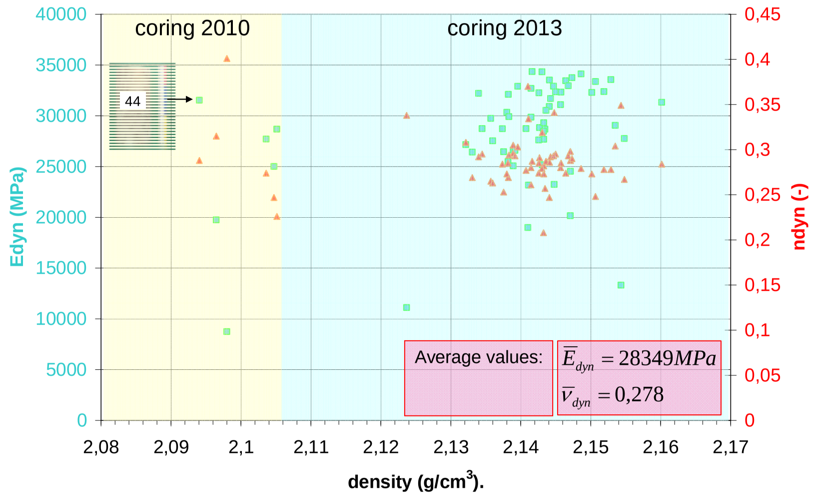
$$E_{dyn} = \frac{vs^2 \cdot \rho \cdot (3vp^2 - 4vs^2)}{vp^2 - vs^2}$$

$$\nu_{dyn} = \frac{vp^2 - 2vs^2}{2 \cdot (vp^2 - vs^2)}$$

physical parameter argillaceous salt WIPP



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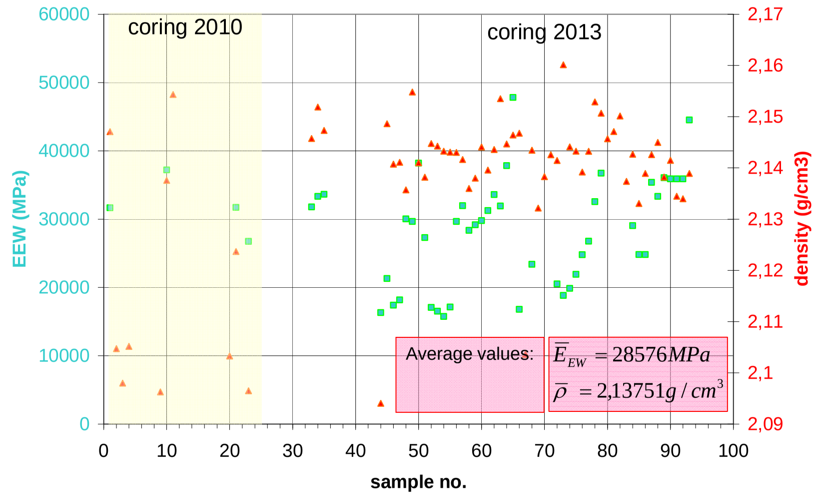
physical parameter argillaceous salt WIPP



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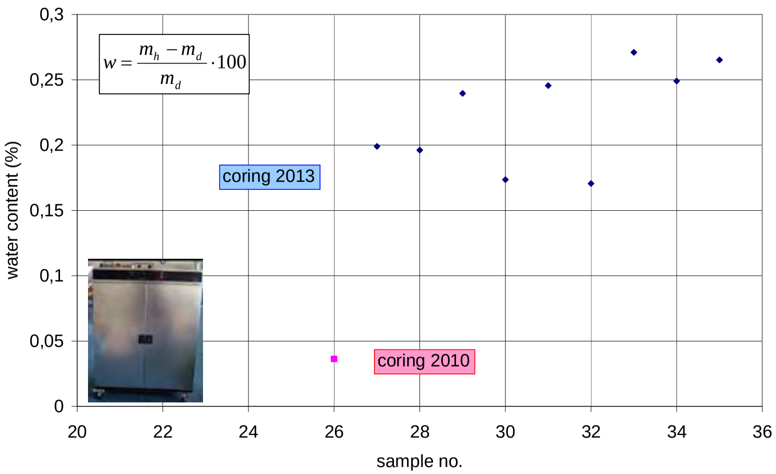

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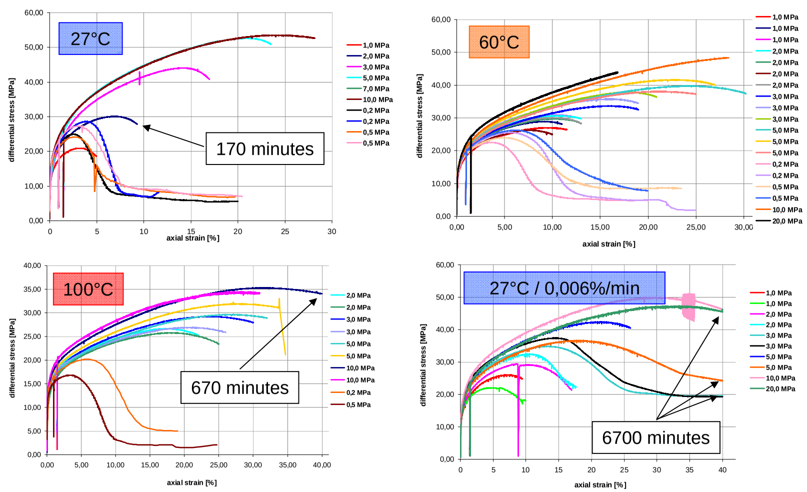
strength tests argillaceous salt WIPP



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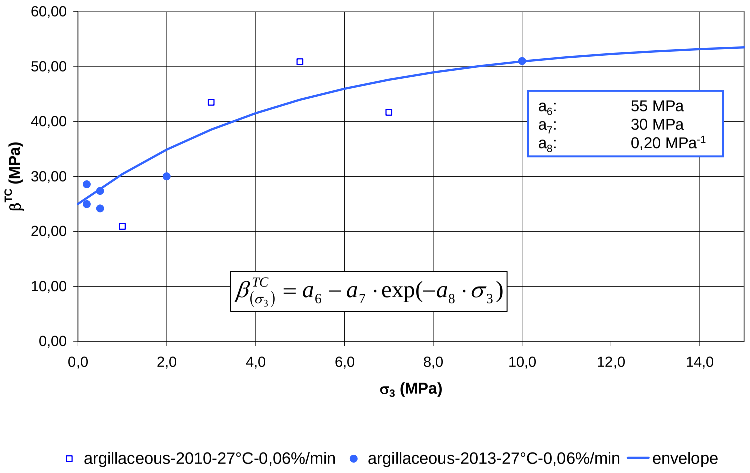
Failure strength argillaceous salt WIPP



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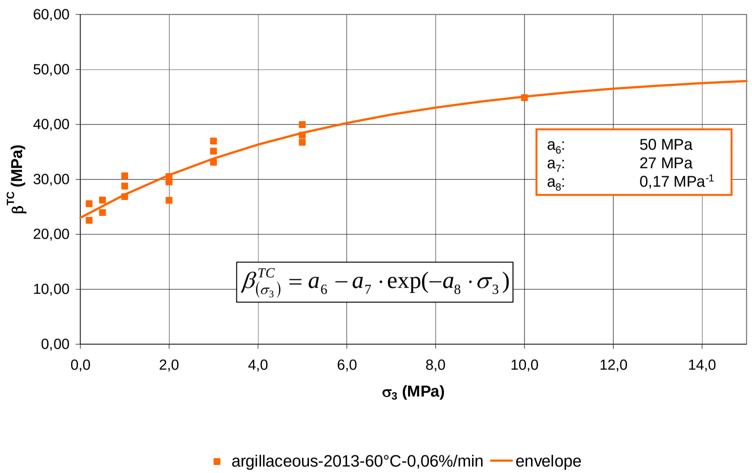
Failure strength argillaceous salt WIPP



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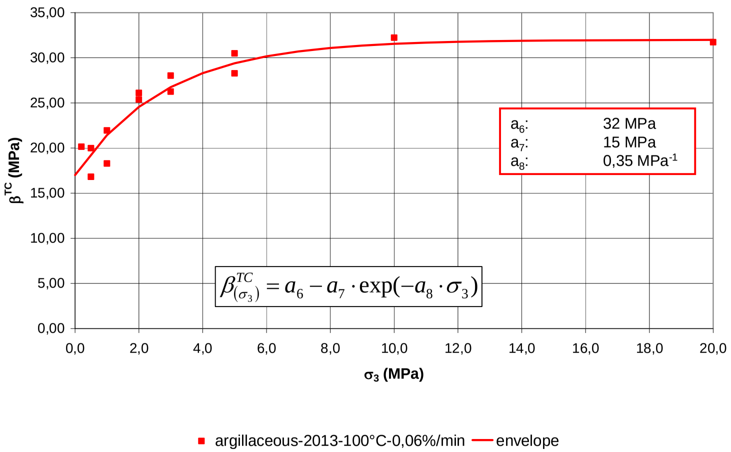
Failure strength argillaceous salt WIPP



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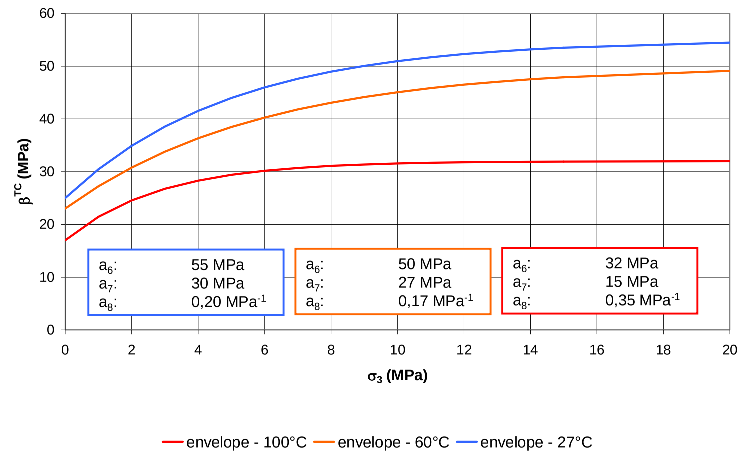
Failure strength argillaceous salt WIPP

$$\beta^{TC}_{(\sigma_3)} = a_6 - a_7 \cdot \exp(-a_8 \cdot \sigma_3)$$



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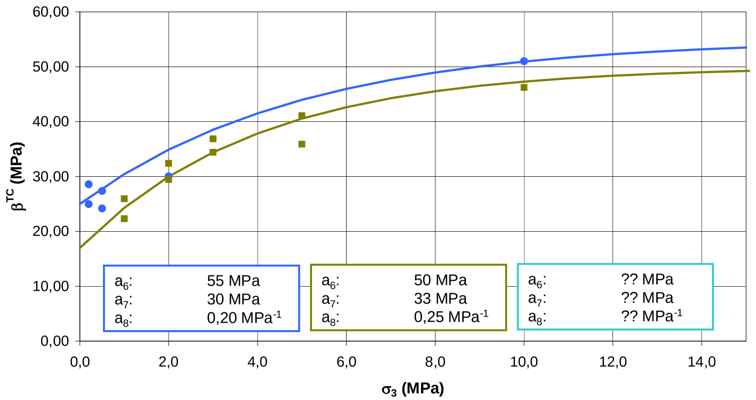
Failure strength argillaceous salt WIPP

$$\beta^{TC}_{(\sigma_3)} = a_6 - a_7 \cdot \exp(-a_8 \cdot \sigma_3)$$



argillaceous-2013-27°C-0,06%/min — envelope-0,06%/min
argillaceous-2013-27-0,006%/min — argillaceous-27°C-0,6%/min
envelope-0,006%/min

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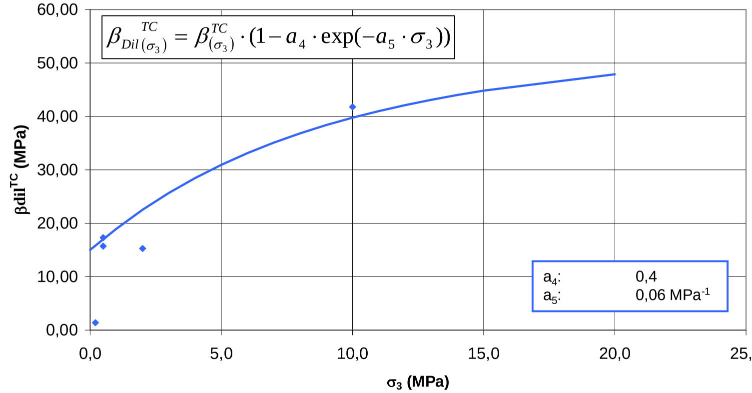
Dilation strength argillaceous salt WIPP

$$\beta^{TC}_{Dil(\sigma_3)} = \beta^{TC}_{(\sigma_3)} \cdot (1 - a_4 \cdot \exp(-a_5 \cdot \sigma_3))$$



argillaceous-2013-27°C-0,06%/min — envelope

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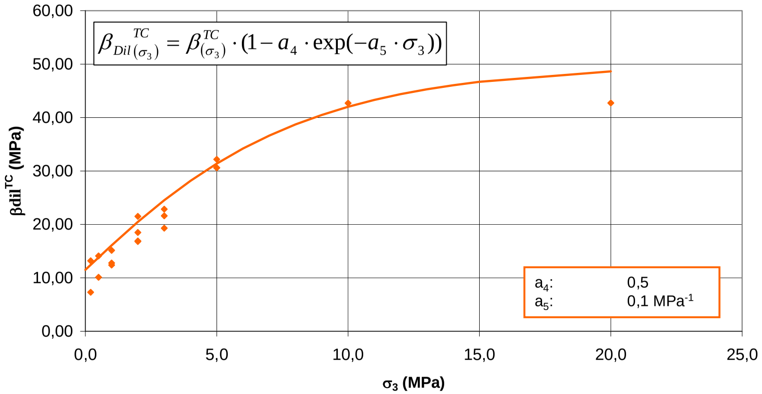
Dilation strength argillaceous salt WIPP

$$\beta^{TC}_{Dil(\sigma_3)} = \beta^{TC}_{(\sigma_3)} \cdot (1 - a_4 \cdot \exp(-a_5 \cdot \sigma_3))$$



argillaceous-2013-60°C — envelope

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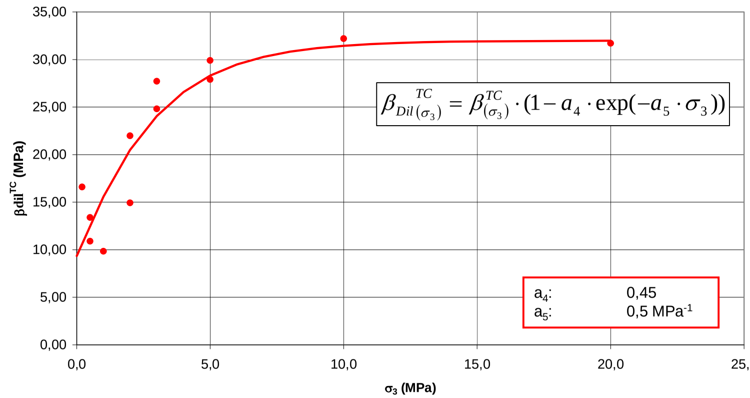
Dilation strength argillaceous salt WIPP

$$\beta^{TC}_{Dil(\sigma_3)} = \beta^{TC}_{(\sigma_3)} \cdot (1 - a_4 \cdot \exp(-a_5 \cdot \sigma_3))$$



argillaceous-2013-100°C — envelope

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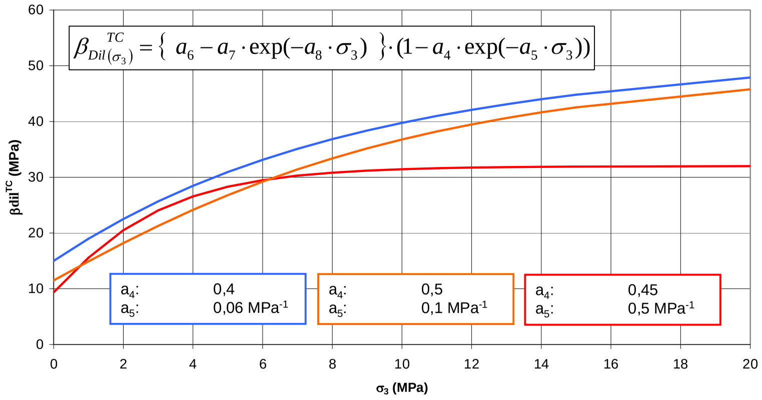
Dilation strength argillaceous salt WIPP



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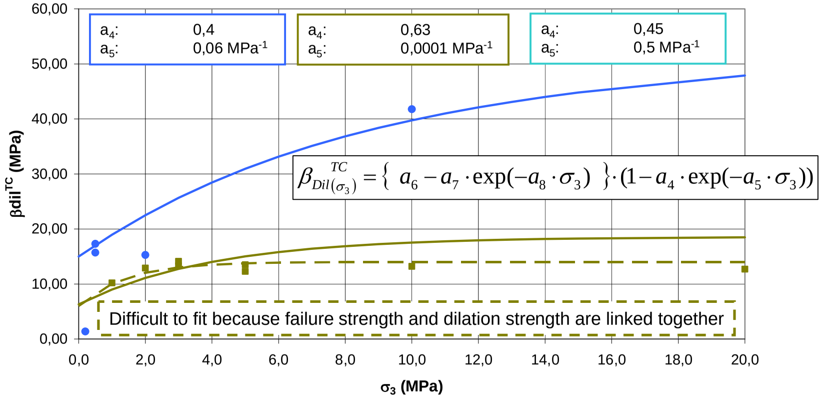
Dilation strength argillaceous salt WIPP



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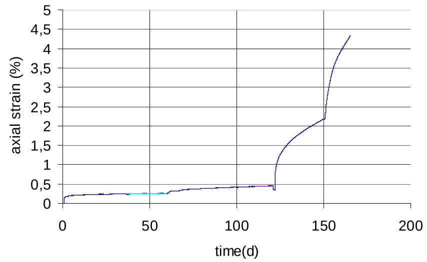
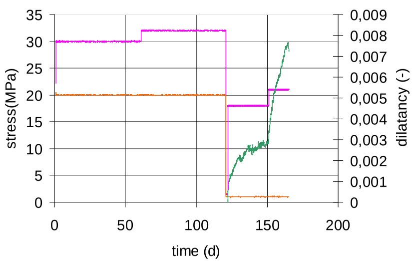
Laboratory program on argillaceous salt from WIPP to determine creep behaviour

σ_3 MPa	σ_{eq} MPa	T °C	load level -	duration d	loading / unloading	above/below dilation strength	planned -	carried out -	in progress -
20	>10	27	2	60/60	L/U	b/b	3	6	0
20	>10	60	2	60/60	L/U	b/b	5	8	0
20	>10	80	2	60/60	L/U	b/b	2	2	0
20	<10	60	1	120	L	b	2	0	0
20		27/60/80	3	60/60/60	L/L/L	b	2	0	0
different	different	27	4	60/60/30/30	L/L/L/L	b/b/a/a	3	4	0
?	?	?	?	?	?	?	3	0	0
							Σ = 20	Σ = 20	Σ = 0





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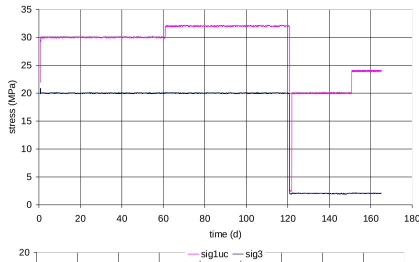
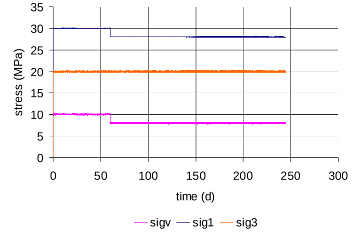
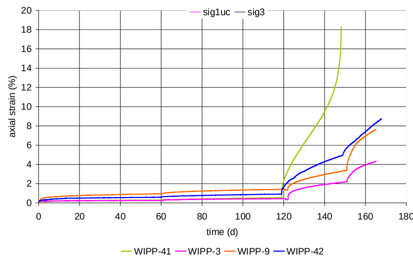
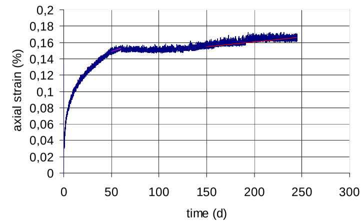
Creep tests argillaceous salt WIPP









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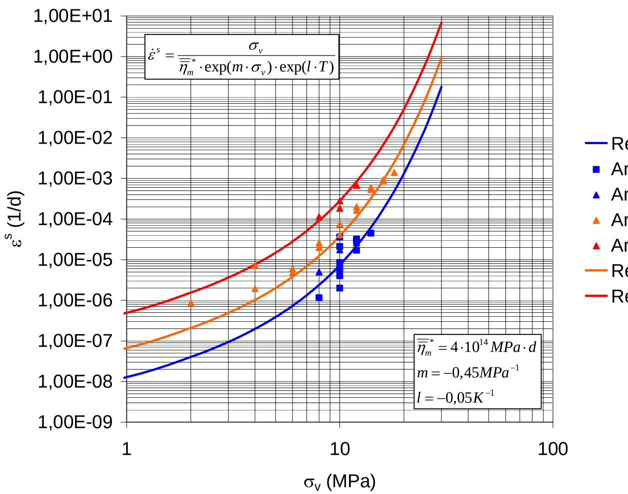
Stationary creep parameter argillaceous salt WIPP



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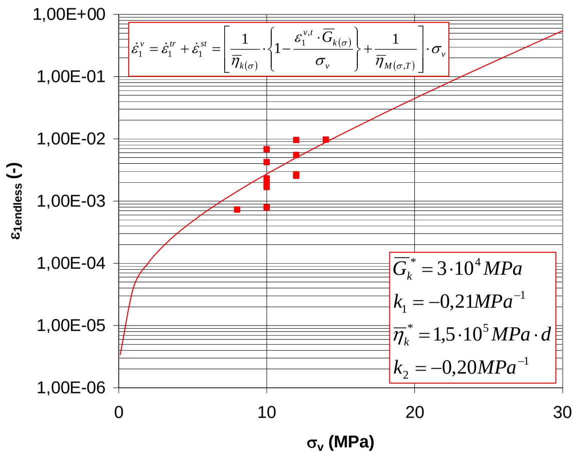
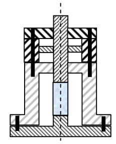
Transient creep parameter argillaceous salt WIPP





Laboratory Tests on WIPP Salt

Clean Salt update

K. Salzer, D. Naumann, Rölke, C., R.-M. Günther,T. Popp

Institut für Gebirgsmechanik GmbH (IfG), 02479 Leipzig, Germany

In cooperation with U. Düsterloh, K. Herchen

Lehrstuhl für Deponietechnik und Geomechanik, TU Clausthal, 38678 Clausthal, Germany

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 investigation program on WIPP-salt has been executed. 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 σ_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.

Fortunately in the long term the response of salt masses is governed by its steady state creep behaviour. Thus, in addition, a series of creep tests has been performed at loading conditions in the non-dilatant stress zone for a wide range of differential stresses. However, because in experiments the time necessary to reach true steady creep rates can last time periods of some few days to years, depending mainly on temperature, an innovative but simple creep testing approach is suggested. A series of multi-step tests with loading and unloading cycles allow a more reliable estimate of stationary creep rates in a reasonable time schedule.

Two index tests with permeability measurements with gas were performed indicating tightness of the salt ($k_{Gas} < 10^{-20}$ m^2) in the undisturbed state, as well, the capability of the rock for efficient crack closure after significant damage, i.e. a permeability decrease from 10^{-16} m^2 to <10^{-20} m^2 was observed within some few weeks at hydrostatic pressures of $\sigma_3 = \sigma_1 =$ 20 MPa.

109 strength and 37 creep tests were carried out in close cooperation between the rock mechanical labs of IfG and TUC. Most of lab tests on “clean salt” were carried out at IfG. The results will be presented in relation to data from “argillaceous salt”, which were obtained at Clausthal University, IfG and additional test at the BGR and the Technical University of Braunschweig.

The outcome can be summarized as follows:

- The investigated “Wipp salt” is generally of excellent quality, i.e. undisturbed (intact) and largely homogeneous.
- The moisture contents of the "clean salt" (CS) are in the order of 0.15 wt. -%, respectively, for the "argillaceous salt" (AS) in a data range: 0.2 - 0.4 - 1.0 wt. -%. The measured humidity content is lower than average values from the literature. However, they are therefore generally higher than those of domal rock salt.
- The strength tests on "clean salt" are already completed. A very consistent set of data and parameters could be obtained:
    - Temperature-increase results in significant strength decrease
    - Referred to in situ deformation rates $<10^{-10}$ 1/s the strength will be reduced
    - The onset of dilatancy, i.e. described by the dilatancy boundary, is nearly independent from temperature and the deformation rates but shows significant data scattering.
    - The comparison with the present strength data for the Asse salt shows generally slightly lower strength values, but is overall in the known properties field of pure rock salt.
- The creep test on “clean salt” and mostly on "argillaceous salt" are now also finished:
    - Unique creep data sets of high quality were obtained for room temperature, 60°C and 80°C, applying the new creep test approach, both for CS and AS. However, differences to older data sets are obvious (SAND92-7291), especially at higher temperature. This may be due to the higher water content of the tested salt specimens.
    - AS creeps slightly faster (2x) than CS, but both show slightly higher creep rates as they have been identified for Asse salt
    - At stresses < 10 MPa the creep behavior deviates from a simple power law relationship which may be referred to a mechanism change from dislocation creep to additional effects of fluid-assisted creep.
- Gas tightness of the WIPP-salt is demonstrated, as well its efficient sealing capability.

With these investigations, a comprehensive data fundus for the WIPP-salt has been set which allows an extrapolation to the expected underground conditions and to carry out the planned benchmark calculations for room D and B.

Laboratory Tests on WIPP-Salt (Clean salt)

K. Salzer, D. Naumann,
R. - M. Günther, C. Roelke & T. Popp

Institut für Gebirgsmechanik GmbH,
Leipzig, Germany

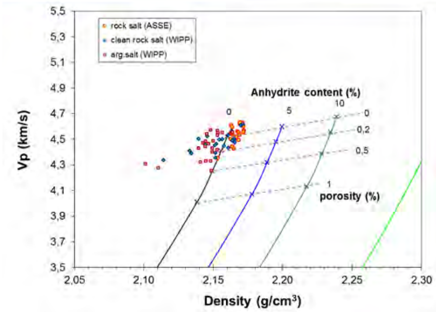
Sandia National Laboratories

DBE TEC DBE TECHNOLOGY GmbH

PTKA Project Management Agency Karlsruhe

- Petrophysical characterisation
- Strength and dilatancy testing
  - Confining pressure
  - Deformation rate
  - Temperature
- Creep tests
  - Creep test procedures
  - Results
- Permeability-testing
- Summary

Petro-physical characterization



- Clean salt ≈ argillaceous salt, but slightly different to pure „Asse-Speisesalz":
  - $\rho_{WIPP-CS} \leq \rho_{Asse-Salz}$
  - The amount of impurities is very low (< 5%)
  - Initial porosity is low (<0.5%) , i.e. undisturbed salt

VELOCITY-POROSITY RELATIONSHIP

after Wyllie et al., 1956

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

Pore space: air

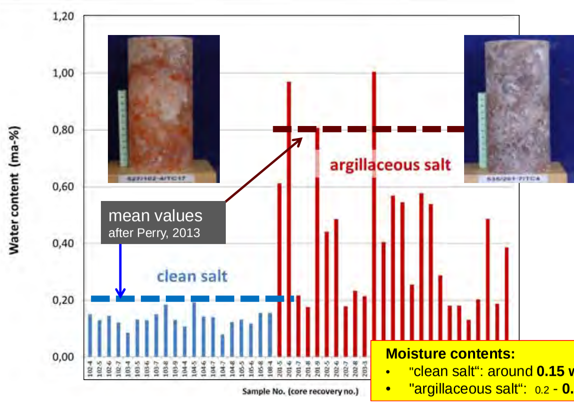
Matrix: halite (2,16 g/cm³) + Anhydrite (2,96 g/cm³)

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

Excellent material!

2

Water content - drying 24 h 105°C



Moisture contents:
- "clean salt": around **0.15 wt. -%**
- "argillaceous salt": 0.2 - **0.4** - 1.0 **wt. -%**

3

Triaxial strength / onset of dilatancy

Factors influencing relevant failure strength and dilatancy strength

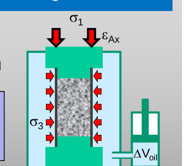
- Confining pressure
- Deformation rate
- Temperature

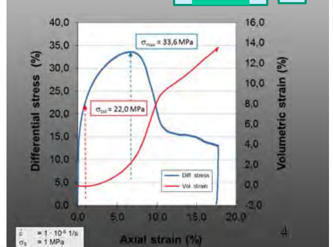
T	Eps-rate	σ_3 (MPa)							Σ CS
25°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
60°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
100°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
25°C	10^{-6} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
25°C	10^{-4} 1/s	0,2	-	1,0	2,0	-	5,0	20,0	5
								Σ Standard tests	33

Triaxial strength testing – state of art

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

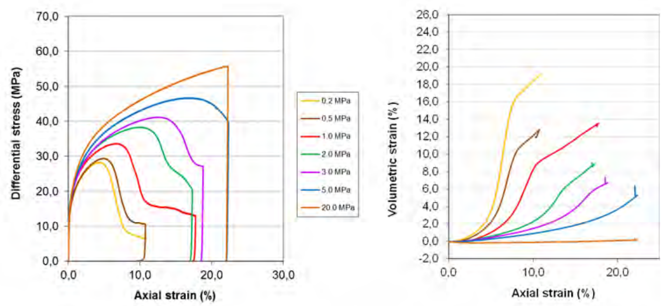
$\sigma_1 > \sigma_3$
$\Delta\sigma = f(\varepsilon_1)$
$\Delta V/V = f(\varepsilon_1)$





4

Triaxial strength tests (1·10^{-5}s^{-1}, 25°C)



WIPP-site, clean rock salt; TC test @ room temperature and strain rate 1*E-05s^{-1}

brittle ⇔ semi-brittle ⇔ ductile

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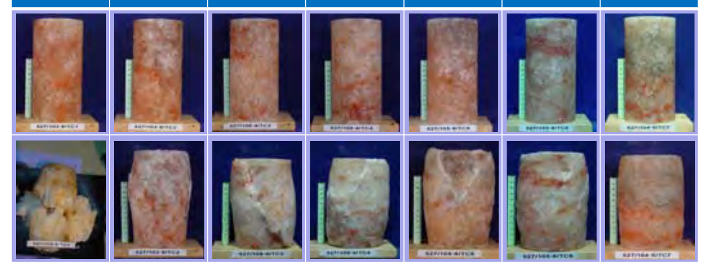
Triaxial strength tests (1·10^{-5}s^{-1}, 25°C)

0.2 MPa	0.5 MPa	1.0 MPa	2.0 MPa	3.0 MPa	5.0 MPa	20.0 MPa



brittle ⇔ semi-brittle ⇔ ductile

6

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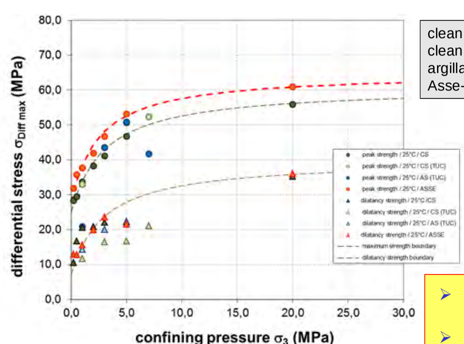
Strength testing - reliability of test results - Reference Asse-Speisesalz



clean salt	- large cores (IfG)
clean salt	- small cores (TUC)
argillaceous salt	- small cores (TUC)
Asse-Salz	- (Joint Project III)

$$\sigma_{Diff,max} = \sigma_D + \frac{\sigma_{MAX} - \sigma_D}{\sigma_\phi + \sigma_3}\sigma_3$$

σ_D	σ_{MAX}	σ_ϕ
28	65	2,5
25	60,3	3
7	40	7

- Reliability of strength results depends on core quality
- Strength: slightly lower than for Asse salt
- Argillaceous salt (AS) higher scattering but comparable to CS
- Dilatancy boundary similar

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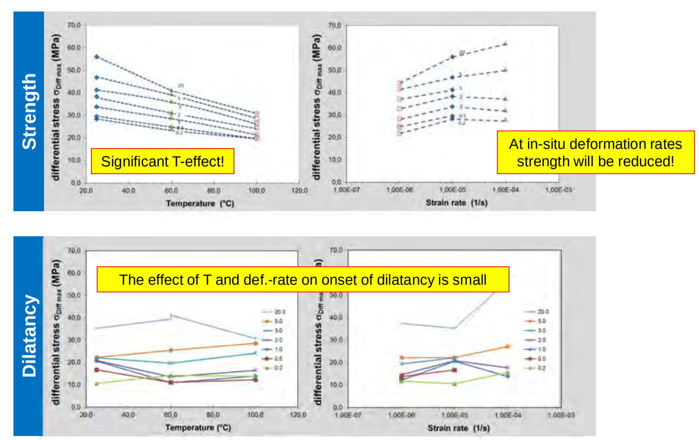
Factors influencing relevant salt properties - Temperature / deformation rate



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Creep behaviour

The challenge …,
how deforms the salt in the long term?

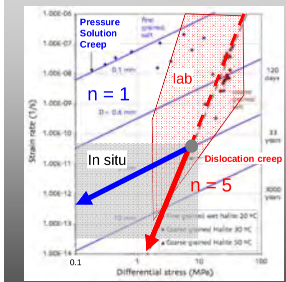
Boundary conditions:

Fore cast period: 10^3 < time (years) < 10^6
Deformations: $0.1 < \varepsilon < 1$
Temperatures: 20°C - 200°C
Def. Rates: $3 \cdot 10^{-14} < \dot{\varepsilon}\ (1/s) < 3 \cdot 10^{-11}$

Creep mechanisms:
Pressure solution creep vs. dislocation creep

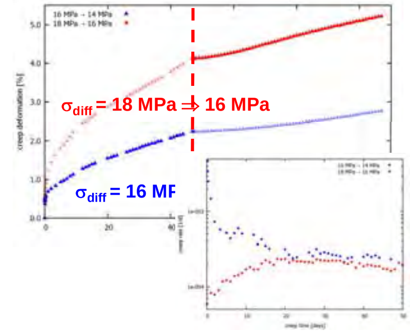
☹ ***Test duration is usually limited!***

Deformation-mechanism map



modified after Urai, 2012

Improved creep test procedures



Details: Günther, R.-M., Salzer, K., Popp, T. and Lüdeling, C., 2014. Steady state-creep of rock salt - Improved Approaches for Lab Determination and Modeling to describe transient, stationary and accelerated creep, dilatancy and healing. 48th U.S. Rock Mechanics Symposium, Minneapolis, Utah, USA, June 1 - 4, 2014. ARMA 14-7051.

IfG approach

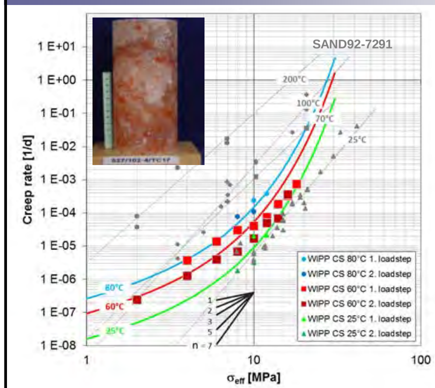
1. Raise temperature to e.g. 333 K (60°C) to speed up process and to involve recovery processes.
2. Use series of two-step tests with unloading, e.g.

(I.) σ_{diff} = 16 MPa ⇒ 14 MPa,
(II.) σ_{diff} = 18 MPa ⇒ 16 MPa

- transient and inverse transient creep **at 16 MPa**
- upper and lower bound on steady-state creep rate

3. Temperature stepping tests for the activation energy

Creep behaviour of clean salt – 25°C, 60°C, 80°C

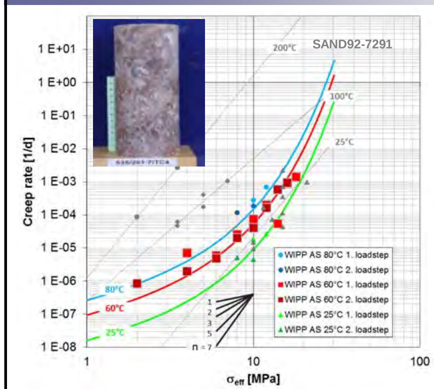


- Consistent data sets, but differences to earlier measurements (SAND92-7291) are obvious
- Mechanism change depending on stress state

IfG-Creep data sets (CS)

Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
1 TCC1	30	20	10	50	24	2,04E-05
	28	20	8	50	24	1,81E-06
1a TCC3	30	20	10	50	24	1,43E-05
	28	20	8	50	24	3,39E-06
2 TCC5	32	20	12	50	24	2,16E-05
	30	20	10	50	24	3,12E-06
3 TCC15	24	20	4	50	60	3,68E-06
	22	20	2	50	60	2,43E-07
4 TCC13	26	20	6	50	60	1,37E-05
	24	20	4	50	60	1,26E-06
5 TCC6	28	20	8	50	60	1,94E-05
	26	20	6	50	60	3,31E-06
6 TCC2	30	20	10	50	60	4,05E-05
	28	20	8	50	60	6,80E-06
6a TCC4	30	20	10	50	60	1,67E-04
	28	20	8	50	60	5,63E-05
7 TCC7	32	20	12	50	60	7,42E-05
	30	20	10	50	60	1,70E-05
8 TCC9	34	20	14	50	60	1,86E-04
	32	20	12	50	60	4,92E-05
9 TCC11	36	20	16	50	60	3,29E-04
	34	20	14	50	60	6,85E-05
10 TCC12	38	20	18	50	60	7,50E-04
	36	20	16	50	60	3,62E-04
11 TCC16	30	20	10	50	80	2,41E-04
	28	20	8	50	80	7,74E-05
12 TCC19	32	20	12	50	80	3,76E-04
	30	20	10	50	80	1,09E-04

Creep behaviour of argillaceous salt – 25°C, 60°C, 80°C

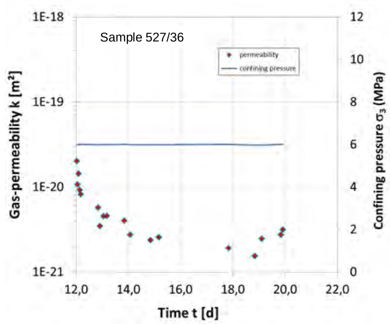


- Argillaceous salt creeps slightly faster (2x) than Clean Salt
- Generally WIPP-salt creeps faster than Asse Salt

IfG-Creep data sets (AS)

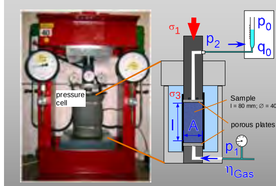
Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
TCC9	30	20	10	50	25	1,75E-05
	28	20	8	50	25	4,98E-06
TCC10	32	20	12	50	25	2,61E-05
	30	20	10	50	25	4,49E-06
TCC1	24	20	4	50	60	7,08E-06
	22	20	2	50	60	8,52E-07
TCC2	26	20	6	50	60	5,87E-06
	24	20	4	50	60	1,94E-06
TCC3	28	20	8	50	60	2,57E-05
	26	20	6	50	60	4,77E-06
TCC4	30	20	10	50	60	7,45E-05
	28	20	8	50	60	2,00E-05
TCC5	32	20	12	50	60	2,00E-04
	30	20	10	50	60	4,10E-05
TCC6	34	20	14	50	60	5,39E-05
	32	20	12	50	60	1,64E-04
TCC7	36	20	16	50	60	8,82E-04
	34	20	14	50	60	5,95E-04
TCC8	38	20	18	50	60	1,40E-03
	36	20	16	50	60	9,24E-04
TCC11	30	20	10	50	80	2,79E-04
	28	20	8	50	80	1,14E-04
TCC12	32	20	12	50	80	6,78E-04
	30	20	10	50	80	1,84E-04

Tightness of the geological barrier – permeability testing



The permeability of the intact salt is very low!

Experimental setup



$$k = \frac{2 \cdot p_0 \cdot q_0 \cdot \eta \cdot l}{A(p_1^2 - p_2^2)}$$

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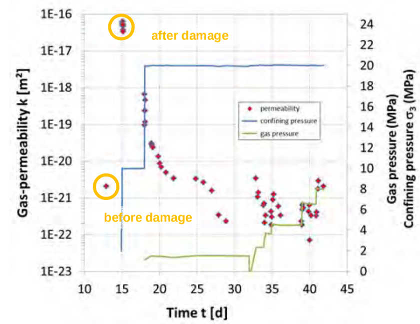
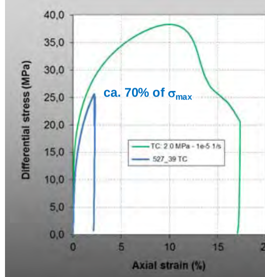
Recovery of tightness after damage – crack closure / healing



After damage tightness is restored within some few weeks …

Pre-damage



Sample 527/39

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Summary laboratory investigations on WIPP salt

- **The "WIPP salt" is of excellent quality**, i.e. undisturbed and homogeneous.
  - Moisture contents:
    - o "clean salt": around 0.15 wt. -%
    - o "argillaceous salt": 0.2 - 0.4 - 1.0 wt. -%
  - ➢ *Lower than reported but generally higher than for domal rock salt*
- **The triaxial tests on "clean salt" are completed, resulting in a very consistent set of data** (strength and dilatancy):
  - o Temperature-increase results in a significant strength decrease
  - o Referred to in situ deformation rates (<10^{-10} 1/s) strength will be reduced
  - o Onset of dilatancy depends not on temperature and the deformation rate
  - ➢ *Comparison with the reference Asse salt shows generally somewhat lower strengths, but it fits into the known properties field of pure rock salt.*
- **Creep tests on "clean salt" and "argillaceous salt" are now also finished**
  - o Unique data sets of high quality due to the new creep test approach, but differences to older results are obvious, especially at increased temperature
  - o AS creeps slightly (2x) faster than CS, and both creep faster than Asse salt
  - ➢ *A creep mechanism change at lower stresses is obvious, i.e. no simple power law*
- **Gas tightness** of the salt is demonstrated, as well ist efficient sealing capability

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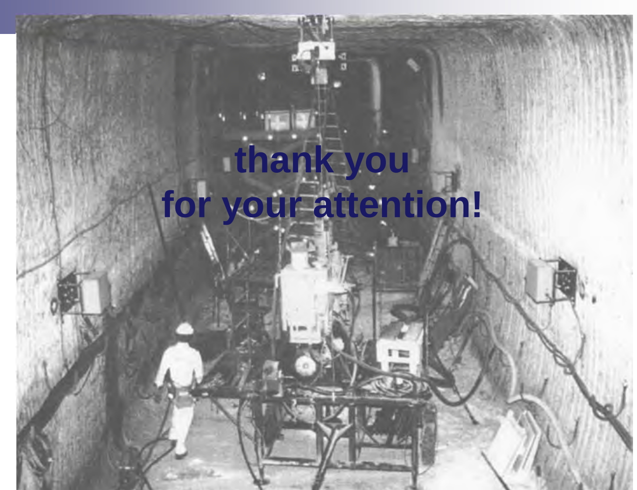

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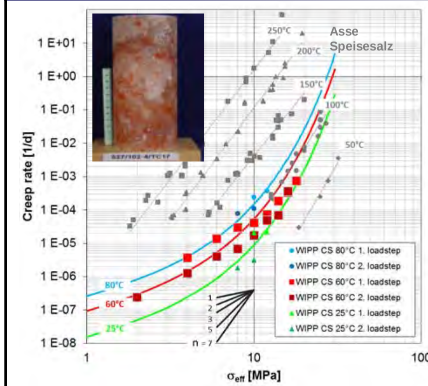
Creep behaviour of clean salt – 25°C, 60°C, 80°C



- Consistent data sets
- Mechanism change depending on stress state ⇒ a simple power law is not sufficient!

IfG-Creep data sets (CS)

Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
1 TCC1	30	20	10	50	24	2,04E-05
	28	20	8	50	24	1,81E-06
1a TCC3	30	20	10	50	24	1,43E-05
	28	20	8	50	24	3,39E-06
2 TCC5	32	20	12	50	24	2,16E-05
	30	20	10	50	24	3,12E-06
3 TCC15	24	20	4	50	60	3,68E-06
	22	20	2	50	60	2,43E-07
4 TCC13	26	20	6	50	60	1,37E-05
	24	20	4	50	60	1,26E-06
5 TCC6	28	20	8	50	60	1,94E-05
	26	20	6	50	60	3,31E-06
6 TCC2	30	20	10	50	60	4,05E-05
	28	20	8	50	60	6,80E-06
6a TCC4	30	20	10	50	60	1,67E-04
	28	20	8	50	60	5,63E-05
7 TCC7	32	20	12	50	60	7,42E-05
	30	20	10	50	60	1,70E-05
8 TCC9	34	20	14	50	60	1,86E-04
	32	20	12	50	60	4,92E-05
9 TCC11	36	20	16	50	60	3,29E-04
	34	20	14	50	60	6,85E-05
10 TCC12	38	20	18	50	60	7,50E-04
	36	20	16	50	60	3,62E-04
11 TCC16	30	20	10	50	80	2,41E-04
	28	20	8	50	80	7,74E-05
12 TCC19	32	20	12	50	80	3,76E-04
	30	20	10	50	80	1,09E-04

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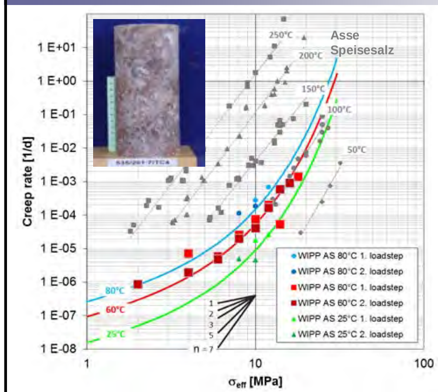
Creep behaviour of argillaceous salt – 25°C, 60°C, 80°C



- Argillaceous salt creeps slightly faster (2x) than Clean Salt
- Generally WIPP-salt creeps faster than Asse Salt

IfG-Creep data sets (AS)

Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
TCC9	30	20	10	50	25	1,75E-05
	28	20	8	50	25	4,98E-06
TCC10	32	20	12	50	25	2,61E-05
	30	20	10	50	25	4,49E-06
TCC1	24	20	4	50	60	7,08E-06
	22	20	2	50	60	8,52E-07
TCC2	26	20	6	50	60	5,87E-06
	24	20	4	50	60	1,94E-06
TCC3	28	20	8	50	60	2,57E-05
	26	20	6	50	60	4,77E-06
TCC4	30	20	10	50	60	7,45E-05
	28	20	8	50	60	2,00E-05
TCC5	32	20	12	50	60	2,00E-04
	30	20	10	50	60	4,10E-05
TCC6	34	20	14	50	60	5,39E-05
	32	20	12	50	60	1,64E-04
TCC7	36	20	16	50	60	8,82E-04
	34	20	14	50	60	5,95E-04
TCC8	38	20	18	50	60	1,40E-03
	36	20	16	50	60	9,24E-04
TCC11	30	20	10	50	80	2,79E-04
	28	20	8	50	80	1,14E-04
TCC12	32	20	12	50	80	6,78E-04
	30	20	10	50	80	1,84E-04

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Complementary laboratory tests on WIPP salt at normal and higher temperatures

Ingo Plischke

Abstract

It has been confirmed that differences in mineralogy, microstructure, cristallography and water content have an influence on long term deformation behaviour of rocksalt. Therefore two different facies types (clean and argillaceous salt) of WIPP rocksalt were and will be tested on its creep behavior. Hence 16 creep tests were carried out during the last year on rocksalt from the WIPP site of which 9 tests were uniaxial tests at normal temperature (22°C) and 7 tests were conducted at higher temperatures of up to 140°C, thereof two under triaxial conditions. In addition, two tests on the same facies types were already carried out in 2001 in the rock mechanic laboratory of BGR. All test contained a change of temperature or stress.
The test series is not finished and will still be ongoing until 2015, to be completed by more triaxial and uniaxial creep tests at higher temperatures. The results will then be compared with results from creep tests of flat bedded rocksalt from the northern German basin, which runs in the past in the rock mechanic laboratory of BGR.

A comparison of the first existing results from WIPP rocksalt with flat bedded rocksalt from the northern German basin offers no greater deviation in creep behaviour. However, the database is still small due to the time-based length of the creep tests at BGR.

Exceptional service in the national interest

Sandia National Laboratories

Laboratory Tests at higher Temperature on different Facies types of WIPP Salt

Ingo Plischke
BGR Hannover, Germany

BGR

Laboratory Tests at higher Temperature on different facies types of WIPP Salt

- Aim of the investigations
  complementation of the tests of other companions
- Creep tests at higher temperature on different facies types
  - Overview of the test programm
  - Results
  - Current and future works
- Petrophysical investigations
  - Mineralogy
  - Results
  - Future works

2

BGR

Laboratory Tests at higher Temperature on different facies types of WIPP Salt

- Analyzed Material

File 13084 clean salt | File 13085 clean salt | File 13079 arg. salt | File 14008 arg. salt

3

BGR

Laboratory Tests at higher Temperature on different facies types of WIPP Salt

- Clean salt (mineralogy)
- Water content ≈ 2.5 w.-% (after Rietveld)!!
- Mineralogy (after Rietveld)

Probe	Halit	Polyhalit	Anhydrit	Kieserit	Qz/Illit/Mag.
2.01	99	0.5			0.5
2.29	99		0.7		0.5
102-5 rot	96	3	≤1	≤1	
102-5 grau	99			≤1	
104 rot	99	≤1			
104 grau	100				
105-5 rot	99		1		
105-5 grau	99		≤1	≤1	

4

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Laboratory Tests at higher Temperature on different facies types of WIPP Salt

- What have we done?
- 9 uniaxial creep tests with two stress steps (14 and 16 MPa)
- each step 70 days
- 4 uniaxial creep tests at higher temperature (100 and 120 ° C)
- *All tests happened at argillaceous salt*
- 3 triaxial creep tests at higher temperature (40 and 140° C)
- *Tests happened on clean and argillaceous salt (partly performed in 2001)*

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Laboratory Tests at higher Temperature on different facies types of WIPP Salt

Data sets creep tests

File	Versuch	σ 3	Δσ	Temp.	Kriechrate	Klasse	Gesetz	Verformung	Fazies	Bemerkungen
		MPA	MPA	°C	1/d		BGR	%		
14002	Kriech1	0	14	22	4.20E-05	5	a	1.97	argillaceous	
14002	Kriech1	0	16	22	1.10E-04	6	a	1.49	argillaceous	
14003	Kriech1	0	14	22	4.40E-05	5	a	1.94	argillaceous	
14003	Kriech1	0	16	22	1.20E-04	6	a	1.59	argillaceous	
14004	Kriech1	0	14	22	8.00E-05	6	a	2.09	argillaceous	
14004	Kriech1	0	16	22	1.60E-04	6	a	2.21	argillaceous	
14005	Kriech1	0	14	22	4.90E-05	5	a	2.28	argillaceous	
14005	Kriech1	0	16	22	1.50E-04	6	a	1.73	argillaceous	
14006	Kriech1	0	14	22	5.90E-05	6	a	1.88	argillaceous	
14006	Kriech1	0	16	22	1.50E-04	6	a	1.93	argillaceous	
13076	Kriech1	0	13.9	22	9.00E-05	6	a	2.61	argillaceous	
13076	Kriech1	0	15.6	22	6.00E-04	8	a	3.11	argillaceous	
13078	Kriech1	0	13.9	22	1.00E-04	6	a	2.55	argillaceous	
13078	Kriech1	0	15.1	22	Bruch		a		argillaceous	
13079	Kriech1	0	14.2	22	5.20E-06	2	a	0.29	argillaceous	
13079	Kriech1	0	16.4	22	2.00E-05	3	a	0.05	argillaceous	
13080	Kriech1	0	14.1	22	4.00E-05	5	a	2.75	argillaceous	
13080	Kriech1	0	16.1	22	1.40E-04	6	a	1.42	argillaceous	
14008	TKriech1	0	6	100	1.70E-04	10	b	2.1	argillaceous	
14009	TKriech1	0	5.9	120	4.90E-04	9	b	3.68	argillaceous	
14010	TKriech1	0		120			b		argillaceous	
14011	TKriech1	0	6.1	120	4.10E-04	9	b	3.19	argillaceous	
14012	TKriech1	0	6	100	1.40E-04	9	b	1.7	argillaceous	
13084	Tkriech3			120			b		clean	
13085	Tkriech3	20	4	140	2.00E-04	9	b		clean	
13085	Tkriech3	20	2	140	3.00E-06	7	b		clean	
1096	Tkriech3	12	14	40	2.30E-04	9	b		argillaceous	performed 2001
1096	Tkriech3	20	14	40	1.70E-04	5	b		argillaceous	performed 2001
1096	Tkriech3	2	14	40	4.30E-04	10	b		argillaceous	performed 2001
1096	Tkriech3	1	14	40	1.30E-04	11	b		argillaceous	performed 2001
1096	Tkriech3	20	14	40	2.50E-04	9	b		argillaceous	performed 2001
1097	Tkriech3	12	14	40	7.30E-05	7	b		clean	performed 2001
1097	Tkriech3	20	14	40	7.10E-05	7	b		clean	performed 2001
1097	Tkriech3	2	14	40	1.30E-04	8	b		clean	performed 2001
1097	Tkriech3	1	14	40	1.70E-04	8	b		clean	performed 2001
1097	Tkriech3	20	14	40	5.20E-05	7	b		clean	performed 2001
										performed 2001
169	FKriech1	0	14	22	2.50E-05	4	a		argillaceous	performed 2001
170	FKriech1	0	14	22	2.70E-05	5	a		clean	performed 2001

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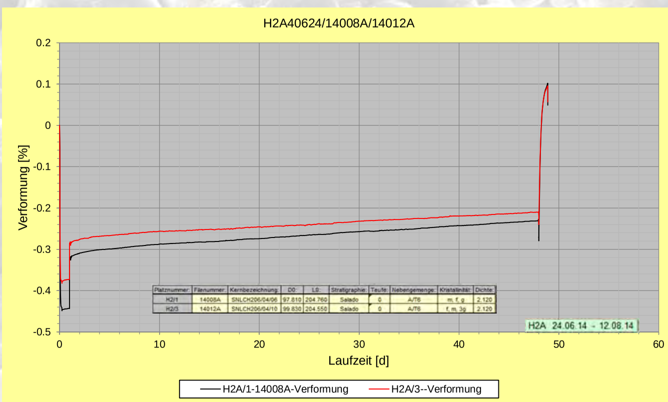
Laboratory Tests at higher Temperature on different facies types of WIPP Salt

Uniaxial Creep test on argillaceous salt from the WIPP-site at 100 ° C



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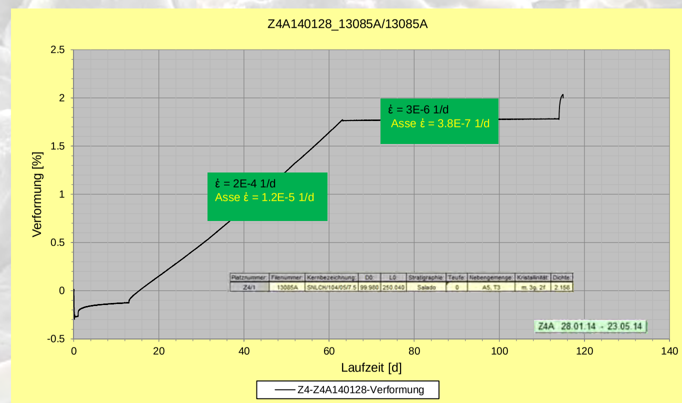
Laboratory Tests at higher Temperature on different facies types of WIPP Salt

Triaxial Creep test on argillaceous salt from the WIPP-site at 140 ° C
(sigma 3 = 20 MPa) stress step 1 Δσ = 4 MPa, stress step 2 Δσ = 2 MPa



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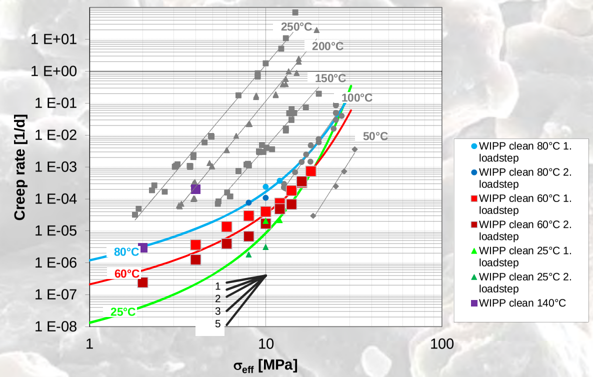
Laboratory Tests at higher Temperature on different facies types of WIPP Salt



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Laboratory Tests at higher Temperature on different facies types of WIPP Salt

- Summary:
- Argillaceous salt creeps slightly faster than „Asse Speisesalz“ at normal temperature
- It creeps up to two orders of magnitude faster than „Asse Speisesalz“ at higher temperatures
- Clean salt creeps up to one order of magnitude faster than „Asse Speisesalz“ at higher temperatures
- Water content measured after Rietveld is five times higher than measured at baking out

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Laboratory Tests at higher Temperature on different facies types of WIPP Salt

- Future works:
- Complementary triaxial tests at higher temperatur at both facies types
- Investigations to determine the influence of the microstructure
- Better determination of the moisture content (freeze desalination?)
  (performed by group of Mr. Hammer)

- What we need:
- More material from the WIPP-site!
- Is this possible?

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Laboratory Tests at higher Temperature on different facies types of WIPP Salt

Thank you for your attention

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Petrography, fluid distribution, geochemistry and microstructures of halite rocks from WIPP-Site (and Gorleben)

Maximilian Pusch[1], Jörg Hammer[1], Christian Ostertag-Henning[1]

[1] Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany

In view of expected differences according to petrography, fluid distribution, geochemistry and microstructures of halite rocks from flat bedding salt formations (WIPP; USA) and salt domes (Gorleben, Germany), several salt samples from WIPP have been analyzed at BGR Hannover, Germany.

WIPP drilling SNLCV302 which contains Marker Bed 139 (MB139) at 2.46 ft - 6.15 ft was used for thin sections and geochemical studies in order to analyze an exemplary profile crossing a salt cycle in North American Permian Salt Basin (Delaware-Basin). The results were compared with the data we gained from Gorleben exploration mine. For studies of hydrocarbon distribution and origin samples from drillings QGU 12, 14, 36, 38 and 39 were used.

The microscopic analyzes of the samples show distinct differences between salt rocks from WIPP and Gorleben. The halitic matrix at the bottom of MB139 (top of the previous salt cycle) is dominated by numerous inclusions of columnar, idiomorphic crystals of polyhalite. In addition intercalations of idiomorphic, columnar anhydrite as well as accessory idiomorphic, columnar crystal of celestine and intersections of clay are visible at the grain boundaries of halite crystals. At the base of MB139 we have an 0,59" thin layer of clay followed by vertical orientated anhydrite with intersections of halite and clay streaks up to 5' 9.09". Until 4.9 ft the cores are dominated by layers of lenticular spiked aggregates and idiomorphic columnar crystals of polyhalite within an anhydritic matrix changing with layers of matted lenticular aggregates of polyhalite with magnesite at the boundaries of the aggregates. Both shapes show intersections of halite-filled pores with large, idiomorphic anhydrite crystals. In the upper part of MB139 up to 2.46 ft anhydrite crystals dominate the rock (sometime with pseudomorphic relics of former gypsum crystals) intersecting with halite and occasionally polyhalite, magnesite or clay. Typical are idiomorphic crystals of celestine all over the anhydritic zone. The halite in the top of MB139 is dominated by halite with intersected cluster of polyhalite. Noticeable are macroscopical visible fluid inclusions up to 0.2" containing brine, brine and gas or brine and crystals of polyhalite, anhydrite or sometimes clay. The content of hydrocarbons within samples from drillings QGU 12, 14, 36, 38 and 39 ranges between 0.2 and 2.4 mg/kg [C_{10}-C_{40}] with a maximum of 4.1 mg/kg [C_{10}-C_{40}]. The concentration of short-chained hydrocarbons ($<C_{10}$) is below detection limit. In comparison, samples from Gorleben exploration mine (crosscut 1 west and 1 east) have an larger range of dispersion with an

hydrocarbon content between 0.006 and 6.88 mg/kg [C_1-C_{40}] and 11 samples with > 6.881mg/kg [C_{10}-C_{40}] up to a maximum of 442 mg/kg [C_{10}-C_{40}].

However, the rock salt from Gorleben salt dome shows a nearly homogeneous texture. It consists of halite with clews of anhydrite and accessory crystals of carbonate and sometimes pyrite, celestine or authigenic quartz.

Petrography, fluid distribution, geochemistry and microstructures of halite rocks from WIPP-Site (and Gorleben)

Maximilian Pusch, Jörg Hammer, Christian Ostertag-Henning

5th US/German Workshop on Salt Repository Research, Design, and Operation
September 7 – 11, 2014 | Santa Fe, New Mexico

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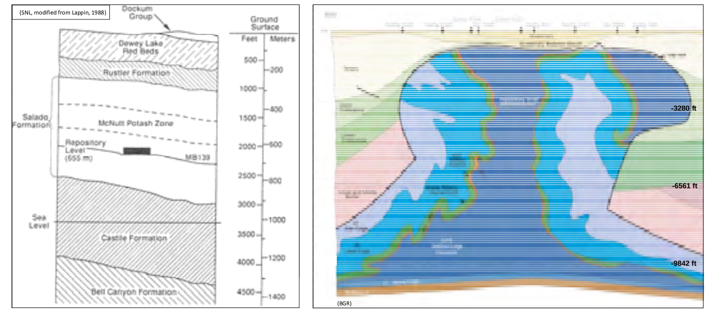
Permian salt formations of WIPP (flat bedding; Delaware basin) & Gorleben (salt dome; North German basin) in comparison



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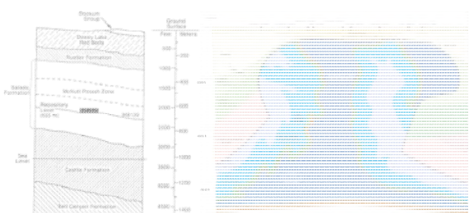
Permian salt formations of WIPP (flat bedding; Delaware basin) & Gorleben (salt dome; North German basin) in comparison

Comparison of halite rocks from flat bedding vs. salt dome
- petrography, mineralogical composition and microstructures
- moisture, composition and distribution of fluids
- concentration and composition of hydrocarbons within the host rocks
- differences in geochemical composition



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Location of WIPP (Delaware basin) & Gorleben (North German basin)

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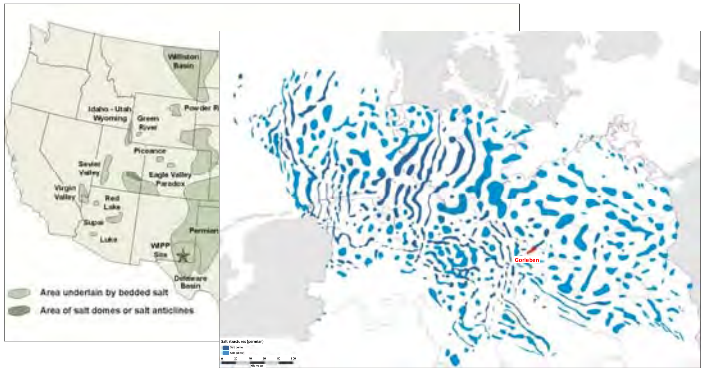
Location of WIPP (Delaware basin) & Gorleben (North German basin)



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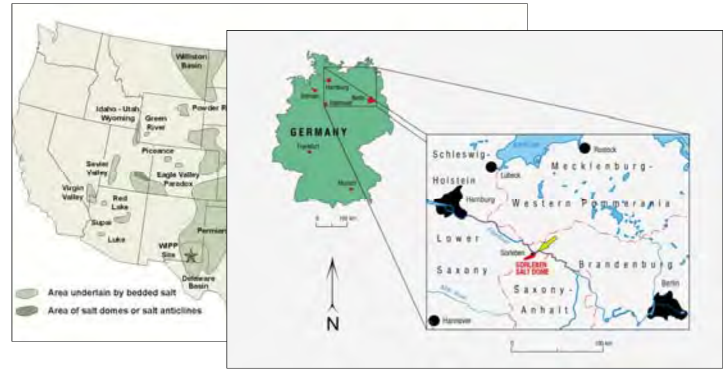
Location of WIPP (Delaware basin) & Gorleben (North German basin)



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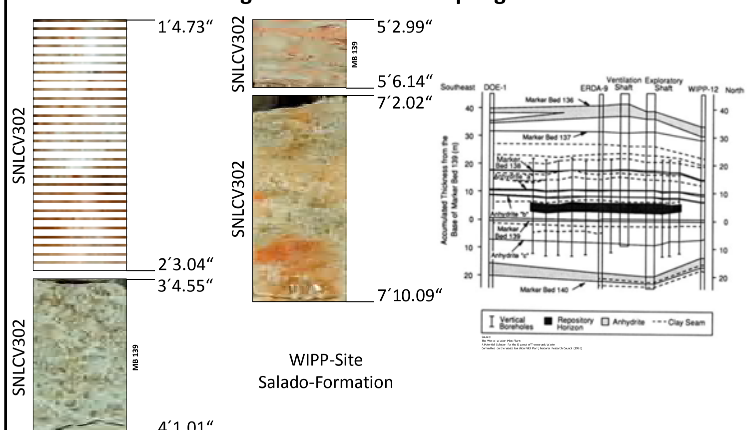
Drill core segments used for sampling of WIPP salt



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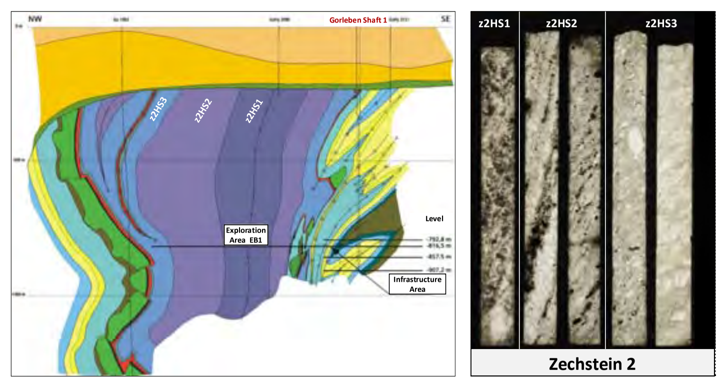
Bisected drill core showpieces of Zechstein z2 and z3 from Gorleben



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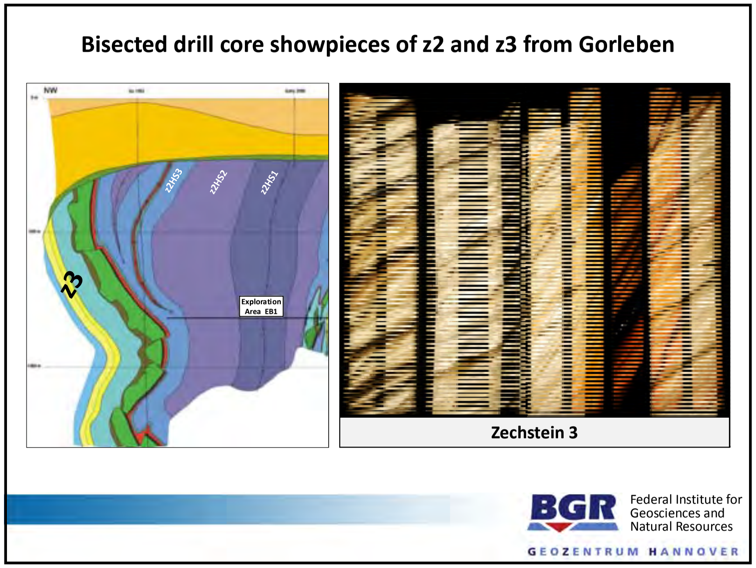
Bisected drill core showpieces of z2 and z3 from Gorleben
NW
z3
z2HS3
z2HS2
z2HS1
Exploration Area EB1
Zechstein 3
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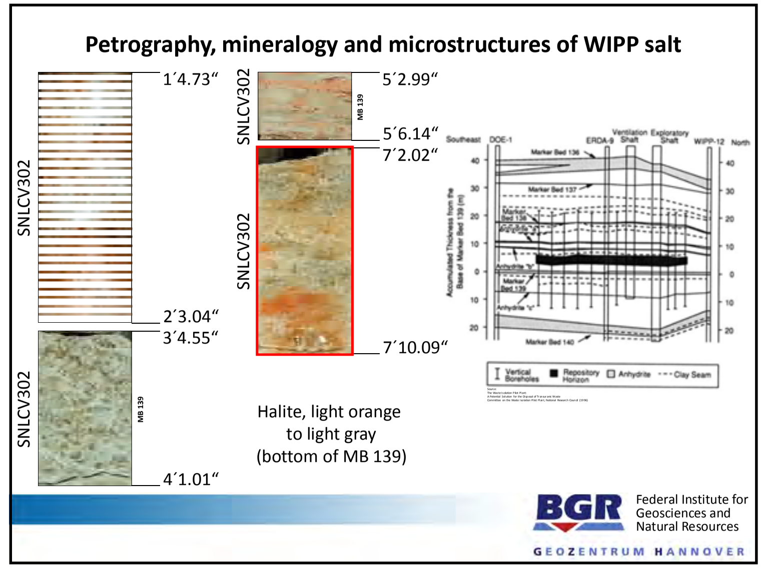
Petrography, mineralogy and microstructures of WIPP salt
SNLCV302
1´4.73“
2´3.04“
3´4.55“
4´1.01“
MB 139
5´2.99“
5´6.14“
7´2.02“
7´10.09“
Halite, light orange to light gray (bottom of MB 139)
Southeast
DOE-1
ERDA-9
Ventilation Shaft
Exploratory Shaft
WIPP-12
North
Marker Bed 136
Marker Bed 137
Marker Bed 140
Vertical Boreholes
Repository Horizon
Anhydrite
Clay Seam
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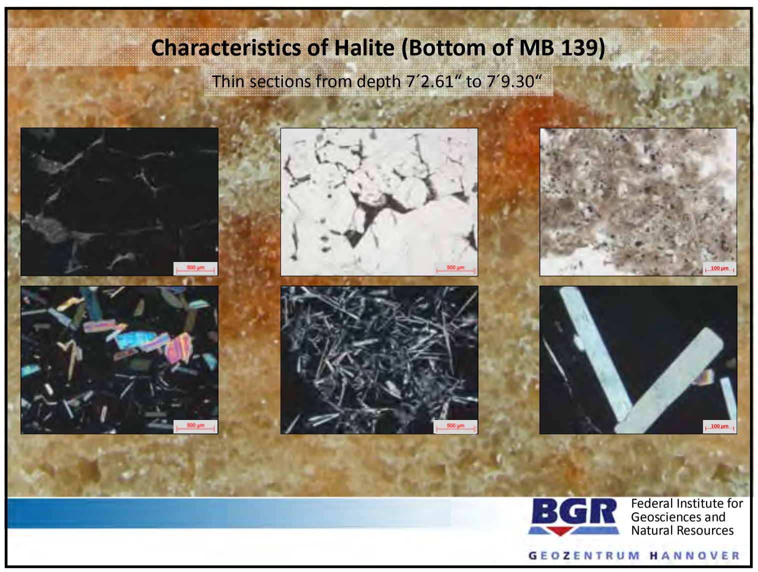
Characteristics of Halite (Bottom of MB 139)
Thin sections from depth 7´2.61“ to 7´9.30“
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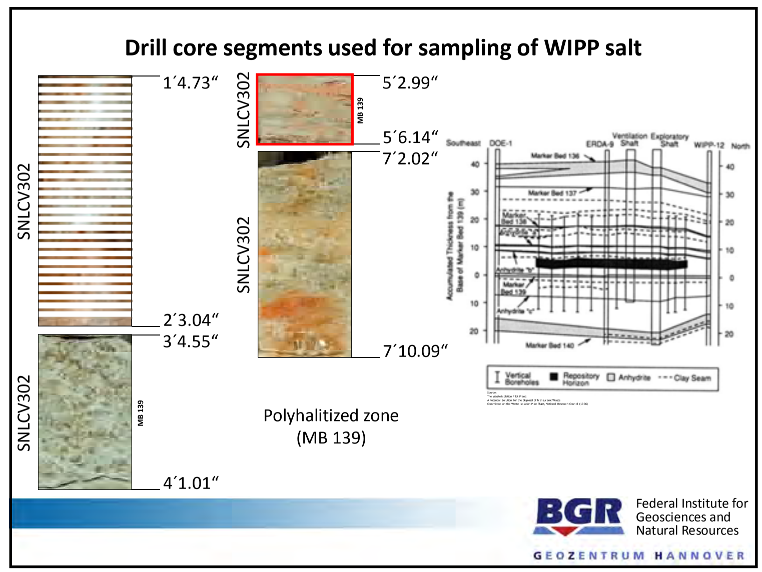
Drill core segments used for sampling of WIPP salt
SNLCV302
1´4.73“
2´3.04“
3´4.55“
4´1.01“
MB 139
5´2.99“
5´6.14“
7´2.02“
7´10.09“
Polyhalitized zone (MB 139)
Southeast
DOE-1
ERDA-9
Ventilation Shaft
Exploratory Shaft
WIPP-12
North
Marker Bed 136
Marker Bed 137
Marker Bed 140
Vertical Boreholes
Repository Horizon
Anhydrite
Clay Seam
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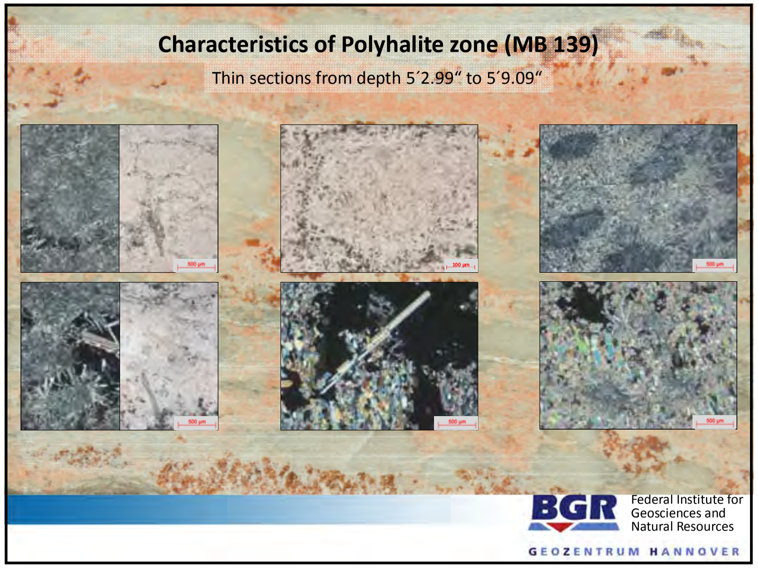
Characteristics of Polyhalite zone (MB 139)
Thin sections from depth 5´2.99" to 5´9.09"
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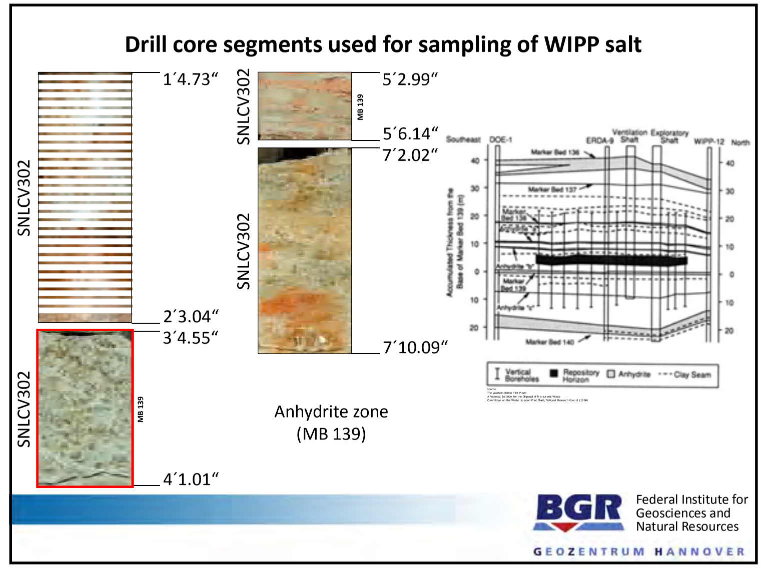
Drill core segments used for sampling of WIPP salt
SNLCV302
SNLCV302
SNLCV302
SNLCV302
1´4.73"
2´3.04"
3´4.55"
4´1.01"
5´2.99"
5´6.14"
7´2.02"
7´10.09"
Anhydrite zone
(MB 139)
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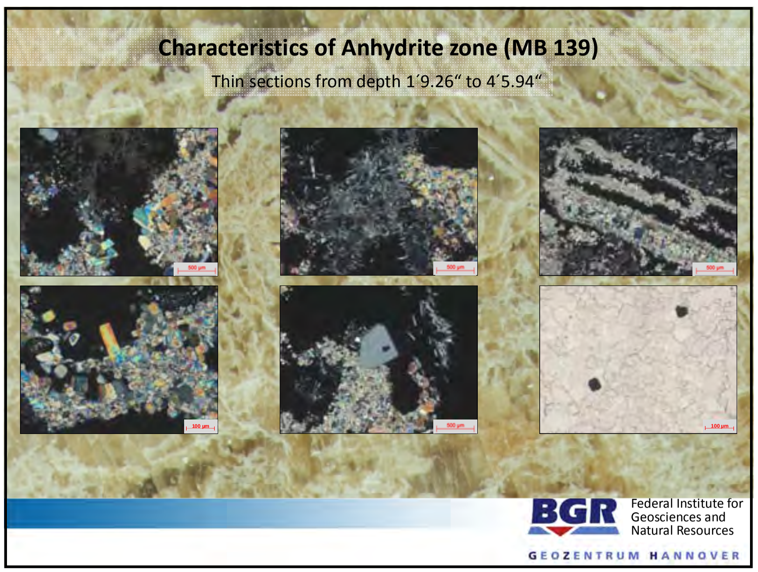
Characteristics of Anhydrite zone (MB 139)
Thin sections from depth 1´9.26" to 4´5.94"
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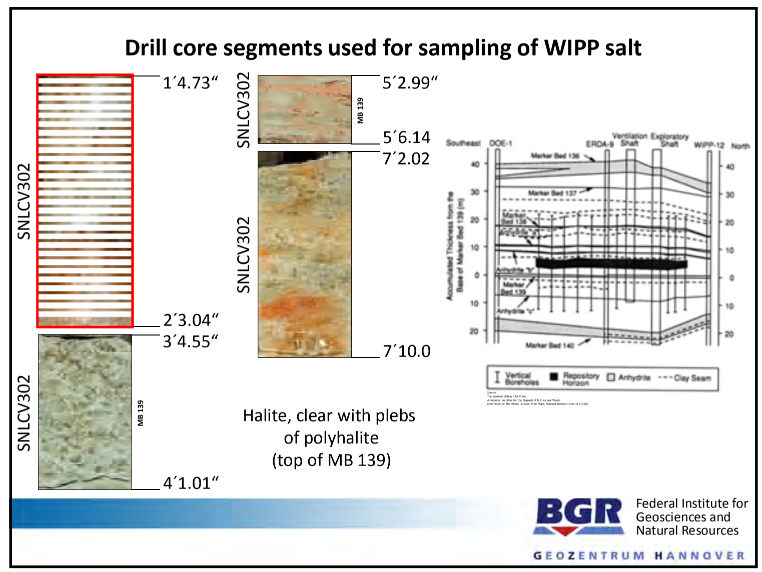
Drill core segments used for sampling of WIPP salt
SNLCV302
SNLCV302
SNLCV302
SNLCV302
1´4.73"
2´3.04"
3´4.55"
4´1.01"
5´2.99"
5´6.14
7´2.02
7´10.0
Halite, clear with plebs
of polyhalite
(top of MB 139)
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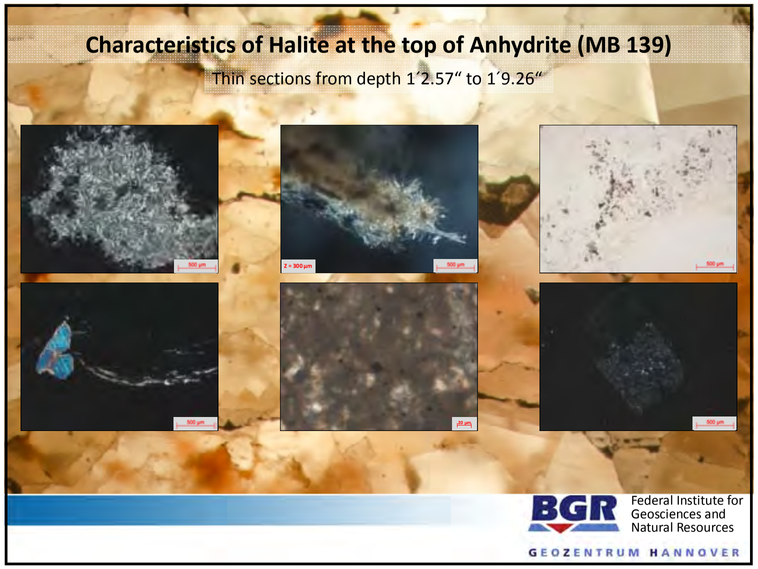
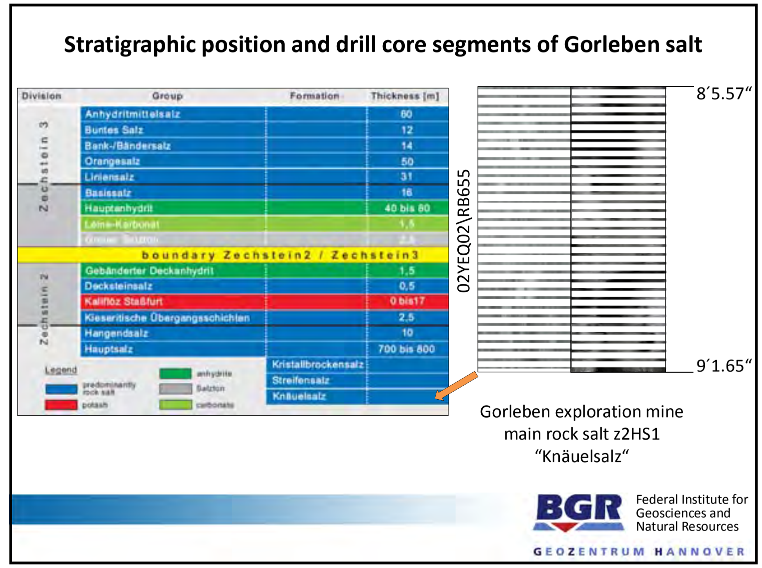
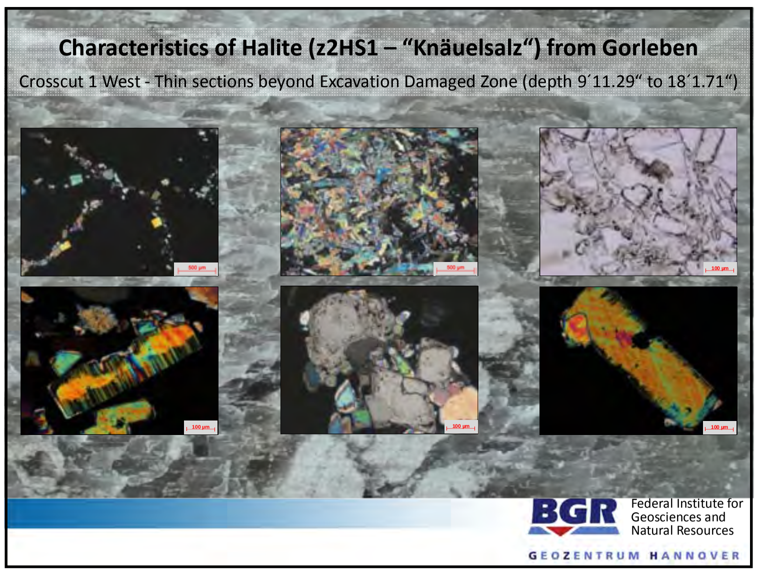
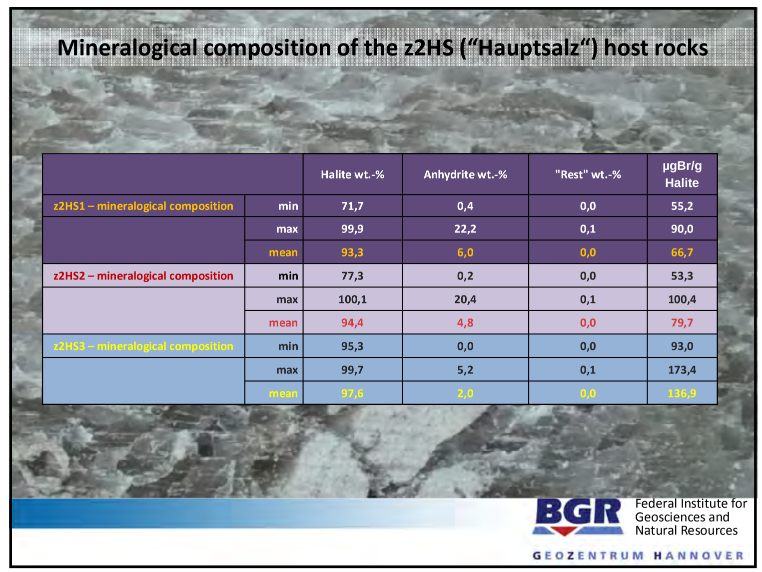




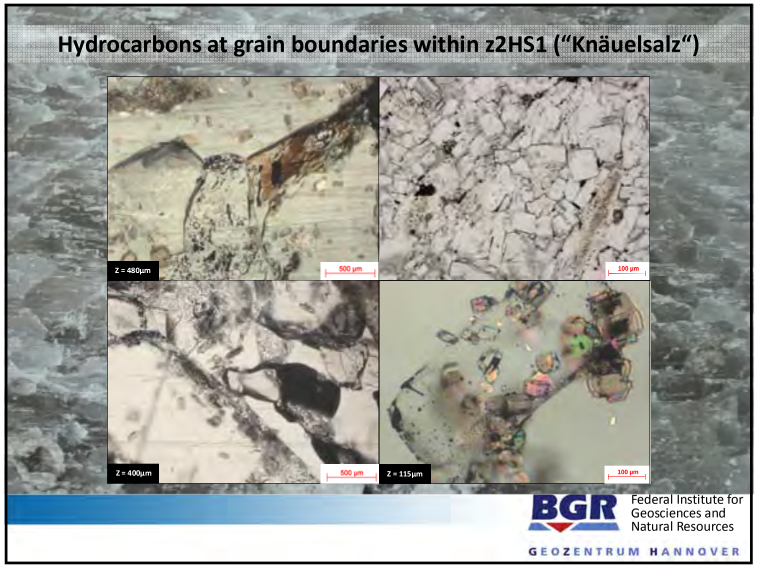
Division	Group	Formation	Thickness [m]
Zechstein 3	Anhydritmittelsalz		60
	Buntes Salz		12
	Bank-/Bändersalz		14
	Orangesalz		50
	Liniensalz		31
	Basissalz		16
	Hauptanhydrit		40 bis 80
	Leine-Karbonat		1,5
	Grauer Salzton		2,5
boundary Zechstein2 / Zechstein3			
Zechstein 2	Gebänderter Deckanhydrit		1,5
	Decksteinsalz		0,5
	Kaliflöz Staßfurt		0 bis17
	Kieseritische Übergangsschichten		2,5
	Hangendsalz		10
	Hauptsalz		700 bis 800
		Kristallbrockensalz	
		Streifensalz	
		Knäuelsalz	

Legend: predominantly rock salt; potash; anhydrite; Salzton; carbonate





		Halite wt.-%	Anhydrite wt.-%	"Rest" wt.-%	µgBr/g Halite
z2HS1 – mineralogical composition	min	71,7	0,4	0,0	55,2
	max	99,9	22,2	0,1	90,0
	mean	93,3	6,0	0,0	66,7
z2HS2 – mineralogical composition	min	77,3	0,2	0,0	53,3
	max	100,1	20,4	0,1	100,4
	mean	94,4	4,8	0,0	79,7
z2HS3 – mineralogical composition	min	95,3	0,0	0,0	93,0
	max	99,7	5,2	0,1	173,4
	mean	97,6	2,0	0,0	136,9


Hydrocarbons at grain boundaries within z2HS1 ("Knäuelsalz")
Z = 480µm
500 µm
100 µm
Z = 400µm
500 µm
Z = 115µm
100 µm
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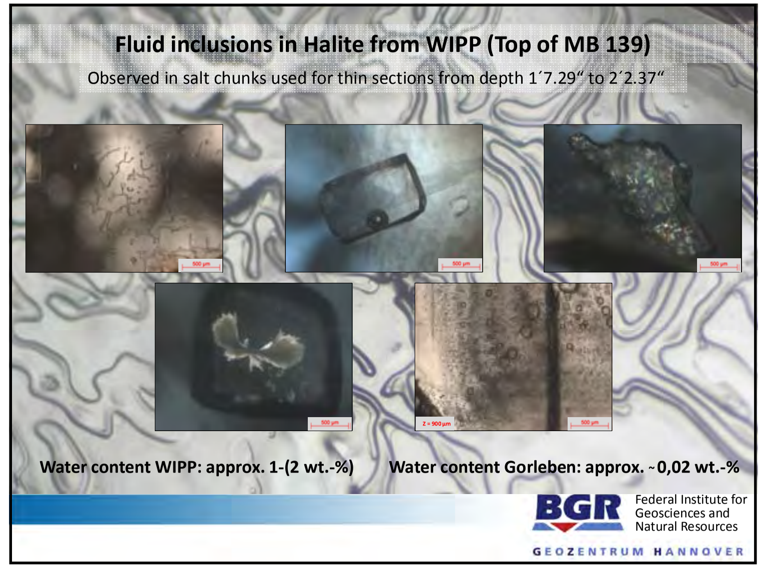
Fluid inclusions in Halite from WIPP (Top of MB 139)
Observed in salt chunks used for thin sections from depth 1´7.29" to 2´2.37"
Water content WIPP: approx. 1-(2 wt.-%)
Water content Gorleben: approx. ~0,02 wt.-%
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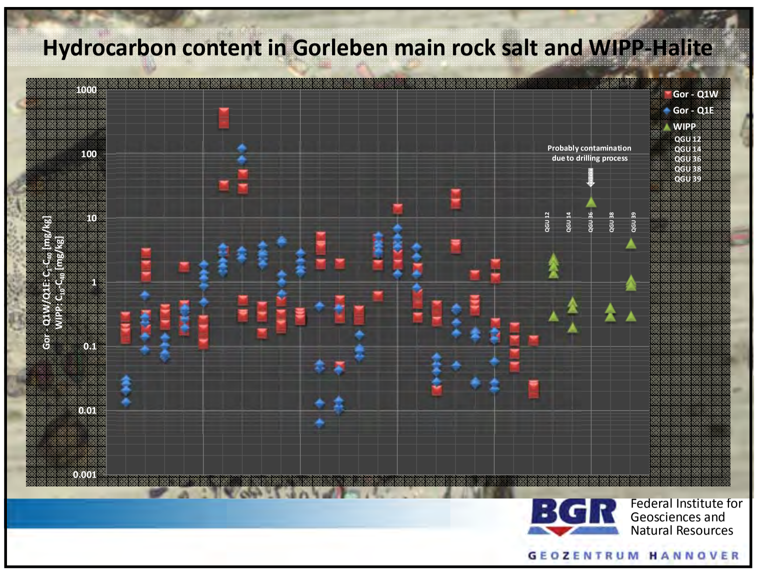
Hydrocarbon content in Gorleben main rock salt and WIPP-Halite
Gor - Q1W/Q1E: C1-C40 [mg/kg]
WIPP: C10-C40 [mg/kg]
1000
100
10
1
0.1
0.01
0.001
Gor - Q1W
Gor - Q1E
WIPP
QGU 12
QGU 14
QGU 36
QGU 38
QGU 39
Probably contamination due to drilling process
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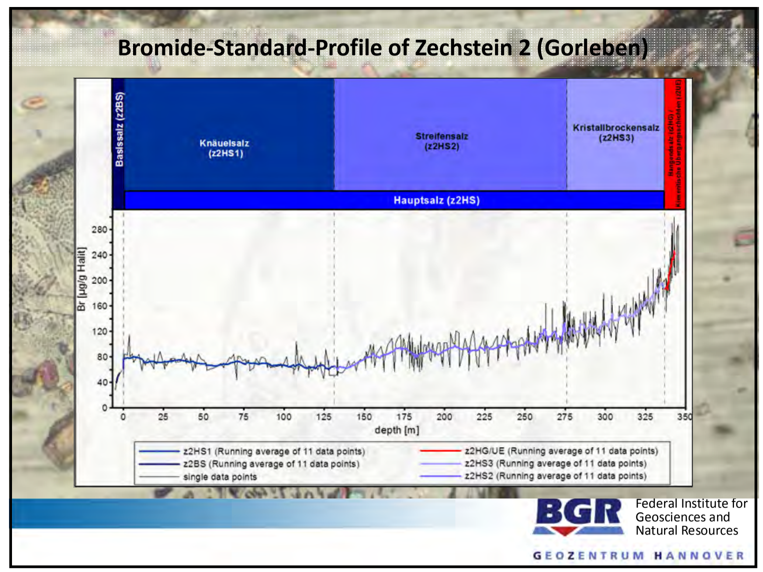
Bromide-Standard-Profile of Zechstein 2 (Gorleben)
Basissalz (z2BS)
Knäuelsalz (z2HS1)
Streifensalz (z2HS2)
Kristallbrockensalz (z2HS3)
Hauptsalz (z2HS)
Br [µg/g Halit]
280
240
200
160
120
80
40
0
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
depth [m]
z2HS1 (Running average of 11 data points)
z2BS (Running average of 11 data points)
single data points
z2HG/UE (Running average of 11 data points)
z2HS3 (Running average of 11 data points)
z2HS2 (Running average of 11 data points)
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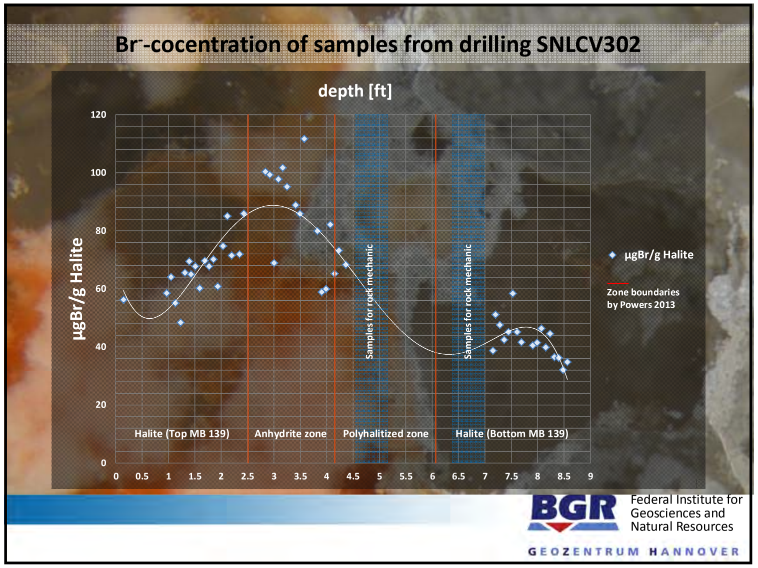

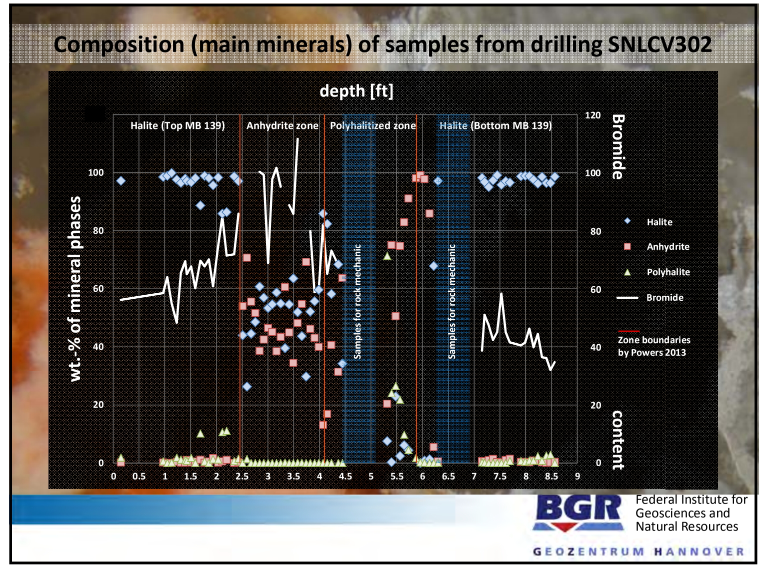

Summary - Differences between WIPP and Gorleben

WIPP-Site (flat bedding)

- Large lithological variations
- Main minerals:
  - Halite (NaCl)
  - Polyhalite ($K_2Ca_2Mg(SO)_4 \cdot 2H_2O$)
  - Celestine ($SrSO_4$)
  - (Pyrite; FeS_2)
- Lots of large fluid inclusions with gases, solid crystal of evaporite minerals or clay
- Higher water content; approx. 1-(2 wt.-%)
- Hydrocarbon concentration **(C_1 to C_{10})** below response level; content of **(C_{10} to C_{40})** up to 4,1 mg/kg; immatured organic matter (rooted plants)
- Br^- - content: seems to be the result of an synsedimentary or diagenetic alteration

Gorleben (salt dome)

- Large homogeneous areas
- Main minerals:
  - Halite (NaCl)
  - Anhydrite ($CaSO_4$)
  - Carbonate ($CaCO_3$; $CaMg(CO_3)_2$; $MgCO_3$)
  - (Pyrite; FeS_2)
- Small fluid inclusions along fissures / grain boundaries & relics of primary inclusions
- Lower water content; approx. ~0,02 wt.-%
- Small amount of hydrocarbons with a max. up to 443 mg/kg **(C_1 to C_{40})**; matured oil
- Br^- - content: is the result of incremental progressive evaporation with some metamorphic zones

BGR Federal Institute for Geosciences and Natural Resources
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Sandia National Laboratories

Shaft seal systems of VSG

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Outline

- Status at US-German Workshops 2010 & 2011
- Technical design procedure
- Selected steps of design procedure
- Results
- Conclusions & outlook

Status at US-German Workshops 2010 & 2011

- Decision to use European Standards in civil engineering (Eurocode) as design basis for the VSG sealing system on a trial basis
  - to derive and apply appropriate technical specifications and procedures
  - to link "long-term SA" and the proof of safety function of sealing systems
  - to assess the consequences of different working lives for sealing systems required in "long-term SA" and Eurocode by decoupling actions and resistances in "short-term" and "long-term" processes as a first approach
- ➢ As a result, corrosion due to geochemical conditions was identified as a "long-term" acting process on sealing systems causing degradation that is not sufficiently covered by Eurocode

Status at US-German Workshops 2010 & 2011

- The conceptual VSG sealing system (shaft & drift seals) is based on prototypes
  - availability of data for technical specifications (minimize expert judgment)
  - constructability is guaranteed (proof of constructability)
- ➢ The sealing system is constructible and the proof of safety function shows a high degree of reliability
- ➢ But as a draft not yet optimized

Technical Design Procedure

(1) Conceptual design
(2) Preliminary dimensioning
(3) Basic Design
(4) Dimensioning
(5) Detailed Design

Focus on selected actions (impacts) with high risk for significant design modifications regarding the „unkowns“

Design working life (functional lifetime)
Actions (impacts)
Resistances (depending on design)
Design situations

- As a result, geochemical actions (corrosion) were analysed first due to lack of knowledge on quantitative effects of a long-term impact

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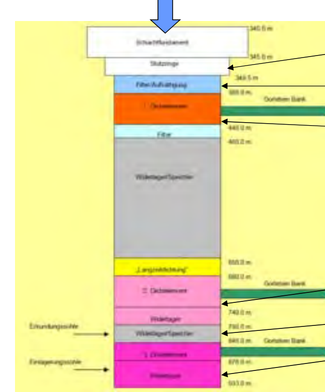
(1) Conceptual design – shaft seal (VSG)

Cap rock solution



GS + standard concrete = G1
G1 + salt top = G2
G2 + bentonite = G3
Brine sequences and sealing materials are compatible. Due to limited amount of $MgCl_2$, only small amounts of salt concrete may be corroded.
G3 + salt concrete = G4
G4 + technical bischofite = G5
G5 + Sorel concrete = G6

(2) Preliminary dimensioning → basic design

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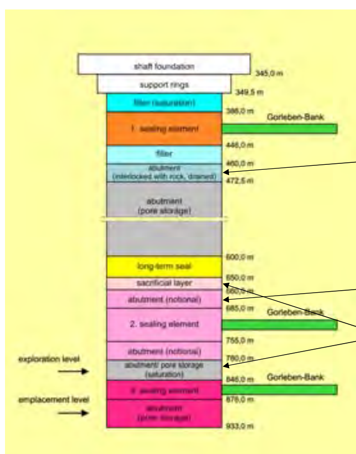
(3) Basic design – shaft seal (VSG)



Basic design includes
- necessary design modifications
- dimensions

seismic event (earthquake)
Brine pressure from overburden
Chemical impact (corrosion)

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(4) Dimensioning

- Basic design is a highly back coupled “input structure” for systems analysis within the safety case
- Significant basic design modifications are possible in principle

- But the structure of the safety case may significantly be affected
- “Good” basic design is essential

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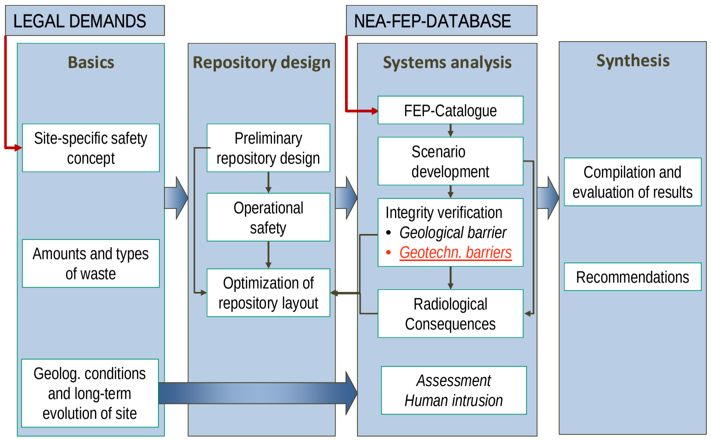
(4a) Structure of safety case - VSG



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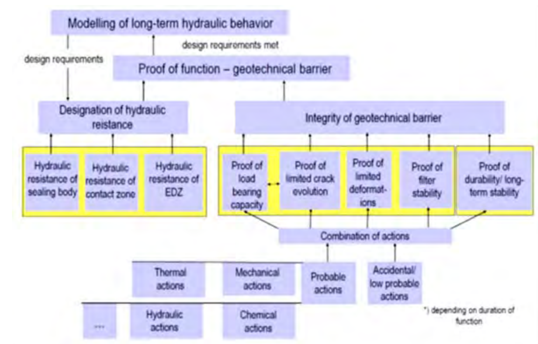
(4b) Scheme of technical functional proof - VSG



$E_d \leq R_d$

E_d: Design values of effects of actions

R_d: Design values of resistances

Unusual design working life: 50,000 years until next ice age

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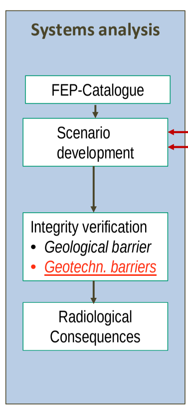
(4c) FEPs affecting geotechnical barriers - VSG



Initial FEPs

FEP-No.	FEP-Name	Affected geotechnical barrier
1.2.03.01	Earthquake	Shaft seal, drift seal
1.2.09.01	Diapirism	Shaft seal, drift
1.2.09.02	Subrosion	Shaft seal
1.3.05.03	Formation of glacial channels	Shaft seal
2.1.05.04	Alteration of drift and shaft seals	Shaft seal, drift seal
2.1.07.01	Convergence	Shaft seal, drift seal
2.1.07.02	Fluid pressure	Shaft seal, drift seal
2.1.07.04	Volume changes in materials – not thermally induced	Shaft seal, drift seal
2.1.07.07	Displacement of shaft seal	Shaft seal
2.1.08.08	Swelling of bentonite	Shaft seal
2.1.09.02	Solution and precipitation	Shaft seal, drift seal
2.1.09.06	Corrosion of materials with cement or magnesium oxychloride phases	Shaft seal, drift seal
2.2.01.01	Excavtion damaged zone	Shaft seal, drift seal
2.2.06.01	Change of stresses	Shaft seal, drift seal

Less likely FEPs

FEP-No.	FEP-Name	Affected geotechnical barrier
2.1.07.05	Early failure of a shaft seal*	Shaft seal
2.1.07.06	Early failure of a drift seal*	Drift seal
2.1.08.05	Piping in seals	Shaft seal, drift seal

*incl. malfunction caused by insufficient construction process

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(4d) Actions & design situations - VSG

No.	Name of action
Chemical actions	
1.	Chemical actions induced by solutions and gases
2.	Chemical actions induced by temperature change
Mechanical actions	
1.	Effects due to forces and stresses
1.1	Dead load
1.2	Rock pressure
1.3	Fluid pressure
1.4	Flow forces
1.5	Restraint stresses
1.6	Mass forces (earthquakes)
2.	Effects due to impressed strains
2.1	Thermal expansion/contraction
2.2	Swelling/shrinking
2.3	Creep/relaxation
2.4	Restraint strains (deformation constraints, settling)

DIN EN 1990, DIN EN 1997 …

Design situation	Characteristic conditions
Transient situations*	Temporary, normal situations, e.g. construction process
Persistent situations*	Normal situations according to normal function and use
Abnormal (accidental) situations**	Rare, mostly extraordinary situations, e.g. accidental situations as impacts or explosions
Seismic situations (earthquakes)***	Short, limited in time, design-defining earthquakes rare

* will occur ** will probably not occur ***regional differences in occurrence

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(4e) Linkage of FEPs, actions & design situations

FEP-No.	FEP-Name	Classification within the functional proof*
1.2.03.01	Earthquake	DS, seismic DS; A, mass forces
1.2.09.01	Diapirism	A, restraint strains
1.2.09.02	Subrosion	Excluded, because significance starts with next glaciation (after selected performance period)
1.3.05.03	Formation of glacial channels	Excluded, because significance starts with next glaciation (after selected performance period)
2.1.05.04	Alteration of drift and shaft seals	A, consequence of chemical action incl. temperature
2.1.07.01	Convergence	A, equivalent to rock pressure due to constitutive equation
2.1.07.02	Fluid pressure	A, fluid pressure
2.1.07.04	Volume changes in materials – not thermally induced	A, swelling/shrinking
2.1.07.07	Displacement of shaft seal	A, restraint strains or a consequence of forces/stresses
2.1.08.08	Swelling of bentonite	A, swelling
2.1.09.02	Solution and precipitation	A, consequence of chemical action incl. temperature
2.1.09.06	Corrosion of materials with cement or magnesium oxychloride phases	A, consequence of chemical action incl. temperature
2.2.01.01	Excavation damaged zone	Neither DS, A nor R but component of the seal
2.2.06.01	Change of stresses	A, dead load, rock pressure, fluid pressure, flow forces, restraint stresses

* If classification is impossible or meaningless, a comment is given

FEP-No.	FEP-Name	Classification within the functional proof
2.1.07.05	Early failure of a shaft seal	DS, abnormal situation
2.1.07.06	Early failure of a drift seal	DS, abnormal situation
2.1.08.05	Piping in seals	A, consequence of chemical actions or flow forces

Classification of FEPs within the technical functional proof

DS = design situation
A = action
R = resistance

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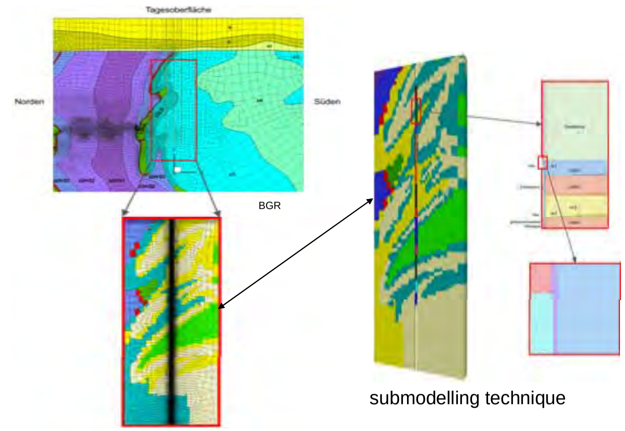
(4f) Calculations - VSG



submodelling technique

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(5) Detailed design

- Insignificant modifications of basic design

➤ Ready to start construction process

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Results – Integrity of Shaft Seal

- Individual proofs to guarantee integrity were successful regarding relevant combinations of thermal, mechanical, and chemical actions

- Thus, the prognosis that hydraulic resistance as planned will really be achieved shows high level of reliability

- Pre-condition: Highly qualified construction process
- "As built" and "as planned" may be different!

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Conclusions & Outlook

- Regarding VSG shaft seal linkage of safety case & technical functional proof was successfully put into practice
- Progress has been made
  - Individual technical proofs forged ahead
  - Technical specifications are available forming the basis for suitability tests
  - Technical basis to establish quality assurance procedures is available
- Open questions
  - Assessing the influence of contact zones/interfaces
  - Especially experimental data is still rare

Acknowledgements

Many thanks

- **to my colleagues Michael Breustedt, Dieter Buhmann, Oliver Czaikowski, Hans-Joachim Engelhardt, Horst Jürgen Herbert, Christian Lerch, Michael Linkamp, Klaus Wieczorek, Johanna Wolf, Mingliang Xie for their contributions to VSG work package 9.2 - Integrity of geotechnical barriers -**
- **to my collegues from BGR, BfS, DBE, GRS, IfG, Asse–GmbH (former HMGU & GSF), IBeWa, TU Clausthal for their collaboration**
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DBE TECHNOLOGY GmbH

Thank you
for your attention!

ELSA – shaft seal project "Phase 2"

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Abstract

Salt and clay formations are potential regions for future HLW-repositories in Germany. To fulfill the principle of a geological barrier, the shaft seals are the most important elements in the geotechnical barrier system for underground repositories. The isolation potential of shaft seals has to be as close as possible to the geological barrier.

While approved shaft seal concepts for HLW- repositories universal suitable for salt and clay formations are actual not available, the emphasis of the ELSA project is to design and construct functional components of a long-term stable sealing system for a shaft seal and demonstrate the constructability and functionality.

The ELSA project is a joint research project between TUBAF and DBE-TEC and is portioned into 3 phases, while the phase 1 "Compilation of boundary conditions and design requirements" is finished with an available report (02E10921). At present, the phase 2 "Concept development for shaft seals and demonstration of functional components" is in progress.

The general aims of the ELSA project are:

- Development of a modular and non-site specific shaft sealing concept for salt and clay formations and
- Test of functional components in laboratory scale and half scale.

Specific investigations are carried out in phase 2 on the following topics:

- producibility of backfill columns from compacted crushed salt (<0.9 ρ_0)
- calottes from Basalt blocks to support a low-settling gravel column
- abutments and seals from long-term stable (3-1-8) MgO concrete
- grouting technologies to seal DRZ and contact between host rock and sealing elements
- emplacement technologies for bitumen / asphalt sealing elements
- bentonite sealing elements in argillaceous host rock
- model-theoretical analysis on different states of construction, as well as loading and flow processes

The first results showing, that a crushed salt with an optimized grain size distribution gets a better compaction behavior than straight mine-run salt. Investigations on the compaction of an optimized crushed salt with added clay suggests that this material mix has an instant sealing potential.

The MgO-concrete with a 3-1-8 phase is an additional material option for long-term stable abutments and seals in shaft-sealing systems for HLW-repositories.

The generation of a CPA based particle model to analyze the behavior of a gravel column is nearly finished. After calibration of the particle model, the behavior of gravel columns during emplacement and operation can be assessed by simulations.

As before, bitumen / asphalt are still a good option as diverse redundant sealing material. Especially since the wetting of the bituminous binder with the host rock (salt and clay) can be improved with a patented primer (no. DE 102008050211). A "cast in place" bitumen / gravel element is an additional option for a combined abutment / sealing element.

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Sandia National Laboratories

September 2014
5th INTERNATIONAL US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Santa Fe, NM

ELSA – shaft seal project Phase 2

Uwe Glaubach
TU Bergakademie Freiberg (TUBAF)

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

Outline

- Introduction
- State of the art
- Aims of the project
- Workprogram & schedule
- Preliminary results
  - Backfill columns made from crushed salt
  - Long-term stable (3-1-8) MgO concrete
  - Model-theoretical analysis of a gravel column
- Summary and outlook

Introduction - general

- Shaft seals are the most important elements in the geotechnical barrier system for underground repositories
- Isolation potential of shaft seals has to be as close as possible to the geological barrier
- Potential repository regions of Germany are in salt and clay formations
- Approved shaft seal concepts for HLW- repositories universal suitable for salt and clay formations are not available
- Knowledge and experience from national and international underground waste disposal projects (mostly site-specific) are important resources for the ELSA – Project

Introduction - partners

- ELSA is a joint research project:

TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
The University of Resources. Since 1765

Verantwortung für Generationen
Responsibility for Generations
DBE TEC DBE TECHNOLOGY GmbH

Project director: W. Kulda W. Bollingerfehr, M. Jobmann

founded by:
German Federal Ministry of Economic Affairs and Energy
by resolution of the German Federal Parliament

supported by:
PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology

with the following partners:

CMM - KIT
GSES
IBeWa Freiberg
IfG Leipzig
TS BAU GMBH, NL Jena

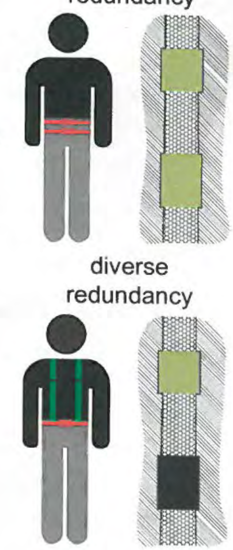
Introduction - project structure

- ELSA project is partitioned in 3 phases:

support code: 02E10921 02E10931	Phase 1: compilation of boundary conditions and design requirements	04/2011 – 01/2013 final report available
support code: 02E11193A	Phase 2: concept development for shaft seals and demonstration of functional components	05/2013 – 12/2015 in progress
	Phase 3: demonstration of the developed sealing concept in full scale test	application in preparation

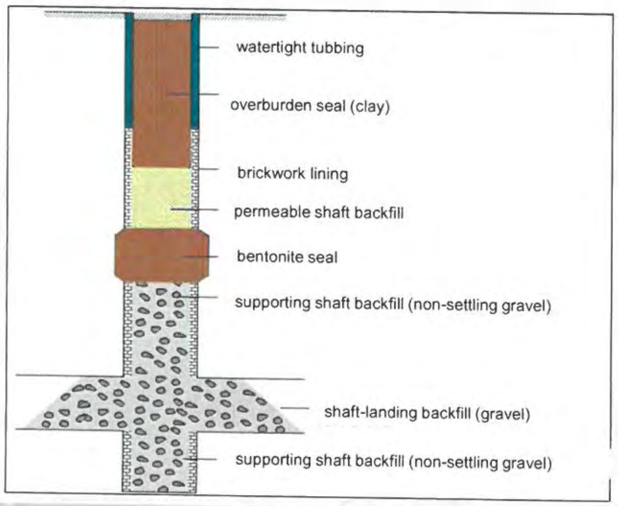
State of the art - general

- The final report of phase 1 describes the state of art for shaft seals with long-term stability
- Shaft sealing system "Salzdetfurth" is the basic concept
- Concepts of ERAM, ASSE, KONRAD, WIPP and NAGRA are respected
- Safety analysis projects ISIBEL, ANSICHT and VSG are considered
- HLW- repositories require a distinctive level of safety, so the principle of redundancy or (better) diverse redundancy must apply



State of the art - selected concept examples

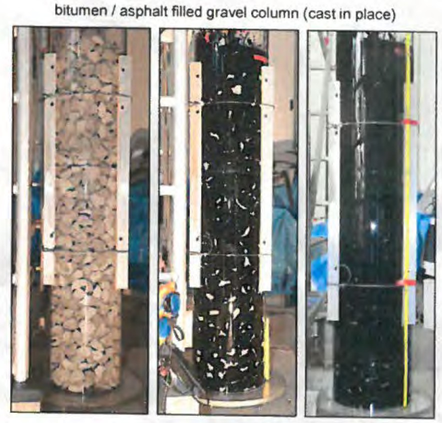
- System „Salzdetfurth"

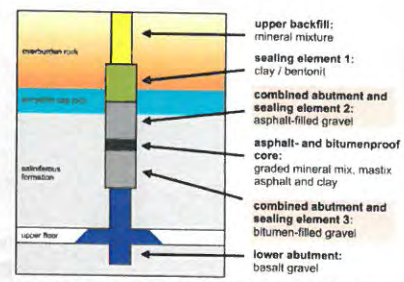


State of the art - selected concept examples

- ERA Morsleben shaft sealing

bitumen / asphalt filled gravel column (cast in place)

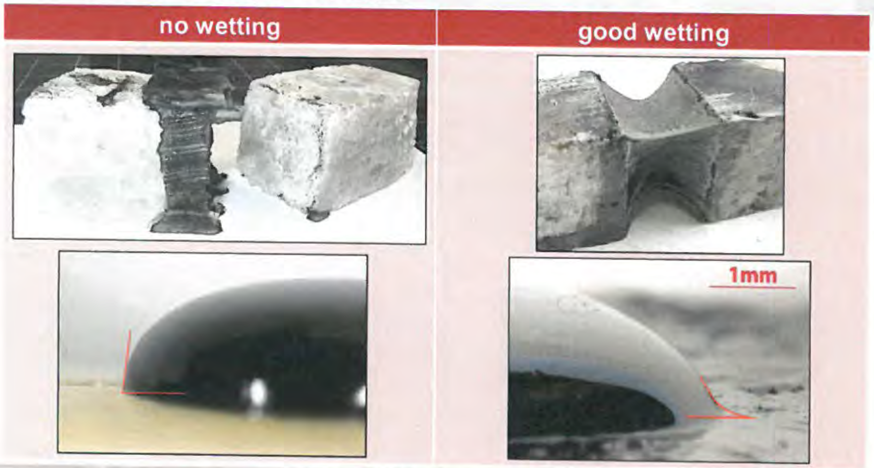




full scale test of asphalt / gravel element (BiSETO)

State of the art - latest development

- Bituminous primer with mining approval
  - patent no. DE 102008050211

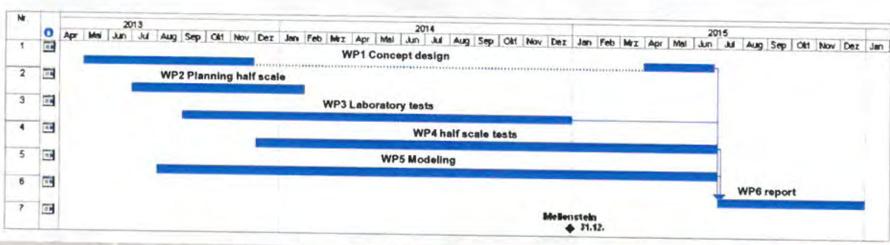


Aims of the project

- general:
  - Development of a modular and non-site specific shaft sealing concept for salt and clay formations
  - Test of functional components in laboratory scale and half scale
- specific investigations in phase 2:
  - producibility of backfill columns from compacted crushed salt ($<0.9\rho_0$)
  - calottes from Basalt blocks to support a low-settling gravel column
  - abutments and seals from long-term stable (3-1-8) MgO concrete
  - grouting technologies to seal DRZ and contact between host rock and concrete sealing element
  - construction technologies for bitumen / asphalt sealing elements
  - bentonite sealing elements in argillaceous host rock
  - model-theoretical analysis on different states of construction, as well as loading and flow processes

Workprogram & schedule

- WP 1: Concept design of shaft seals for HLW-repositories
- WP 2: Planning of half scale tests (in-situ)
- WP 3: Tests in laboratory scale
- WP 4: Tests in half scale (in-situ)
- WP 5: Modeling
- WP 6: Report



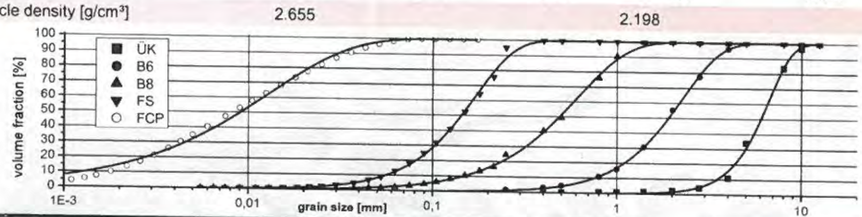
Preliminary results

- Backfill columns made from crushed salt (TUBAF)
  - Optimizing the grain size distribution of crushed salt
  - Comparison between REPOPERM material and optimized material
  - Optimization the water and clay content in relation to the compaction energy
  - Emplacement tests of the optimized material
- Long-term stable (3-1-8) MgO concrete (TUBAF)
  - Construction of a half scale test on in-situ material behavior
  - First results
- Model-theoretical analysis of a gravel column (DBE-TEC)
  - generating a gravel model with Particle Flow Code

Preliminary results – work package TUBAF

- Optimizing the grain size distribution of crushed salt

Fractions from GSES processing plant	Friedland Clay Powder (FCP)	fine salt (FS)	band 8 (B8)	band 6 (B6)	oversize grain (ÜK)
Distribution $d_5 - d_{95}$ [mm]	0.001 - 0.04	0.04 – 0.3	0.1 – 1.2	0.4 - 4	3 - 10
d_{50} [mm]	0.009	0.14	0.49	1.90	6.03
particle density [g/cm³]	2.655			2.198	



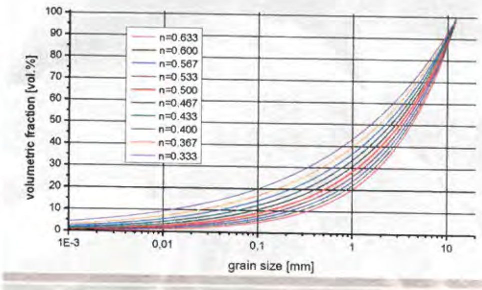
Preliminary results – work package TUBAF

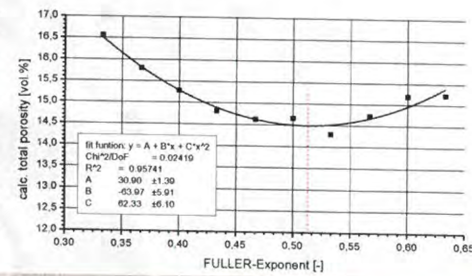
- Optimizing the grain size distribution of crushed salt
  - FULLER-distribution as a first approximation

$$F_F(d) = 100\% \left(\frac{d}{d_{max}}\right)^n$$

d grain diameter
d_{max} maximum of the grain diameter
F_F FULLER volumetric grain size distribution
n Fuller-Exponent, distribution-coefficient

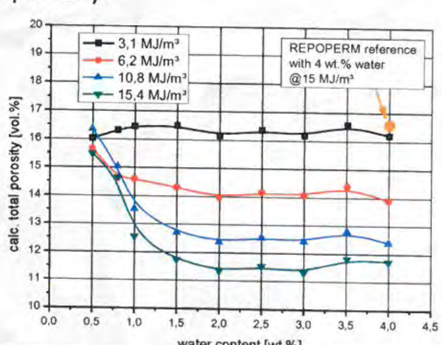
  - Compaction tests with 6 MJ/m³ using a percussive Marshall-compactor on different Fuller distributed mixtures
  - Minimum of total porosity with a FULLER-Exponent of n~0.51





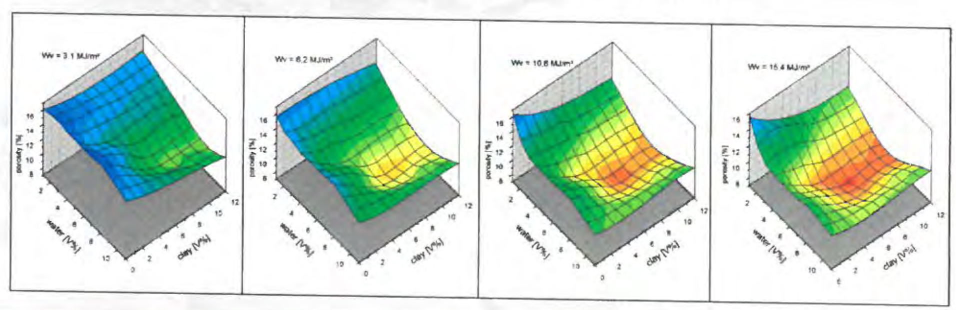
Preliminary results – work package TUBAF

- Comparison between REPOPERM material and optimized material
  - Analysis was made with respect to the compaction energy and water content
  - In contrast to the REPOPERM material, which gained 16.5 vol% porosity with 4 wt% water @ 15 MJ/m³, the FULLER-optimized salt mixture gained around 11.5 vol% porosity.
  - An addition of 1.0 to 1.5 wt% water suffice for an optimum compaction, which confirms the earlier investigations of AHRENS & HANSEN (Sandia National Laboratories 1996)



Preliminary results – work package TUBAF

- Optimizing the water and clay content regarding the compaction energy (according to BUTCHER 1991)
  - optimal clay content is approx. 8 vol% (of dry solids)
  - optimal water content depends from compaction energy
  - for compaction energies > 10 MJ/m³ the optimal water content is approx. 6.2 vol% (mixture specific ~ 2.7 wt%)
  - the lowest gained porosity was 7.7 vol.% @ 15.4 MJ/m³



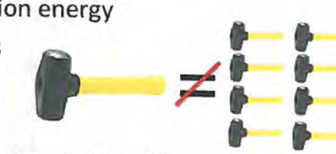
Preliminary results – work package TUBAF

- Emplacement tests of the optimized material
  - in-situ compaction test in drifted dies using conventional vibrating compactors
  - test on optimized salt-clay-mixture
  - compaction in 0.1 m layers

Reversible Vibratory Plate (750 kg)

Trench compactor (1450 kg)

- Emplacement tests of the optimized material
  - on site mixing using conventional concrete equipment is problematic
    - further investigations:
      - with intensive mixers (Co. EIRICH)
      - specific coating of the salt fractions with clay
  - gained porosities are around 15 ± 4 vol%
  - critical evaporation during the emplacement due to the low water content of 2.7 wt% (dust formation during compaction)
  - on the optimized mixture the conventional vibrating compactors are only useful for pre-compaction
  - the outcome from the applied compaction energy depends on the applied partial amounts
  - material optimization depends also on favored compaction principle
  - final compaction by a percussive Compactor (favored!)



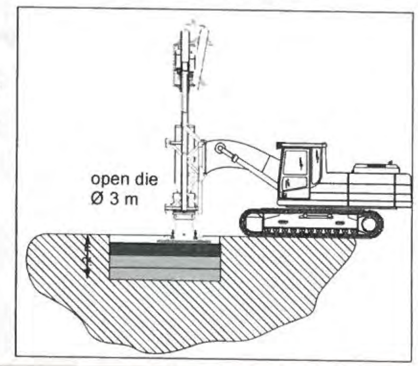
Preliminary results – work package TUBAF

- Compaction by a percussive Compactor
  - using commercial "Rapid Impact Compactor" for feasibility study
  - first field test in summer 2013 was promising
  - compactor spec. (hydraulic drive)
    - high blow ratio of ~40 blows per minute
    - falling weight 9000 kg with controllable falling height of 0.3 – 1.2 m
    - controllable energy per blow of 26.5 - 106 kJ (power: 1.1 - 4.2 MJ/min)
    - compaction foots with diameter from 0.8 m to 2.0 m available

TERRA-MIX™ STRAIGHT AHEAD

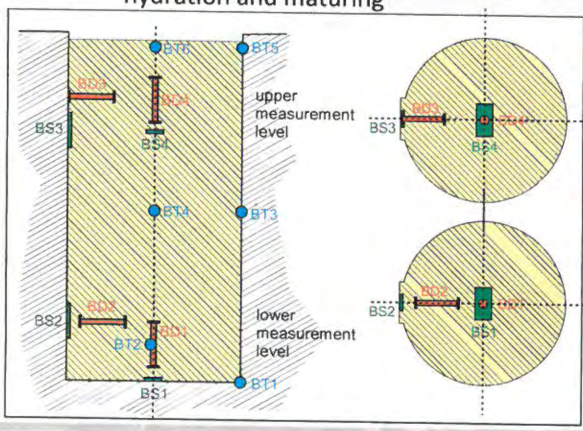
Preliminary results – work package TUBAF

- Compaction by a percussive Compactor
  - half scale field test in preparation (may 2015)
  - drifted die in a hard rock quarry or made from reinforced concrete
  - impact compaction of every distinctive pre-compacted emplacement layer (0.4 m) with 15 MJ/m³ (3 layers in total)
  - applying the compaction energy at the layer surface with minimal overlapping areas (practical aspect)
  - investigations on:
    - material behavior during compaction
    - spatial distribution of porosity in the compacted body
    - gas- and liquid permeability
    - laboratory tests as reference and quality control



Preliminary results – work package TUBAF

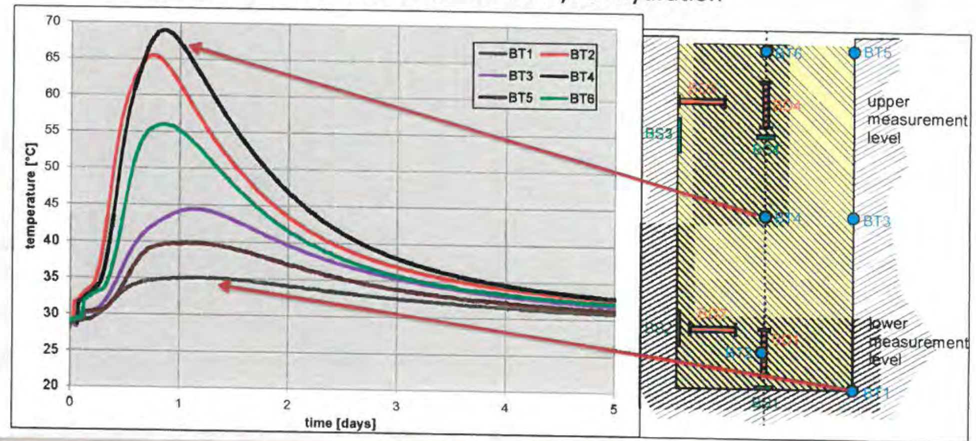
- Long-term stable (3-1-8) MgO concrete
  - construction of a half scale test on in-situ material behavior
  - measuring of temperature (BTx), stress (BSx), strain (BDx) and changing of moisture content (TDR sensors) during construction, hydration and maturing



borehole Ø 1m and 2 m deep

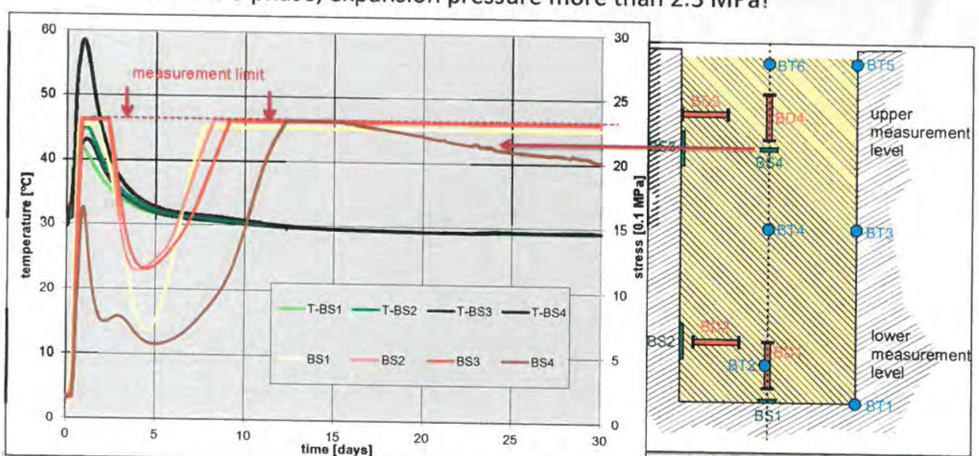
Preliminary results – work package TUBAF

- Long-term stable (3-1-8) MgO concrete
  - max. temperature during hydration reached ~ 69 ° C 24 h after placing
  - heat generation ended after ~ 2 - 3 days of hydration



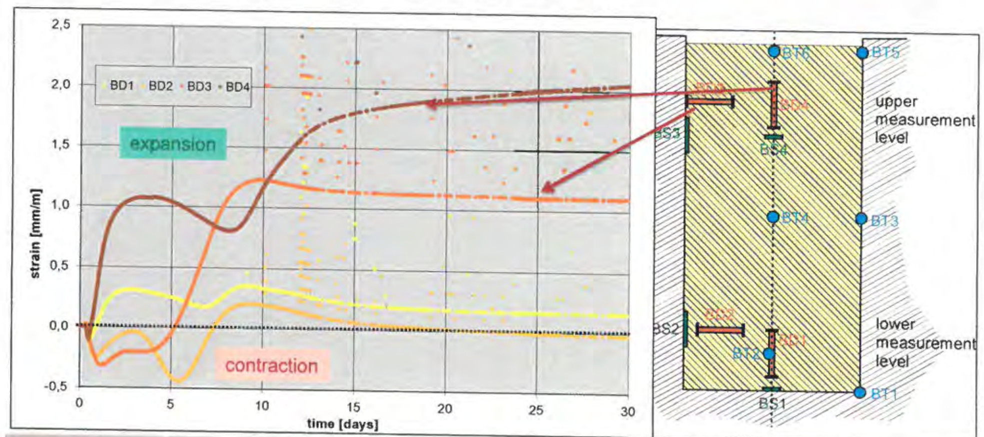
Preliminary results – work package TUBAF

- Long-term stable (3-1-8) MgO concrete
  - thermal induced stress temporally over 2.3 MPa during hydration
  - 5 -6 days after placing the stresses rises again due to crystallization of the 3-1-8 phase, expansion pressure more than 2.3 MPa!



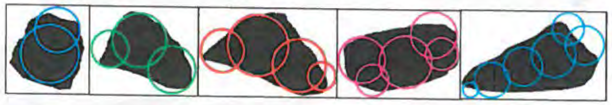
Preliminary results – work package TUBAF

- Long-term stable (3-1-8) MgO concrete
  - general expansion comes with the crystallization of the 3-1-8 phase
  - strains in the upper measurement level are much higher due to the lower restraint at the drift floor (salt creep!)

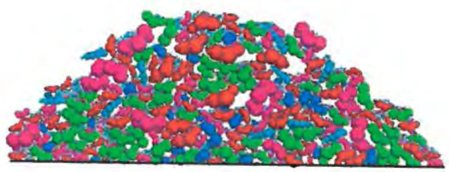


Preliminary results – work package DBE-TEC

- Model-theoretical analysis of a gravel column
  - generating a gravel model with Particle Flow Code (PFC – ITASCA) using particle clumps based of statistical data from CPA
  - calibration on dump tests



classification in grain size with 5 different grain shapes with different aspect ratios (1.4 – 2.8)



all pictures by P. Herold – DBE-TEC

Summary and outlook

- The Phase 1 of the ELSA project states the state of the art and requirements and demands for shaft seals in salt and clay formations. As a result, promising construction materials were optimized, modeled and tested in Phase 2.
- Crushed salt with an optimized grain size distribution gets a better compaction behavior than straight mine-run salt. The addition of a filler-like material (e.g. Friedland Clay Powder) reduces the total porosity and permeability.

  In cooperation with the Institute for Rock Mechanics GmbH (IfG Leipzig) the mechanic and hydraulic properties of the optimized salt/clay mixture will be investigated during further consolidation under insitu stress conditions.

  Backfill columns made from crushed salt and clay probably include an instant sealing function (enrichment for the diverse redundancy).

Summary and outlook

- MgO-concrete with 3-1-8 phase is long-term stable in thermodynamic perception, has a lower heat generation than common concrete and therefore a lower thermal shrinkage. The MgO-concrete (3-1-8) is an additional material option for abutments and seals in shaft-sealing systems for HLW-repositories.
- The generation of a CPA based particle model to analyze the behavior of a gravel column is nearly finished. After calibration of the particle model, the behavior of gravel columns during emplacement and operation can be assessed by simulations.
- As before, bitumen / asphalt are a good option as a diverse redundant sealing material. The wetting of the bituminous binder with the host rock (salt and clay) can be improved with a patented primer (German mining approval). A "cast in place" bitumen / gravel element is an additional option for a combined abutment / sealing element.

Thank you for your attention!

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Shaft seal systems of VSG

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Outline

- Status at US-German Workshops 2010 & 2011
- Technical design procedure
- Selected steps of design procedure
- Results
- Conclusions & outlook

Status at US-German Workshops 2010 & 2011

- Decision to use European Standards in civil engineering (Eurocode) as design basis for the VSG sealing system on a trial basis
  - to derive and apply appropriate technical specifications and procedures
  - to link "long-term SA" and the proof of safety function of sealing systems
  - to assess the consequences of different working lives for sealing systems required in "long-term SA" and Eurocode by decoupling actions and resistances in "short-term" and "long-term" processes as a first approach
- ➢ As a result, corrosion due to geochemical conditions was identified as a "long-term" acting process on sealing systems causing degradation that is not sufficiently covered by Eurocode

Status at US-German Workshops 2010 & 2011

- The conceptual VSG sealing system (shaft & drift seals) is based on prototypes
  - availability of data for technical specifications (minimize expert judgment)
  - constructability is guaranteed (proof of constructability)
- ➢ The sealing system is constructible and the proof of safety function shows a high degree of reliability
- ➢ But as a draft not yet optimized

Technical Design Procedure

(1) Conceptual design
(2) Preliminary dimensioning
(3) Basic Design
(4) Dimensioning
(5) Detailed Design

Focus on selected actions (impacts) with high risk for significant design modifications regarding the „unkowns"

Design working life (functional lifetime)
Actions (impacts)
Resistances (depending on design)
Design situations

➢ As a result, geochemical actions (corrosion) were analysed first due to lack of knowledge on quantitative effects of a long-term impact

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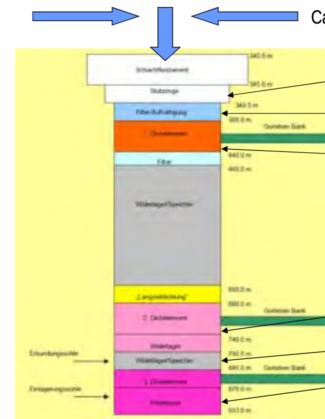
(1) Conceptual design – shaft seal (VSG)

Cap rock solution



GS + standard concrete = G1

G1 + salt top = G2

G2 + bentonite = G3

Brine sequences and sealing materials are compatible. Due to limited amount of $MgCl_2$, only small amounts of salt concrete may be corroded.

G3 + salt concrete = G4

G4 + technical bischofite = G5

G5 + Sorel concrete = G6

(2) Preliminary dimensioning → basic design

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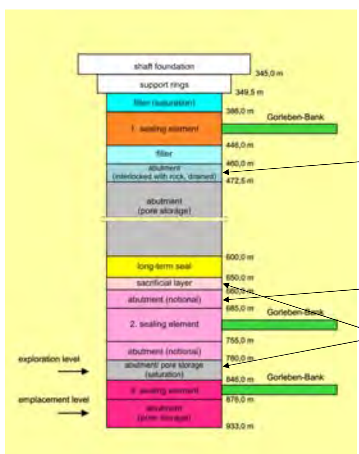
(3) Basic design – shaft seal (VSG)



Basic design includes
- necessary design modifications
- dimensions

seismic event (earthquake)

Brine pressure from overburden

Chemical impact (corrosion)

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(4) Dimensioning

- Basic design is a highly back coupled "input structure" for systems analysis within the safety case
- Significant basic design modifications are possible in principle

➢ But the structure of the safety case may significantly be affected
➢ "Good" basic design is essential

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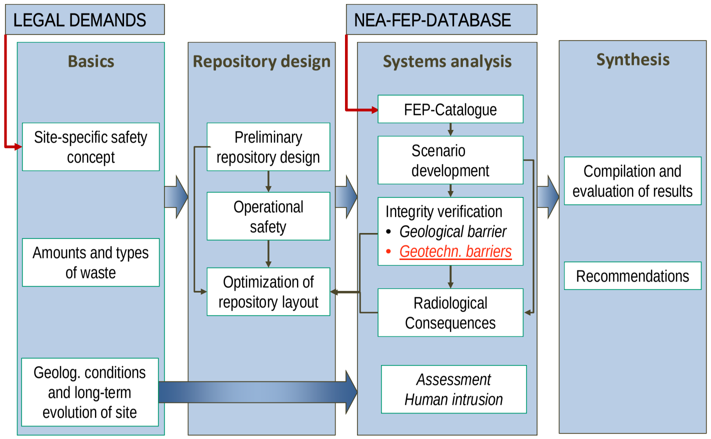
(4a) Structure of safety case - VSG



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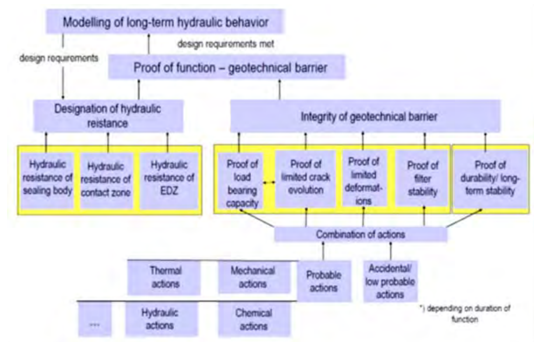
(4b) Scheme of technical functional proof - VSG



$E_d \leq R_d$

E_d: Design values of effects of actions

R_d: Design values of resistances

Unusual design working life: 50,000 years until next ice age

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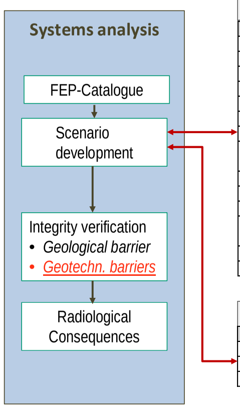
(4c) FEPs affecting geotechnical barriers - VSG



Initial FEPs

FEP-No.	FEP-Name	Affected geotechnical barrier
1.2.03.01	Earthquake	Shaft seal, drift seal
1.2.09.01	Diapirism	Shaft seal, drift
1.2.09.02	Subrosion	Shaft seal
1.3.05.03	Formation of glacial channels	Shaft seal
2.1.05.04	Alteration of drift and shaft seals	Shaft seal, drift seal
2.1.07.01	Convergence	Shaft seal, drift seal
2.1.07.02	Fluid pressure	Shaft seal, drift seal
2.1.07.04	Volume changes in materials – not thermally induced	Shaft seal, drift seal
2.1.07.07	Displacement of shaft seal	Shaft seal
2.1.08.08	Swelling of bentonite	Shaft seal
2.1.09.02	Solution and precipitation	Shaft seal, drift seal
2.1.09.06	Corrosion of materials with cement or magnesium oxychloride phases	Shaft seal, drift seal
2.2.01.01	Excavtion damaged zone	Shaft seal, drift seal
2.2.06.01	Change of stresses	Shaft seal, drift seal

Less likely FEPs

FEP-No.	FEP-Name	Affected geotechnical barrier
2.1.07.05	Early failure of a shaft seal*	Shaft seal
2.1.07.06	Early failure of a drift seal*	Drift seal
2.1.08.05	Piping in seals	Shaft seal, drift seal

*incl. malfunction caused by insufficient construction process

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(4d) Actions & design situations - VSG

No.	Name of action
Chemical actions	
1.	Chemical actions induced by solutions and gases
2.	Chemical actions induced by temperature change
Mechanical actions	
1.	Effects due to forces and stresses
1.1	Dead load
1.2	Rock pressure
1.3	Fluid pressure
1.4	Flow forces
1.5	Restraint stresses
1.6	Mass forces (earthquakes)
2.	Effects due to impressed strains
2.1	Thermal expansion/contraction
2.2	Swelling/shrinking
2.3	Creep/relaxation
2.4	Restraint strains (deformation constraints, settling)

DIN EN 1990, DIN EN 1997 …

Design situation	Characteristic conditions
Transient situations*	Temporary, normal situations, e.g. construction process
Persistent situations*	Normal situations according to normal function and use
Abnormal (accidental) situations**	Rare, mostly extraordinary situations, e.g. accidental situations as impacts or explosions
Seismic situations (earthquakes)***	Short, limited in time, design-defining earthquakes rare

* will occur ** will probably not occur ***regional differences in occurrence

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(4e) Linkage of FEPs, actions & design situations

FEP-No.	FEP-Name	Classification within the functional proof*
1.2.03.01	Earthquake	DS, seismic DS; A, mass forces
1.2.09.01	Diapirism	A, restraint strains
1.2.09.02	Subrosion	Excluded, because significance starts with next glaciation (after selected performance period)
1.3.05.03	Formation of glacial channels	Excluded, because significance starts with next glaciation (after selected performance period)
2.1.05.04	Alteration of drift and shaft seals	A, consequence of chemical action incl. temperature
2.1.07.01	Convergence	A, equivalent to rock pressure due to constitutive equation
2.1.07.02	Fluid pressure	A, fluid pressure
2.1.07.04	Volume changes in materials – not thermally induced	A, swelling/shrinking
2.1.07.07	Displacement of shaft seal	A, restraint strains or a consequence of forces/stresses
2.1.08.08	Swelling of bentonite	A, swelling
2.1.09.02	Solution and precipitation	A, consequence of chemical action incl. temperature
2.1.09.06	Corrosion of materials with cement or magnesium oxychloride phases	A, consequence of chemical action incl. temperature
2.2.01.01	Excavation damaged zone	Neither DS, A nor R but component of the seal
2.2.06.01	Change of stresses	A, dead load, rock pressure, fluid pressure, flow forces, restraint stresses

* If classification is impossible or meaningless, a comment is given

FEP-No.	FEP-Name	Classification within the functional proof
2.1.07.05	Early failure of a shaft seal	DS, abnormal situation
2.1.07.06	Early failure of a drift seal	DS, abnormal situation
2.1.08.05	Piping in seals	A, consequence of chemical actions or flow forces

Classification of FEPs within the technical functional proof

DS = design situation
A = action
R = resistance

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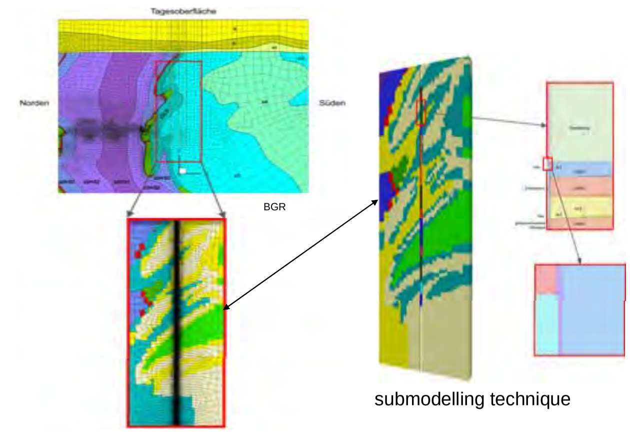
(4f) Calculations - VSG



submodelling technique

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(5) Detailed design

- Insignificant modifications of basic design
- ➢ Ready to start construction process

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Results – Integrity of Shaft Seal

- Individual proofs to guarantee integrity were successful regarding relevant combinations of thermal, mechanical, and chemical actions
- Thus, the prognosis that hydraulic resistance as planned will really be achieved shows high level of reliability
- Pre-condition: Highly qualified construction process
- “As built” and “as planned” may be different!

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Conclusions & Outlook

- Regarding VSG shaft seal linkage of safety case & technical functional proof was successfully put into practice
- Progress has been made
  - Individual technical proofs forged ahead
  - Technical specifications are available forming the basis for suitability tests
  - Technical basis to establish quality assurance procedures is available
- Open questions
  - Assessing the influence of contact zones/interfaces
  - Especially experimental data is still rare

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Acknowledgements

Many thanks

- to my colleagues Michael Breustedt, Dieter Buhmann, Oliver Czaikowski, Hans-Joachim Engelhardt, Horst Jürgen Herbert, Christian Lerch, Michael Linkamp, Klaus Wieczorek, Johanna Wolf, Mingliang Xie for their contributions to VSG work package 9.2 - Integrity of geotechnical barriers -
- to my collegues from BGR, BfS, DBE, GRS, IfG, Asse–GmbH (former HMGU & GSF), IBeWa, TU Clausthal for their collaboration
- to the Federal Ministry for the Environment, Nature Conservation, Building, and Nuclear Safety (BMUB) for funding the project

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Thank you
for your attention!

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Salt Reconsolidation Principles and Application

5th US/German Workshop on
Salt Repository Research, Design and Operations

Santa Fe, New Mexico, USA

September 7-11, 2014

Frank Hansen--Sandia National Laboratories, Albuquerque New Mexico USA

Till Popp--Institut für Gebirgsmechanik (IfG), Leipzig, Germany

Klaus Wieczorek--Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Braunschweig, Germany

Dieter Stührenberg--Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany

Abstract

Mechanical and hydrological properties of reconsolidating salt are functions of porosity which decreases as the surrounding salt formation creeps inward and compresses granular salt within the rooms, drifts or shafts. Construction circumstances within a vertical shaft provide substantial advantage for dynamic compaction techniques capable of creating high emplacement density and low initial porosity. Placement of granular salt in a horizontal drift suffers from a less favorable construction orientation and may yield lower emplaced density and significant initial porosity for its evolutionary evaluation. Drift placement of granular salt is expected to function as a low-porosity, low-permeability structural element with vital repository performance expectations. The material covered in this presentation demonstrates collaboration on a key technical issue to establish the state-of-the-art for a Salt Club report. It provides a review of essential aspects of engineering barriers of low-porosity crushed salt, which will continue to consolidate and decrease permeability.

The current state of knowledge benefits from large amounts of pertinent information on granular salt reconsolidation ranging over a length scale from atomic spacing to tens of meters. However, repository applications are concerned with very long time periods and in some cases properties of reconsolidating salt are predicted to occur far into the future after initial placement. Extrapolation based on modeling is often invoked to estimate engineering performance beyond the human experience, which by its very nature introduces an element of uncertainty. Construction techniques capable of emplacing granular salt seals, perhaps with additives, to near final performance conditions greatly reduce the need for extrapolation. Much of the potential performance uncertainty can be removed by deepening the mechanistic understanding through continued research and additional validation garnered from analogues from industry practice and nature.

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Salt Reconsolidation Principles and Application

Frank Hansen--Sandia National Laboratories, Albuquerque New Mexico USA

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5th US/German Workshop on Salt Repository Research, Design and Operations

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Presentation Content

- Background
- Micromechanics--hydro-mechanical interactions
- Experimental salt reconsolidation mechanics
- Transport properties of compacted crushed salt
- Natural analogues--Field-scale observations--Applications
- Perceptions--Future work

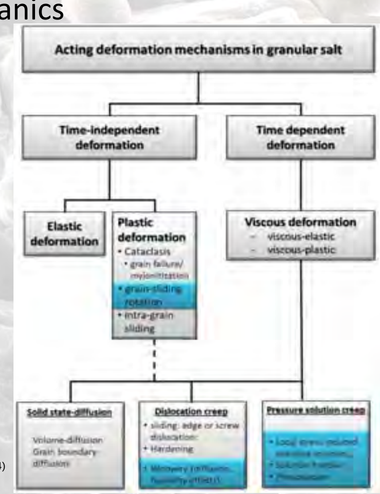
2

Background—Role of Reconsolidated Salt

- Act as a long-term barrier against inflowing brine or water and eliminate release pathways via drifts and shafts
- Conduct heat generated by radioactive decay from the waste to the host rock
- Stabilize repository excavations
- Provide low permeability and/or diffusivity and/or long-term retardation
- Key questions involve how, when, and to what degree properties of reconsolidating granular salt approach or attain those of the native salt formation

3

Micromechanics



Note/Source: (modified after Elliger, 2004)

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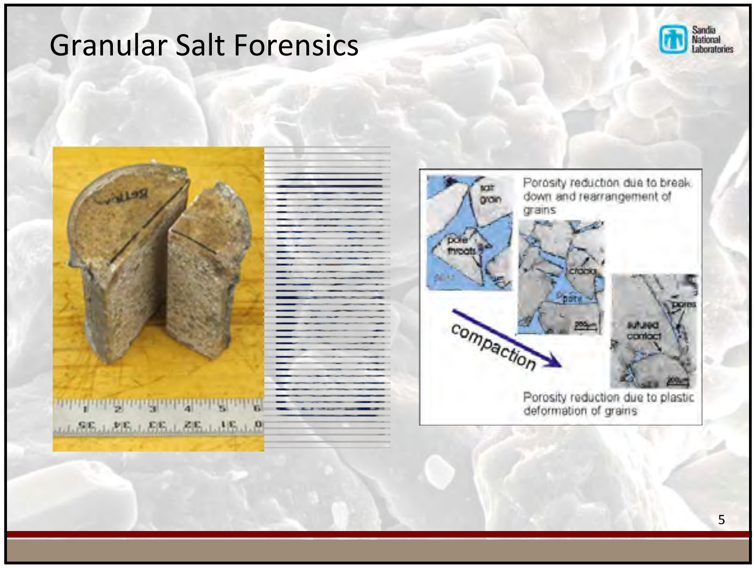
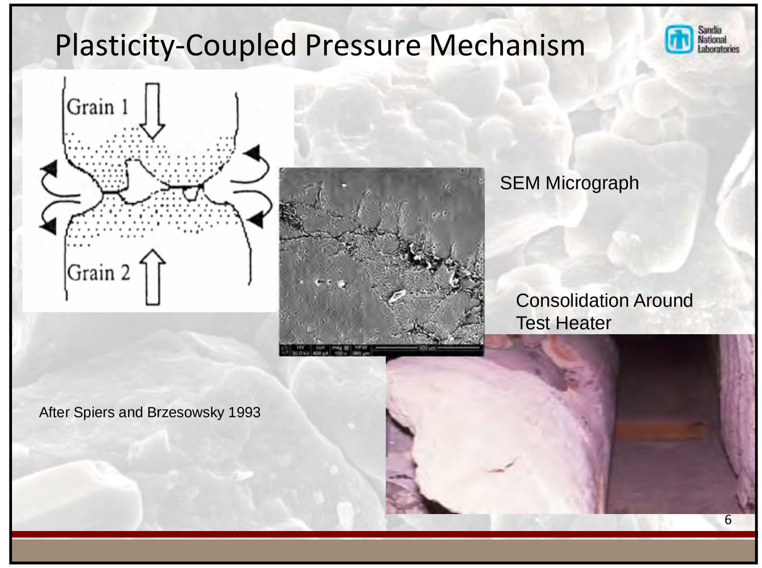
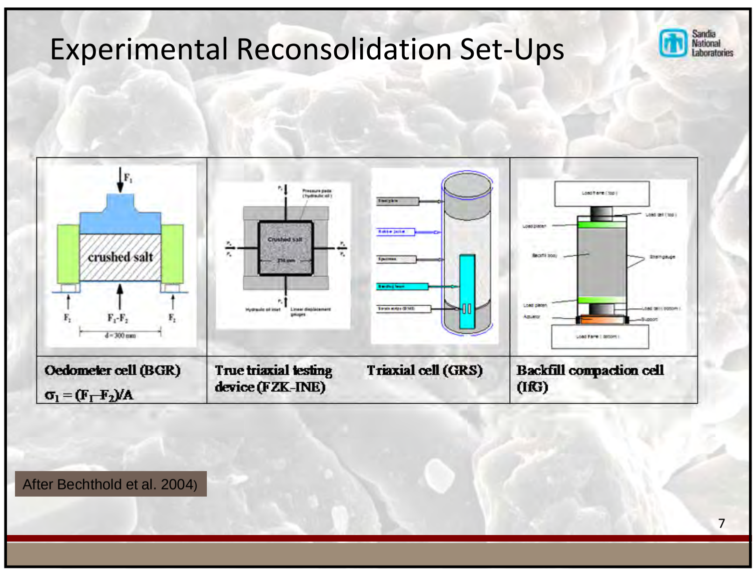
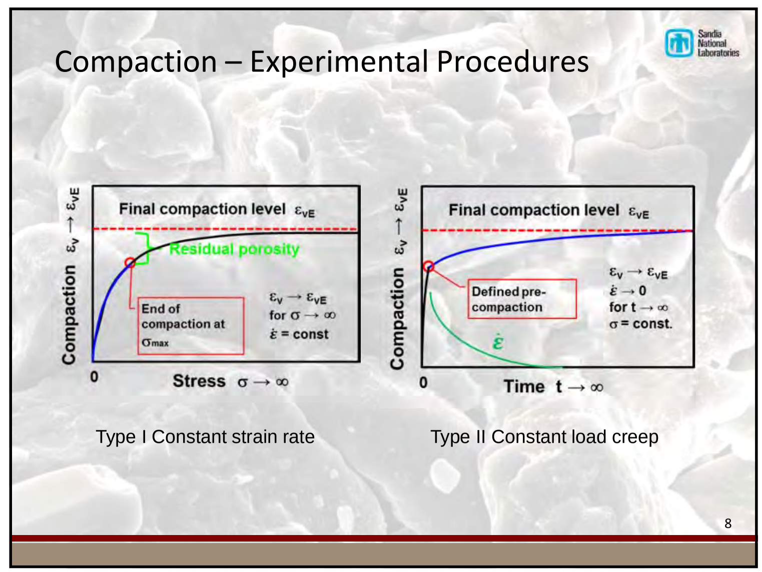
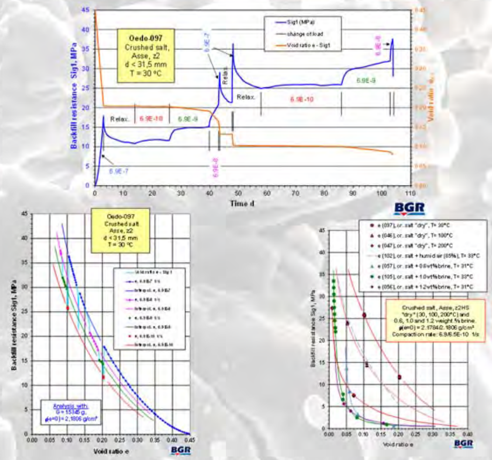

Granular Salt Forensics
Porosity reduction due to break down and rearrangement of grains
salt grain
pore throats
cracks
pore
sutured contact
pores
compaction
Porosity reduction due to plastic deformation of grains
5


Plasticity-Coupled Pressure Mechanism
Grain 1
Grain 2
SEM Micrograph
Consolidation Around
Test Heater
After Spiers and Brzesowsky 1993
6


Experimental Reconsolidation Set-Ups
crushed salt
Oedometer cell (BGR)
$\sigma_1 = (F_1 - F_2)/A$
True triaxial testing device (FZK-INE)
Triaxial cell (GRS)
Backfill compaction cell (IfG)
After Bechthold et al. 2004)
7

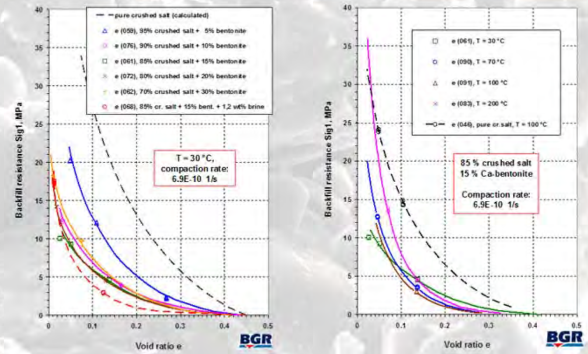

Compaction – Experimental Procedures
Final compaction level ε_{vE}
Residual porosity
End of compaction at σ_{max}
$\varepsilon_v \rightarrow \varepsilon_{vE}$ for $\sigma \rightarrow \infty$ $\dot{\varepsilon}$ = const
Compaction $\varepsilon_v \rightarrow \varepsilon_{vE}$
Stress $\sigma \rightarrow \infty$
Defined pre-compaction
$\varepsilon_v \rightarrow \varepsilon_{vE}$ $\dot{\varepsilon} \rightarrow 0$ for $t \rightarrow \infty$ σ = const.
Time $t \rightarrow \infty$
Type I Constant strain rate
Type II Constant load creep
8

Consolidation under Oedometer Test Conditions



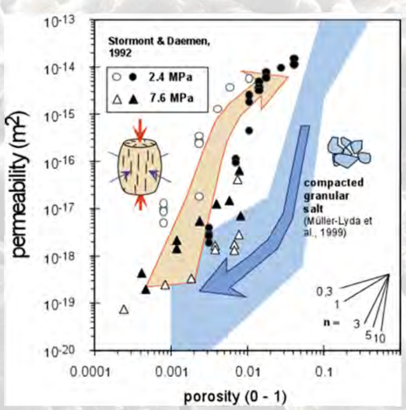
9

Impact of Additives on the Compaction Behavior



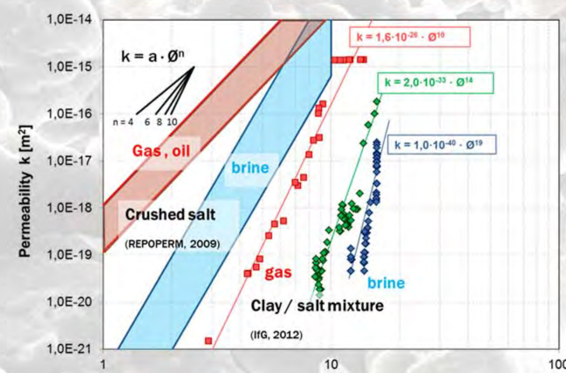
10

Permeability-Porosity Relations of Dilating Rock Salt and Reconsolidating Granular Salt



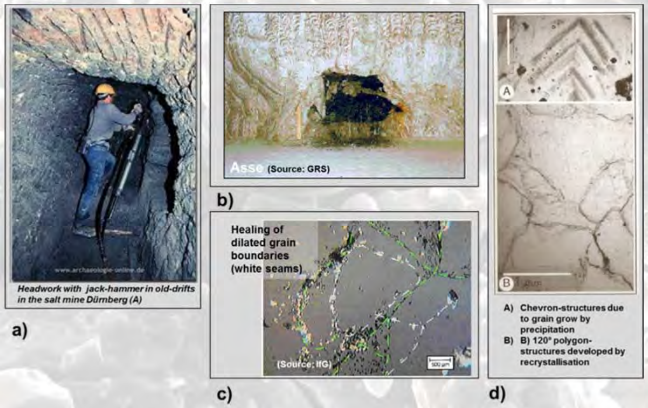
11

Permeability-Porosity Data Sets for Crushed Salt Aggregates

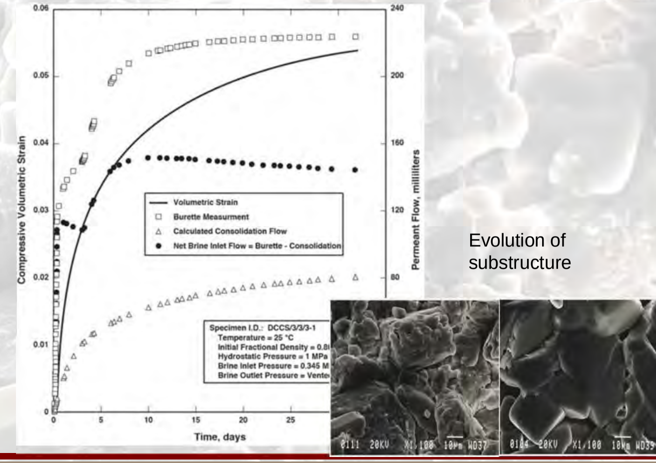


12

Summary of Analogues



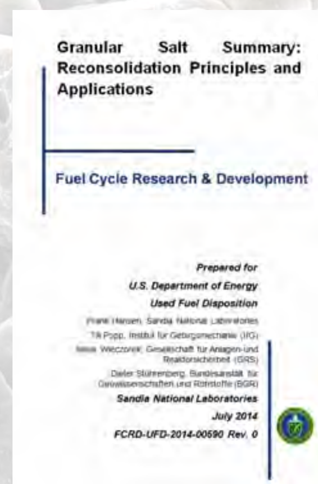
Volumetric Strain and Brine Flow Measurements



Perceptions--Future Work

- What final porosity of crushed salt is necessary to achieve an efficient seal and at which time can it be reached?
- Capability of additives such as moisture and clay can be optimized for construction and attainment of sealing properties
- The nature of testing fluids (brine or gas) and the resultant permeability/porosity relationships warrant further examination
- Numerical modeling provides capabilities but lacks low porosity verification
- Further analogue experience from underground sources is imperative

Used Fuel Report



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U.S. DEPARTMENT OF ENERGY NNSA

Discrepancy between modeling and measurement in the realization of seals

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Outline

- Pre-conditions & pilot seals in Germany
- Goals of the Asse seal project
- Test field & in situ investigations
- Calculation procedure and results
- Comparison of calculated and measured stresses
- Evaluation and conclusions 2008 & 2014

Pre-conditions

Pilot seal → but very few are realized

(1) Measuring data must be available
(2) Calculation results suitable for comparison must be available
(3) Good documentation status
(4) Advantageous: Finished project to avoid change of interpretation subsequently
(5) Measuring data as well as calculation results must be publicly available
(6) How to report about discrepancies between measurements and calculations?

Pilot seals in Germany

Projects:

- Shaft seal Salzdetfurth
- Asse-seal (Asse-Vordamm)
- Asse pilot flow barriers (PSB A1 and PSB A2)
- ERAM plug
- other seal projects (CARLA, Sondershausen)

→ Asse-seal is chosen for example
→ All reports were published in the framework of VSG thanks to BMUB and BfS

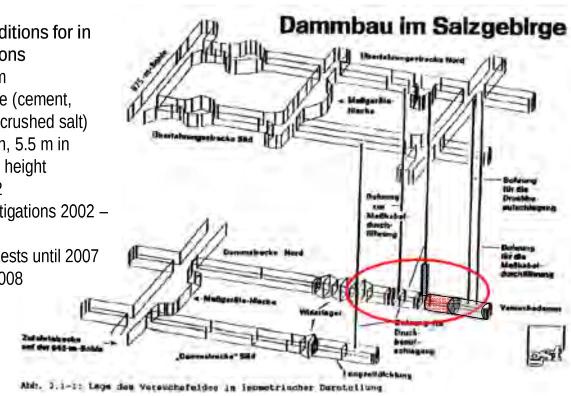
Goals of the Asse-seal Project (2001 - 2008)

"In context with the closure of the Morsleben repository (ERAM) the potential migration of brine and gas passing salt-concrete seals has to be evaluated. According to present knowledge the contact zone between the sealing body and the surrounding rock is an important migration path and thus is decisive for the permeability of the seal. In order to show that the hydraulic conductivity of the seal is sufficiently small, the permeability of the contact zone has to be quantified. Respectively, it has to be shown that no defects exist in the contact zone leading to an intolerable degree of permeability of the seal, i.e. exceeding a permeability of 10^{-18} m^2 on average. According to technical regulations in Germany investigations on comparable structures are required to assess the tightness of contact zones.

For this purpose a 10-year-old salt-concrete seal in the Asse mine in Lower Saxony has been investigated, whose structure is comparable to the seals planned for the ERAM. This seal had been built within the framework of an abandoned research project. A detailed investigation concept comprising in-situ measurements and laboratory tests was developed and a method has been established to transfer the boundary conditions of the Asse mine to the ERAM, where the seals will be constructed. " Source /Contribution WM-5233, Waste Management Conf. 2005/

Pilot seal test field

Boundary conditions for in situ investgations
- Depth 945 m
- Salt concrete (cement, NaCl-brine, crushed salt)
- 8 m in length, 5.5 m in width, 3.4 in height
- Built in 1992
- In situ investigations 2002 – 2004
- Laboratory tests until 2007
- Reporting 2008

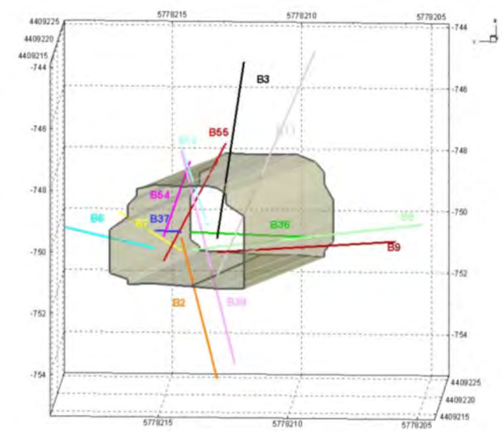


In situ investigations

- Permeability tests at representative measuring positions (mainly contact zone)
- Ultrasonic measurements covering the whole contact zone to underpin representativeness of permeability tests
- Hydrofrac-measurements to determine present stress state to asses stress and deformation history in order to transfer results to ERAM conditions

- Additionally, long-term measurements (temperature, deformation, stress) at the pilot seal test field were available because the test field was included into geotechnical surveillance of the Asse mine

Borehole positions

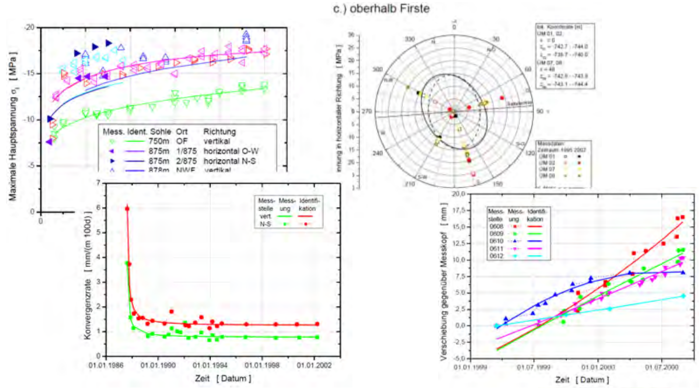


Permeability:
all boreholes

Hydrofrac:
B2, B3, B6,
B7, B8, B9,
B11, B38

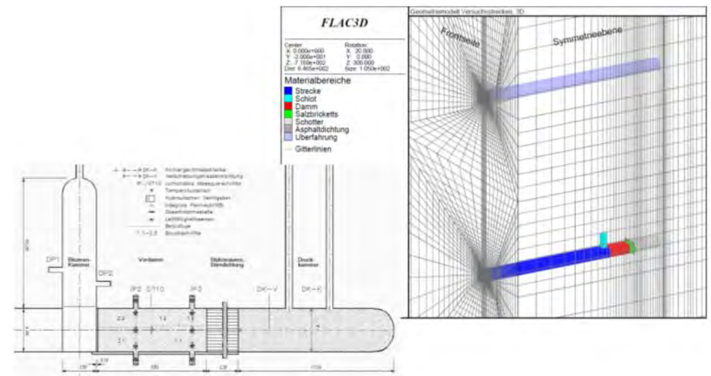
Calibration of calculation model

- Calibration of the calculation model of the test field using geotechnical surveillance measurements



Calibration of calculation model

- A large number of variants were calculated and ranked against each other

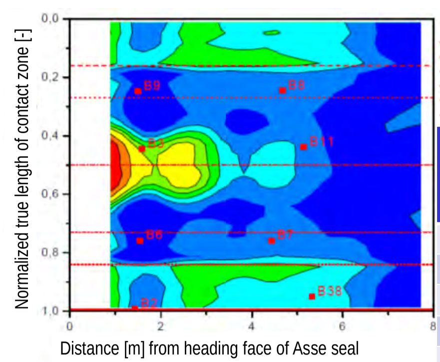


Calibration of calculation model

- The "best fit" was not unique
- Three "best fits" showing a slight anisotropy
- The influence of boundary conditions was negligible (sf/uf)

Variant	Boundary conditions		Stress component [MPa]			Stress invariants [MPa]	
	stress	displ.	σ_{xx}	σ_{yy}	σ_{zz}	σ_0	σ_{eff}
M32	sf	uf	-20	-20	-20	-20	0
M27	sf	uf	-18.0	-20.0	-20.0	-19.3	2,00
M41	sf	uf	-18.5	-19.0	-20.0	-19.2	1.32
M29	sf	uf	-17.0	-17.5	-19.6	-18.0	2.39
M35	sf	-	-15.0	-17.0	-19.0	-17.0	3.46
M15	-	uf	-15.0	-16.0	-20.0	-17.0	4.58

Calculated vs. measured stress (hydrofrac)

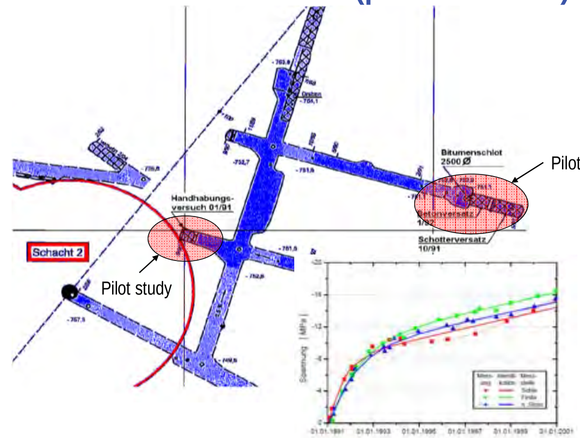


Pos.	Meas. values	Calculated variants		
		mean	max.	min.
B2	3.45	-16,2	-15.5	-17.2
B3	n. m.	-14.0	-13.5	-14.9
B6	2.53	-17.3	-16.9	-18.2
B7	6.93	-16.3	-15.8	-17.4
B8	13.09	-16.4	-15.9	-17.5
B9	6.64	-18.1	-17.6	-19.1
B11	2.05	-17.5	-16.8	-18.3
B38	15.59	-15.7	-14.9	-16.6

Calculated vs. measured stresses (hydrofrac)

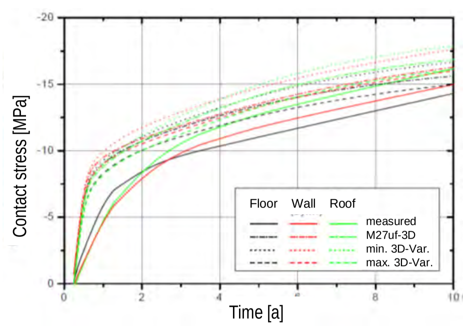
- Approximately comparable calculated stresses at similar positions, only slight deviations due to anisotropic stress boundary conditions
- Wide range of measured stresses (hydrofrac) at comparable positions
- Large discrepancies between calculated and measured stresses, good agreement only at 2 (out of 8) positions (B8 and B38)
- Explanation?

Stress measurements (pressure cells)



Measured stresses (pressure cells) in contact zone of pilot study

Calculated vs. measured stress (pressure cells)



Good agreement of calculated and measured stress

Explanation: The direction of least principal stress and contact stress is not identical!

Evaluation & conclusion 2008

- The discrepancy between calculated and measured stresses (hydrofrac) lead to detailed investigations
- Fortunately, additional stress measurements (pressure cells) were available
  - Applying pressure cells the direction of measured stress is fixed, the stress component within the stress tensor may vary
  - Applying hydraulic fracturing the least principal stress is measured, the direction may vary
  - Calculated stresses and measured stresses from pressure cells agree well
  - Hydraulic fracturing shows wide range of least principal stresses and varying directions in the contact zone
- ➢ In 2008 permeability was assumed to be constant material property → The goals of the Asse seal project were successfully achieved showing a sufficiently low permeability of the contact zone

Evaluation & conclusion 2014

- Review of 2008 results: The discrepancy itself was explained but the origin of the wide range and varying directions hydrofrac measurements is still an open question
- Residual stresses from construction process ?
- Restraint stresses due to different material properties of salt concrete sealing body and surrounding rock salt?

➢ **From todays knowledge this aspect needs further investigation as permeability of tight and damaged rock salt depends – due to strong hydromechanically coupling - on the effective least principal stress**

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Acknowledgements

Many thanks

- **to my colleagues F. Gläß, R. Mauke, G. Eilers, J. Preuss from BfS for their contributions**
- **to my colleagues from Asse–GmbH (former HMGU & GSF), IBeWa, KUTEC, GMuG, DMT, IfG for their collaboration**
- **to the BfS for funding the project**

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**Thank you
for your attention!**

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Summary and open questions of the VSG

Jörg Mönig

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Theodor-Heuss-Str. 4, 38122 Braunschweig, Germany

Preliminary Safety Analysis of the Gorleben Site

Basics	site characterisation and long-term prediction waste characterization and quantity safety concept and demonstration concept
Repository design	repository concept repository design and optimisation
System analyses	FEP catalogue and scenario development integrity assessment geol. /geotechnical barrier assessment of RN release scenarios human intrusion scenarios
Synthesis	assessment of results recommendations

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

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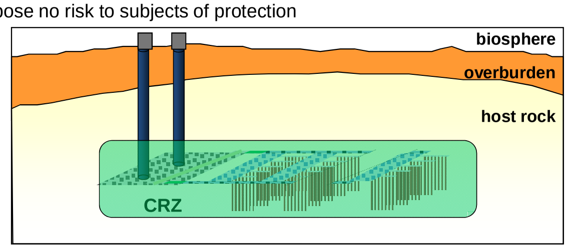
Safety and Demonstration Concept

The post-closure safety concept focusses on safe containment

- **Safe containment** describes the status of the repository system in which there is at the most an insignificant release of radionuclides from the containment-providing rock zone (CRZ) during the demonstration period
- An **insignificant release** from the CRZ is a release whose radiological consequences calculated by a biosphere model are below permissible limits and thus pose no risk to subjects of protection



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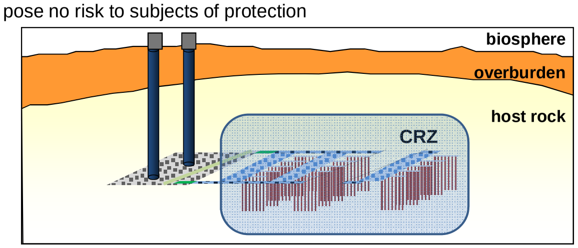
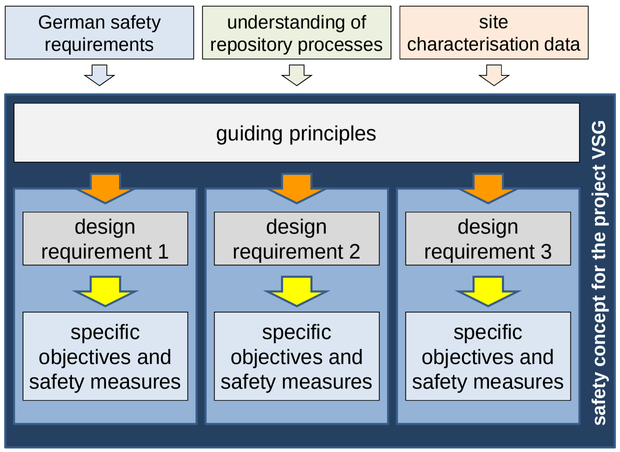


Systematic derivation of the Safety Concept



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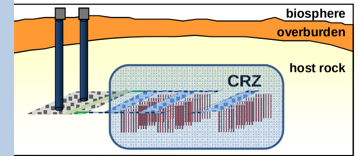
System analysis

Main questions addressed

- Will the integrity of the salt barrier remain intact under the expected loads (thermal impact, glacial cycles, etc.)?
- Will significant amounts of brine reach the waste emplacement areas?
- Will radionuclides be released from the waste?
  - ➢ If yes, will they be released from the CRZ?
  - ➢ And if so, what radiological consequences have to be expected?



- Answers needed for all probable and less probable scenarios
  - ➢ Distinction is required by German regulation
- Scenarios are systematically identified and described by using FEPs

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Some important results (I)

Integrity of rock salt barrier

- Thermo-mechanical calculation show that dilatancy and brine pressure criterion is temporarily violated at top of salt dome due to thermal stresses.
- Above the repository, several 100 m of rock remain without integrity violation
- EDZ: Local violations of the dilatancy criterion (several cm – approx. 3 m).
- Temperature criteria for carnallitite are met (no thermal disintegration)

Fluid-dynamic system evolution

- Significant gas release from waste with negligible heat evolution, affecting the pressure regime in emplacement area for HLW (→ optimization)
- Pore volume in a number of emplacement drifts for HLW will become solution-saturated, depending on boundary assumptions for model calculations

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Some important results (II)

Radionuclide release from CRZ

- solution pathway
  - no RN release from CRZ at 1% final porosity in crushed salt backfill
  - Insignificant release at 2% final porosity
- 2-Phase modelling (3D)
  - Independent of final porosity relevant C-14-release in the gas phase via drift seal
  - Gas formation enhances gas flow through compaction
  - Crushed salt reconsolidation due to salt creep is main driving force for gas flow
  - Results are affected by location of individual waste forms (→ optimization)

Methodological approaches, in general, have been applied successfully & are considered to be applicable for other sites with domal (bedded) rock salt

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Important scientific issues to revisit

Process understanding

- Re-consolidation of crushed salt backfill, transport relevant properties at low porosities
- 2-phase-flow behaviour (model parameters) in consolidating crushed salt backfill
- Release Mechanisms of volatile radionuclides from waste forms

Safety significance of hydrocarbons present in rock salt

Suitability of methodological approach to scenario development

Relevance of processes not dealt with

Preliminary Safety Analysis of the Gorleben Site

Basics	site characterisation and long-term prediction	GRS-273, GRS-275
	waste characterization and quantity	GRS-274, GRS-278
	safety concept and demonstration concept	GRS-271, GRS-277
Repository design	repository concept	GRS-272, GRS-279
	repository design and optimisation	GRS-281
System analyses	FEP catalogue and scenario development	GRS-282, GRS-283, GRS-284
	integrity assessment geol. /geotechnical barrier	GRS-286, GRS-288
	assessment of RN release scenarios	GRS-289
	human intrusion scenarios	GRS-280
Synthesis	assessment of results	GRS-290
	recommendations	GRS-304

VSG Reports (I)

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-277: Sicherheits- und Nachweiskonzept (*replaces GRS-271)*

GRS-278: Abfallspezifikation und Mengengerüst: Basis Ausstieg aus der Kernenergienutzung (u*pdate of report GRS-273 after Fukushima*)

GRS-279: Einschätzung betrieblicher Machbarkeit von Endlagerkonzepten

VSG Reports (II)

GRS-280: Human Intrusion

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: Integritätsanalyse der geotechnischen Barrieren – Teil 1: Vorbemessung

VSG Reports (III)

GRS-288: Integritätsanalyse der geotechnischen Barrieren – Teil 2: Vertiefte Nachweisführung

GRS-289: Radiologische Konsequenzenanalyse

GRS-290: Synthesebericht

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

Reflections on the ISIBEL Project and Perspectives on Modeling Salt Reconsolidation

R. Chris Camphouse

Sandia National Laboratories†, Carlsbad, NM, 88220

ABSTRACT

The thrusts of R&D project ISABEL were to summarize the state of the art in high level waste (HLW) disposal in salt and to determine if the demonstration of HLW disposal in salt is technically feasible. The repository concept envisioned in the ISABEL project took full advantage of the favorable properties associated with salt formations, and their benefits in regard to underground waste disposal. The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, has been developed by the U.S. Department of Energy (DOE) for the geologic (deep underground) disposal of transuranic (TRU) waste. U.S. legacy TRU waste is transported to the WIPP facility and interred underground in a bedded salt formation. The bedrock upon which WIPP performance assessment (PA) sits is an understanding of the features, events, and processes (FEPs) that must be considered when quantifying repository performance. From these FEPs, scenarios are developed that represent the state of the repository for undisturbed and disturbed conditions. Numerical models provide responses of the repository over the set of scenarios, where epistemic and aleatory uncertainties are captured through sampling. Results are tabulated and assembled into curves that are then compared to regulatory compliance limits. The safety and demonstration concept developed as part of the ISIBEL project has many components in common with those used for the WIPP. As the ISIBEL concept provides a framework for a HLW repository in salt, many physical processes important to the ISIBEL project are those important to the WIPP project as well. Comparisons are made of the ISIBEL and WIPP projects, highlighting areas in which these projects are similar as well as ways they are different.

As part of the ISIBEL concept, void volume in emplacement areas and mine workings are to be filled with crushed salt, which will naturally compact due to creep closure of the surrounding salt rock. The ability of the reconsolidated crushed salt to provide sufficient sealing must be demonstrated. Recently, the temporal and physical characteristics of run-of-mine (ROM) salt reconsolidation were investigated as part of a proposed WIPP component design change. The 1998 rulemaking that certified WIPP to receive TRU waste placed conditions on the waste panel closure design to be implemented in the repository. The engineering of the panel closure has been re-assessed, and a revised design has been established that is simpler, cheaper, and easier to construct. It consists of 100 feet of ROM salt with barriers at each end. The ROM salt is generated from ongoing mining operations at the WIPP and may be compacted and/or moistened as it is emplaced in a panel entry. The representation of ROM salt reconsolidation in WIPP PA was a result of an iterative process with the federal regulator, the U.S. Environmental Protection Agency (EPA). The DOE has submitted a planned change request to the EPA, seeking regulatory approval to replace the currently mandated panel closure design with the ROM salt design. The modeling approach used for ROM salt reconsolidation, and insights gained from the regulatory change process, are discussed.

† *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.* **SAND2014-16786A.** This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy.

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This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S Department of Energy.

Outline

- ISIBEL and WIPP Common Ground
- Compare/Contrast the ISIBEL safety demonstration concept and WIPP PA – Methodologies, FEPs, Scenario Development, Uncertainty
- Discussion of the salt reconsolidation approach taken for a recent WIPP design change – Processes Modeled, Temporal Behavior, Regulator Interactions
- Conclusions

2

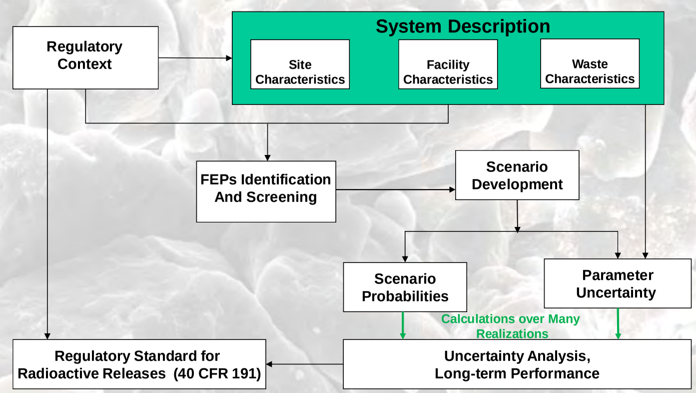
Common Ground

The ISIBEL repository concept and the WIPP have many common aspects.

- Both are underground waste disposal facilities in salt
- Both repositories have been designed to take advantage of salt properties
- Salt reconsolidation processes are important in ISIBEL (backfilled mine workings) and the WIPP (panel closures)
- WIPP PA is established and in use. ISIBEL safety demonstration capability is drafted with future work defined

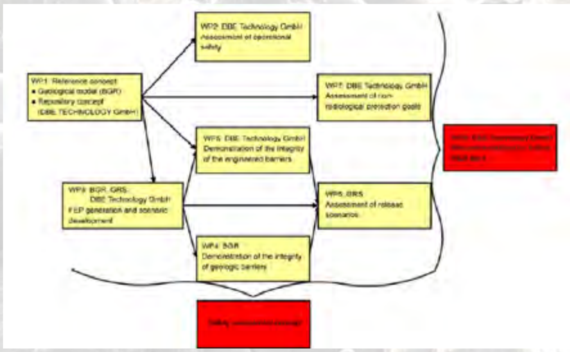
3

WIPP Performance Assessment



4

ISIBEL Safety Demonstration Concept



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Bedrock of WIPP PA and ISIBEL

Fundamental to WIPP PA and the ISIBEL safety demonstration concept are:

- A catalog of the features, events, and processes (FEPs) that must be considered
  - screening process → what needs to be considered and what doesn't
- Repository scenarios, informed by the set of FEPs, that capture future states of the repository
  - undisturbed and disturbed conditions
- Proper consideration of uncertainty
  - parameters, models, facility futures

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ISIBEL FEPs

The Gorleben site was used to develop a generic FEP catalog for salt formations.

Iterative approach:

- A comparison with the NEA-FEP database, with an emphasis on salt as the host rock
- A bottom-up approach identifying all FEPs relevant to the future evolution of the repository
- A top-down approach identifying FEPs that could play a role in conceivable scenarios
- FEPs added to represent interdependencies between FEPs found above

FEPs catalog evaluated in the course of a national peer review. Catalog consists of 92 probable and 4 less probable FEPs.

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FEPs Screening for WIPP

WIPP FEPs are screened according to:

- Probability: If a FEP has a probability of occurring less than 10^{-4} in 10,000 years it does not have to be included in PA (e.g., meteorite impact)
- Consequence: If a FEP is beneficial to performance, is not relevant to WIPP, or has a insignificant consequence to the disposal system, it does not have to be included in PA (e.g. lakes, oceans, tides, floods). If a FEP is related to the WIPP disposal system and/or impacts the repository, it must be accounted for in PA (e.g., chemical effects of corrosion).
- Regulation: Certain FEPs are either screened in or out by regulation (e.g., mining, resource extraction following drilling).
- 245 FEPs were screened in for the most recent WIPP compliance calculation.

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ISIBEL/VSG Scenario Development

Possible repository futures categorized as probable, less probable, and improbable.

- Binning of futures results in one reference scenario and 17 alternative scenarios
- Reference scenario represents probable repository futures
  - includes climate change (100,000 year cycle), waste heat generation, mobilization and transport, initial barrier integrity
- Alternative scenarios differ in only one aspect from the reference scenario
  - improvised barrier functionality, less probable mobilization and transport, etc.

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WIPP Scenario Development

- All retained (screened-in) FEPs must be accounted for in WIPP PA in at least one scenario.
- FEPs can be included by explicit modeling or by parameter assignment.
- Expected FEPs are included in all scenarios
  - Creep closure
  - Brine flow, gas generation
- Disruptive FEPs are included in disturbed scenarios.
  - Drilling, mining, brine pocket

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Uncertainty

Proper representation of uncertainty is vital to WIPP PA and the ISIBEL safety demonstration concept.

- Uncertainties reduced by information gained via site characterization
- Data generated by individual R&D programs can reduce uncertainty and inform parameter distribution assignments
- Uncertainties with regard to future events must be represented
- Uncertainty distributions used for parameter sampling may be iterated with or prescribed by the site regulator

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WIPP Panel Closure Redesign

The waste panel closure implemented in WIPP has recently been redesigned.

- Current design based on Salado Mass Concrete was mandated by the EPA as part of their 1998 WIPP certification decision
- Redesigned panel closure consists of 100 feet run-of-mine (ROM) salt with barriers at each end – termed the ROMPCS
- Including the ROMPCS in WIPP PA required spatial and temporal modeling of ROM salt reconsolidation
- ROMPCS modeling in WIPP PA was a negotiated process with the EPA – federal rulemaking process

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ROMPCS Processes

The representation of the ROMPCS in WIPP PA needed to account for several physical processes.

- Creep closure of the surrounding salt rock resulting in consolidation of ROM salt placed in panel entries
- ROM salt comprising the closures approaching a condition similar to intact salt
- Imposed back stress on the surrounding rock resulting in eventual healing of the surrounding salt rock

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ROMPCS Evolution

The ROMPCS is modeled as having short-term and long-term characteristics in WIPP PA, with properties based on three time periods

- 0 to 100 years: Emplaced ROM salt undergoes some re-consolidation with no impact on surrounding salt rock
- 100 to 200 years: ROMPCS continues to re-consolidate with no impact on surrounding salt rock
- 200 to 10000 years: ROMPCS is re-consolidated and the surrounding salt rock is healed

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Regulator Interaction

The approval of the ROMPCS design by the EPA regulator is slated to appear in the Federal Register soon.

- Federal rulemaking aspect of design change invoked a lengthy and involved process for the regulator
- Good communication with the EPA was critical in gaining their approval of the new design
- Representation of spatial and temporal ROMPCS behaviors was an iterative process – consensus between EPA and DOE
- Extensive support of EPA verification calculations increased regulator comfort with the new design
- Regulatory comfort in the new design → stakeholder defense

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Conclusions

- The ISIBEL repository concept and the WIPP have many aspects in common.
  - repositories in salt rock, taking advantage of physical and temporal salt characteristics
- FEPs, repository scenarios, and consideration of uncertainty are fundamental to the WIPP and ISIBEL safety demonstrations.
- The spatial and temporal behaviors of "loose" salt are important to ISIBEL and the WIPP
  - Backfill of mine workings for ISIBEL
  - WIPP panel closures
- Modeling of ROM salt has recently been undertaken, with consensus by the EPA, for a WIPP design change

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PA Development (PFLOTRAN) and the Safety Case

Glenn Hammond

Sandia National Laboratories

Abstract:

This presentation introduces the massively-parallel, reactive multiphase flow and transport code PFLOTRAN and describes Sandia's recent enhancements to the code that enable its use within nuclear waste repository performance assessment models. Code capability and infrastructure support are briefly outlined followed by a presentation of the conceptual model description and simulation results for a generic salt repository performance assessment model.

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.
SAND2014-17007A

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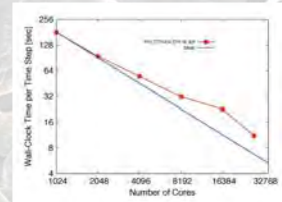
PA Development (PFLOTRAN) and the Safety Case

Glenn Hammond

Sandia National Laboratories

PFLOTRAN

- Petascale reactive multiphase flow and transport code
- Open source license (GNU LGPL 2.0)
- Object-oriented Fortran 9X/2003/2008
  - Pointers to procedures
  - Classes (extendable derived types with member procedures)
- Founded upon PETSc parallel framework
  - Parallel communication through MPI
  - Parallel I/O through binary HDF5
  - Unstructured domain decomposition through METIS/ParMETIS (Cmake)
- Demonstrated performance
  - Maximum # processor cores: 262,144 (Jaguar supercomputer)
  - Maximum problem size 3.34 billion degrees of freedom
  - Scales to over 10K cores



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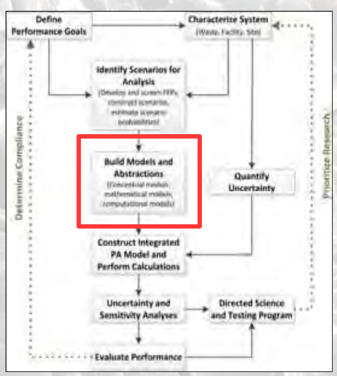
Role of PFLOTRAN in PA Methodology

PA Methodology



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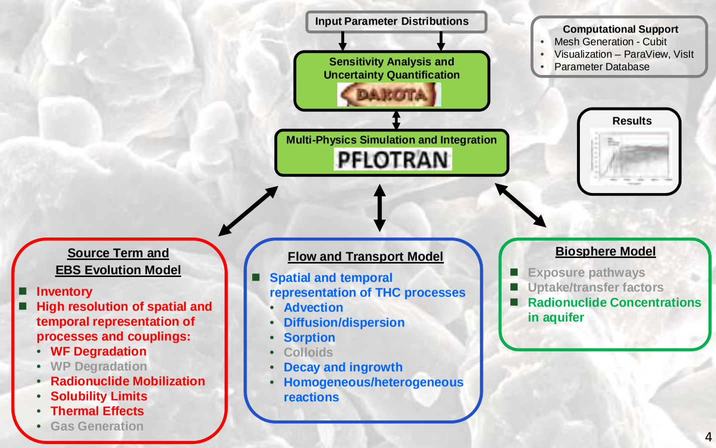

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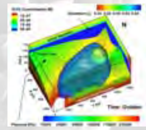
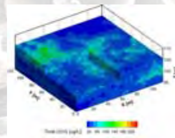
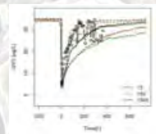
PFLOTRAN Multi-Physics Capabilities

- Flow
  - Multiphase gas-liquid
  - Interchangeable constitutive models and equations of state
- Energy
  - Thermal conduction and convection
- Multi-Component Transport
  - Advection, hydrodynamic dispersion
- Geochemical Reaction
  - Aqueous speciation (ion activity models)
  - Mineral precipitation-dissolution
  - Surface complexation, ion exchange, isotherm-based sorption
  - Radioactive decay with daughter products



Hammond and Lichtner, WRR, 2010





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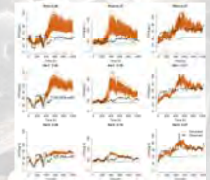
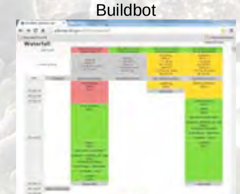
PFLOTRAN Computing Capabilities

- High-Performance Computing (HPC)
  - Increasingly mechanistic process models
  - Highly-refined 3D discretizations
  - Massive probabilistic runs
- Open Source Collaboration
  - Leverages a diverse scientific community
  - Sharing among subject matter experts and stakeholders from labs/universities
- Modern Fortran (2003/2008)
  - Domain scientists remain engaged
  - Modular framework for customization
- Leverages Existing Capabilities
  - Meshing, visualization, HPC solvers, etc.
  - Configuration management and QA

Data Assimilation



Buildbot



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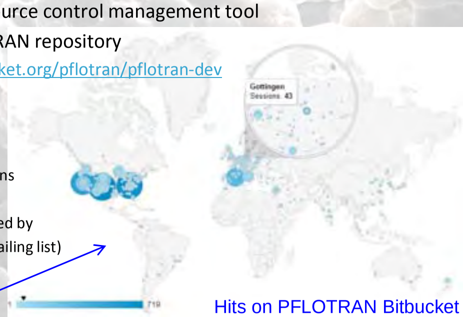
PFLOTRAN Support Infrastructure

- **Mercurial:** distributed source control management tool
- **Bitbucket:** online PFLOTRAN repository
  - hg clone https://bitbucket.org/pflotran/pflotran-dev
  - Source tree
  - Commit logs
  - Wiki
    - Installation instructions
    - Quick guide
    - FAQ (entries motivated by questions on mailing list)
  - Change requests
  - Issue tracker
- **Google Analytics:** tracks behavior on Bitbucket
- **Buildbot:** automated building and testing (regression and unit)
- **Google Groups:** pflotran-users and pflotran-dev mailing lists



Hits on PFLOTRAN Bitbucket site over past year

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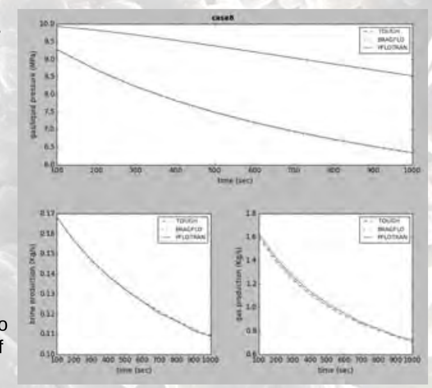
PFLOTRAN Verification

- Test cases for WIPP codes (BRAGFLO and NUTS) set up and executed with PFLOTRAN
  - E.g., BRAGFLO Case #8 "Well production at a specified bottom hole pressure"

PFLOTRAN results compared to BRAGFLO and WIPP version of TOUGH2 (TOUGH28W)



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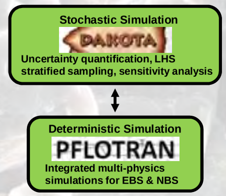
Generic Salt Repository PA Model – Simulation Summary

- DAKOTA / PFLOTRAN simulations:
  - Deterministic PA simulation with mean values
  - 100-realization probabilistic simulation with 10 sampled parameters
  - Deterministic thermal simulation
- Run on SNL Red Sky HPC cluster
  - Nested parallelism
  - Many concurrent realizations
  - Each realization distributed across many processors



- Total nodes: 2,816 nodes / 22,528 cores
- 505 TeraFlops peak

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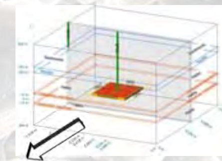
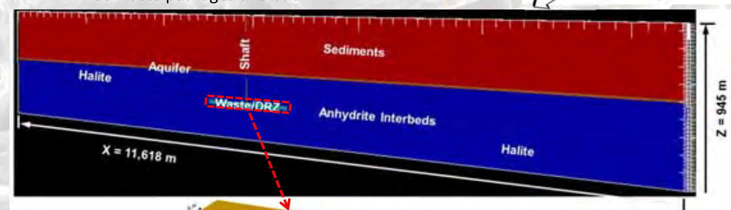
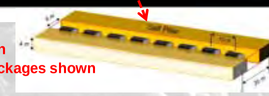
Generic Salt Repository PA Model – 3D Model Domain

- Simulation domain
  - 3D vertical slice
  - 20-m wide pillar to pillar
  - 1 drift pair (2 800-m long drifts)
    - 160 waste packages and backfill







1 of 2 drifts shown
8 of 160 waste packages shown

X = 11,618 m	NX = 455		
Y = 20 m	NY = 5		
Z = 945 m	NZ = 92		
	Cells = 209,300		

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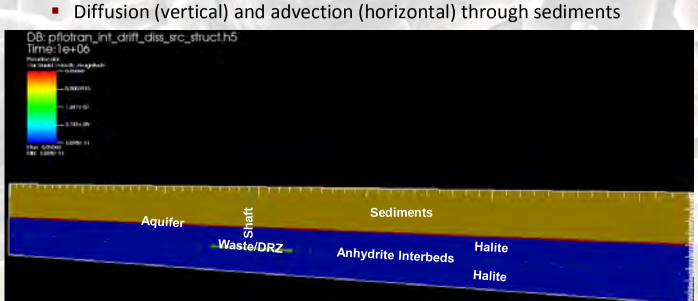
Generic Salt Repository PA Model – Deterministic Simulation Results

- Horizontal Darcy velocity (m/yr)
  - Diffusion through DRZ, bedded salt, and shaft
  - Advection (horizontal) through aquifer
  - Diffusion (vertical) and advection (horizontal) through sediments



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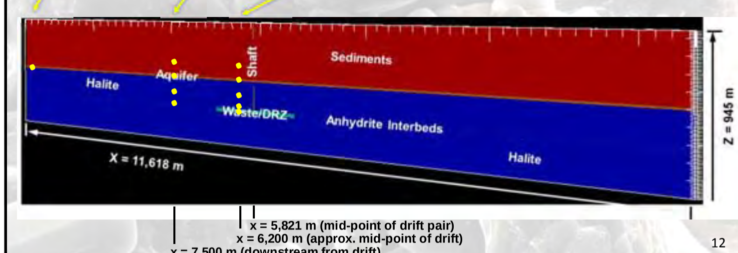
Generic Salt Repository PA Model – Probabilistic Simulations

- Sensitivity analysis (partial rank correlation) at 10 locations

"well" location (1)
- aquifer

"midx" location (4)
- sediment
- aquifer
- halite
- anhydrite

"near" location (5)
- sediment
- aquifer
- halite
- anhydrite
- waste package



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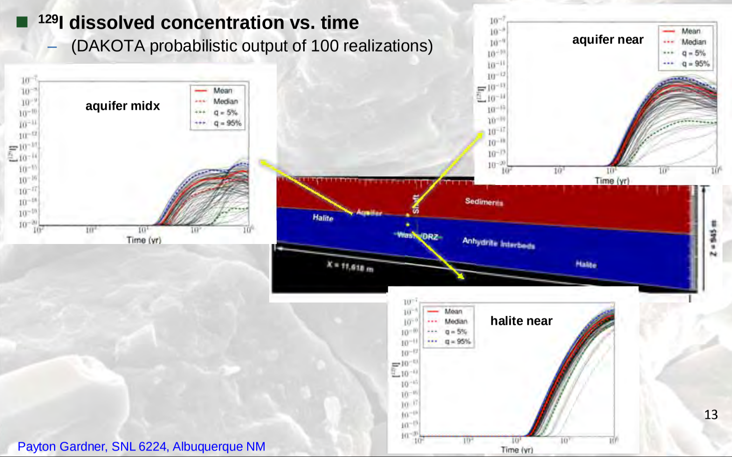
Generic Salt Repository PA Model – Multi-Realization Analysis

- ^{129}I **dissolved concentration vs. time**
  - (DAKOTA probabilistic output of 100 realizations)



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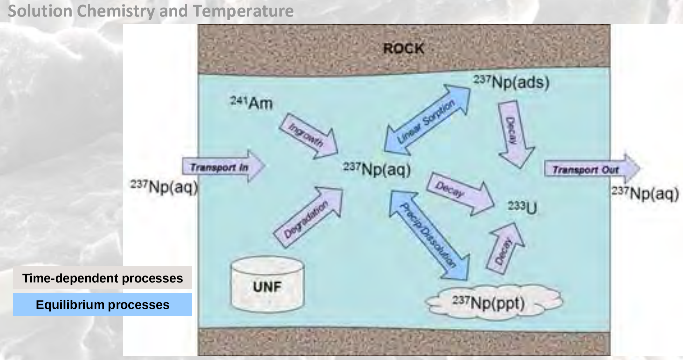
Future Directions – Coupled Radionuclide Mobilization and Transport Processes

- **Waste Form Degradation (IRF and matrix dissolution)**
- **Transport (advection, diffusion, linear sorption (K_d))**
- **Decay and Ingrowth**
- **Precipitation/Dissolution**
- Solution Chemistry and Temperature



Visualization Tool VIRTUS

Klaus Wieczorek*, Steffen Masik**, Joachim Behlau***, Christian Mueller****

*Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS) mbH, Germany
**Fraunhofer Institut fuer Fabrikbetrieb und –automatisierung, Germany
***Federal Institute for Geosciences and Natural Resources (BGR), Germany
****DBE TECHNOLOGY GmbH, Germany

VIRTUS is a “virtual underground laboratory” which can illustrate repository concepts, geologic situations and physical processes taking place in an underground lab or a repository. It centrally provides the necessary consolidated data (geologic models, mine structures, material data for numerical simulation) as well as means for the integrated visualization and evaluation of various types of information.

VIRTUS consists of a visualization software platform, material database and interfaces to CAD programs like BGR’s openGEO which provide geologic models and to process level codes (PLC) for numerical model simulations. A “hot spot” system allows easy access to all available information.

Geologic models are imported into VIRTUS, powerful editing functions allow the creation of mine structures. The resulting combined models can be exported to PLC pre-processors, where they are used as input for model calculations on the coupled thermal-hydraulic-mechanical behavior of the system consisting of waste, technical components and rock formation. The simulation results can be visualized in VIRTUS in context with the underlying geology.

The above features have been implemented. Testing and improvement are continuously performed.

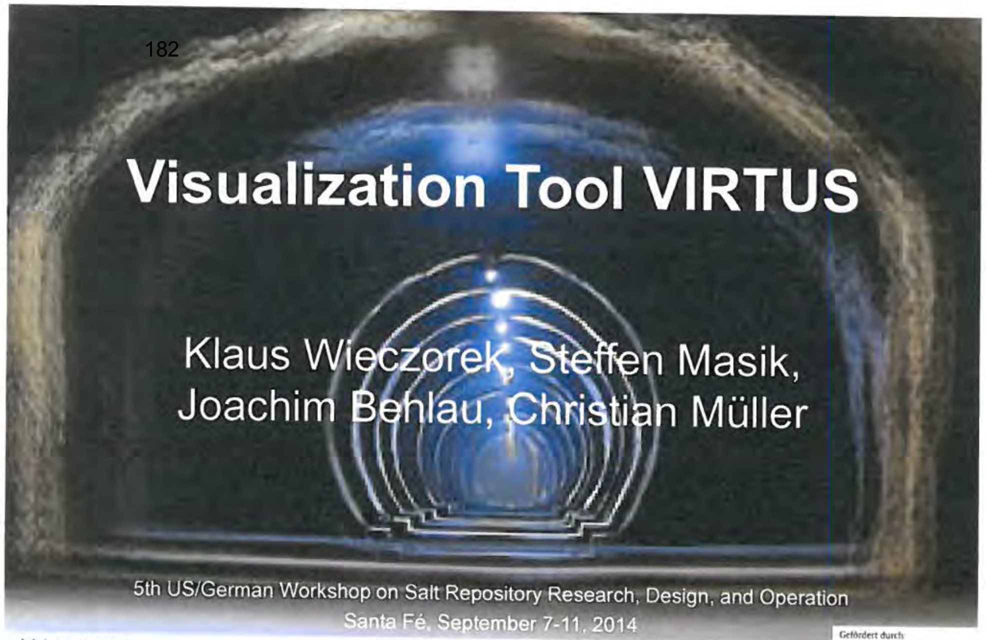
Three demonstration experiments have been defined for prototypical simulation by the partners using their individual PLCs:

- An isothermal mechanical simulation of a drift passing through different types of rock (BGR: JIFE)
- A thermal simulation of an array of emplacement boreholes (DBE TEC: FLAC^{3D})
- A coupled thermal-mechanical simulation of a heated drift in rock salt approaching a potash layer and anhydrite blocks (GRS: CODE_BRIGHT)

The geometrical models have been extracted from VIRTUS and the simulations are underway.

For a given repository or underground laboratory site, the capabilities of VIRTUS can help to facilitate design of meaningful experiments, to prepare benchmark exercises or simulation variants for optimization and compare their results, to evaluate simulation results to make sure that safety criteria are met, to design actual repository structures in a given geology, and to present repository research to the public.

VIRTUS has been developed in the frame of a joint project of the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), the Federal Institute for Geosciences and Natural Resources (BGR), the DBE TECHNOLOGY GmbH (DBE TEC), and the Fraunhofer Institut für Fabrikbetrieb und –automatisierung (IFF). The VIRTUS project is financed by the Federal Ministry of Economics and Technology (BMWi) under contract 02E10890. The current phase of VIRTUS is ending in October 2014.



A joint project of GRS BGR DBE TEC Fraunhofer IFF

Gefördert durch: Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages

What is VIRTUS?

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- It centrally provides the necessary consolidated data (geologic models, mine structures, material data for numerical simulation).
- It provides means for the integrated visualization and evaluation of various types of information.

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Concept of the "Virtual URL"

- Components:

Software platform for visualization of - geology - mine structures - THM simulation results	**Database** for material parameters - host rock - geotechnical components - waste forms	Input/output **interfaces** to process level codes (PLC)

- Features:
  - Provides combined view of URL or repository structure & processes
  - Makes available consolidated data on material behavior
  - Easy access to all information via "hot spots"

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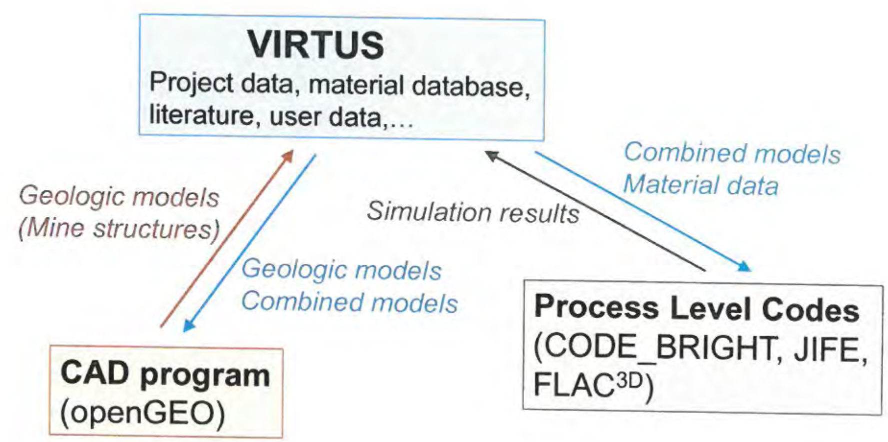
VIRTUS Data Exchange



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VIRTUS Functionality & Workflow

Import, check, and processing of the **geologic model**

→ **Mine structure** generation or import

→ Model **combination**

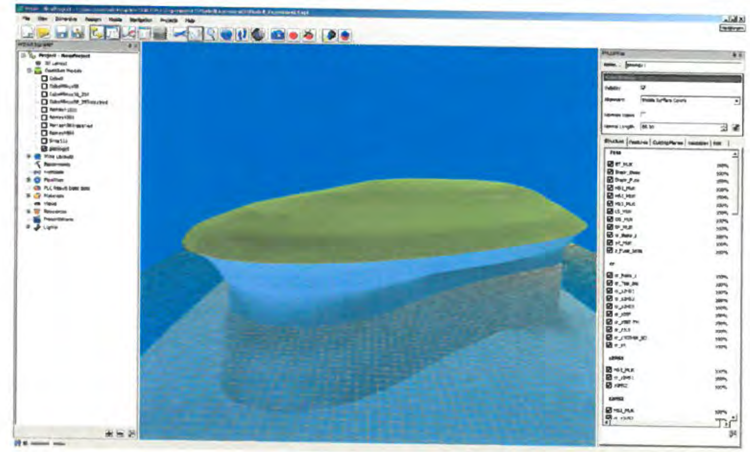
→ **Export** of model and material data **to PLC**

→ FE mesh generation and PLC simulation (outside VIRTUS)

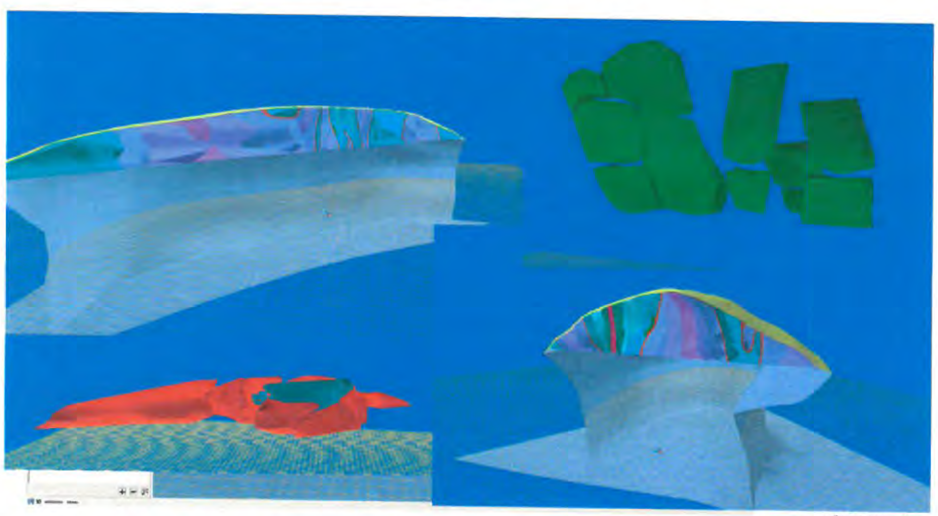
→ Import and **Visualization** of simulation results

Geology: Virtual Salt Anticline

- VIRTUS site: a synthetic geologic model



Geology: Virtual Salt Anticline

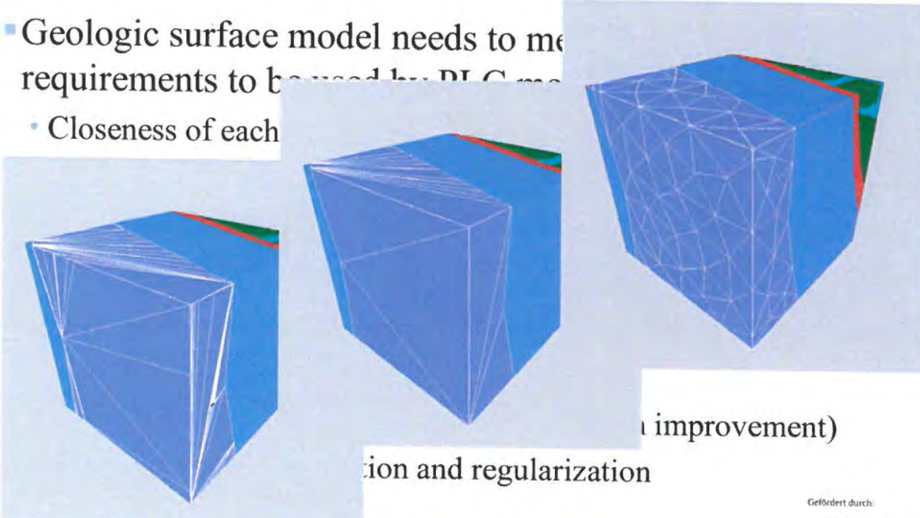


Geology: Geometry Processing

- Geologic surface model needs to meet several requirements to be used by PLC mesh generators
  - Closeness of each geologic body
  - Exclusion of interpenetration of geologic bodies
  - Area ration of large and small surface triangles
  - Balance of inner angles of the surface triangles
- Automatic processing is required
  - Removal of zero-area triangles
  - Rectification of surface normals (visualization improvement)
  - Surface mesh simplification and regularization

Geology: Geometry Processing

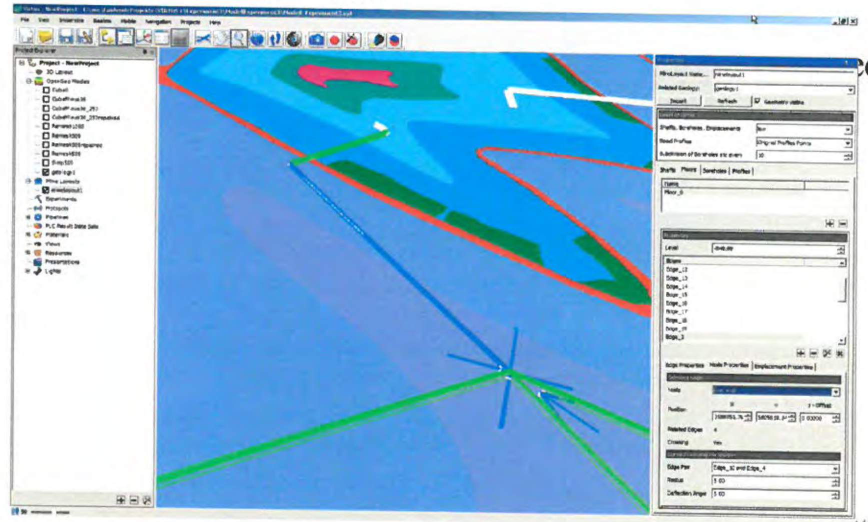
- Geologic surface model needs to me
requirements to b
  - Closeness of each



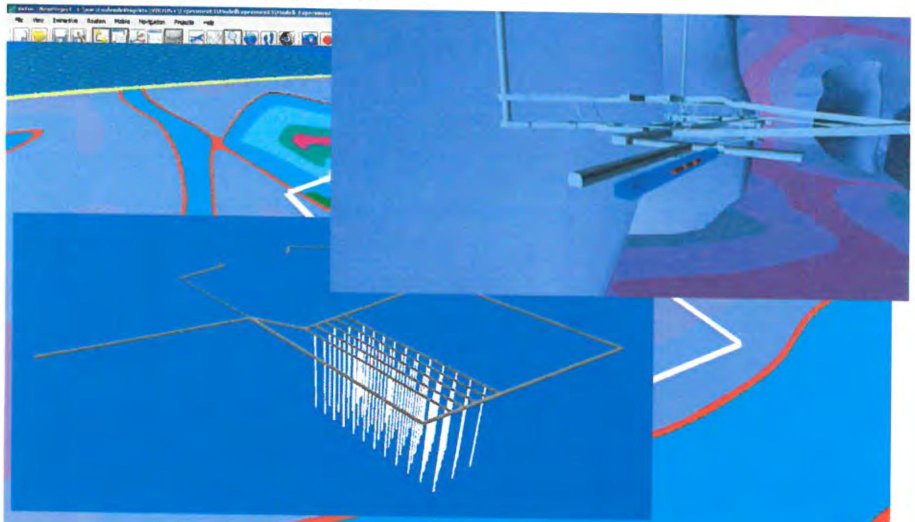
ı improvement)

:ion and regularization

Mine Structure



Mine Structure

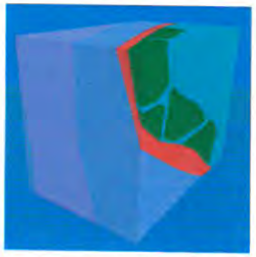


Combination of Geology and Mine

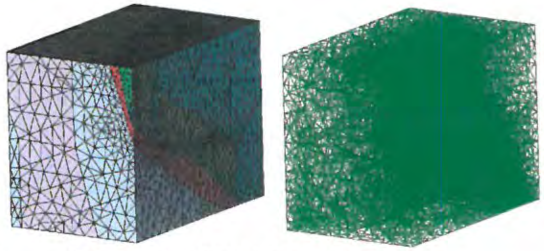
- From the separate geometric models of geology and mine structure, a combined surface model is created

Export to PLC and Meshing

- Cuboid sections from the combined model an be freely defined for export (various formats available)
- FE meshing by PLC pre-processors



Cube section from VIRTUS



FE mesh (GiD) in different representations

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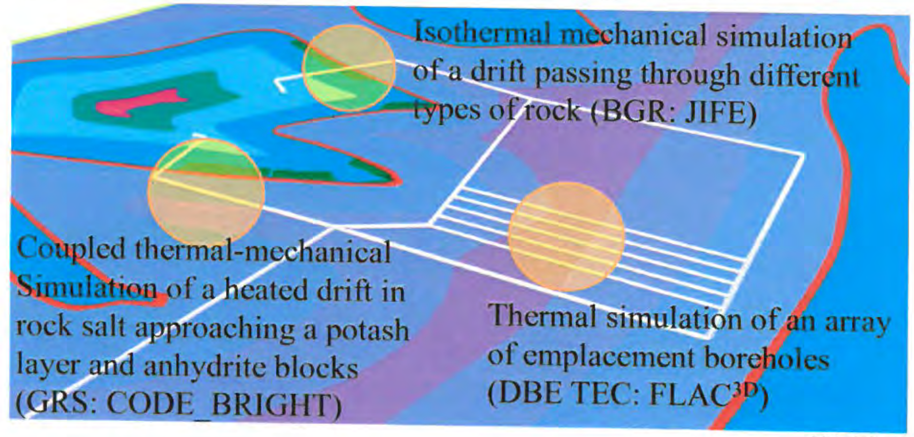
PLC Simulation

- PLC simulation of 3 demonstration experiments



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Result Import and Visualization

- Thermal data: temperature and heat flow
- Hydraulic data: fluid pressure, flow rates, saturation
- Mechanical data: stress, deformation, porosity

Result data can be

- Scalars (temperature, porosity,…)
- Vectors (heeat flow, deformation,…)
- Tensors (stress, strain,…)

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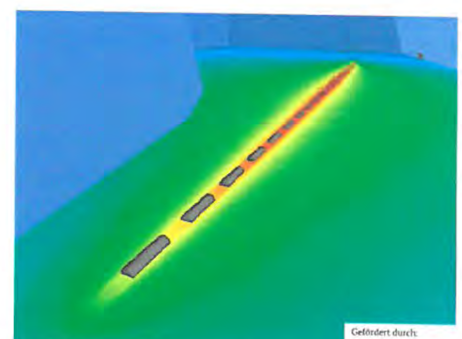
Visualization: Scalar

Temperatur field of a drift charged with 20 POLLUX containers 200 years after emplacement (red: 50°C iso-surface)



Horizontal section in the plane of the containers: temperature field

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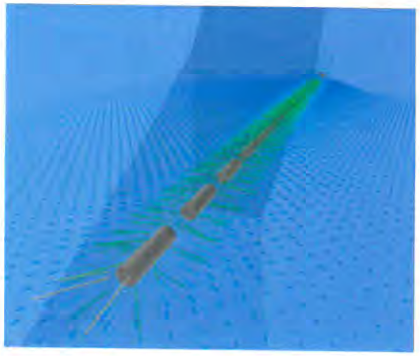
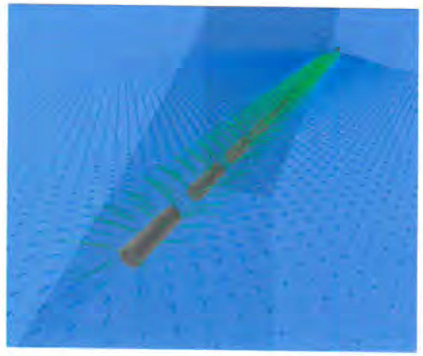
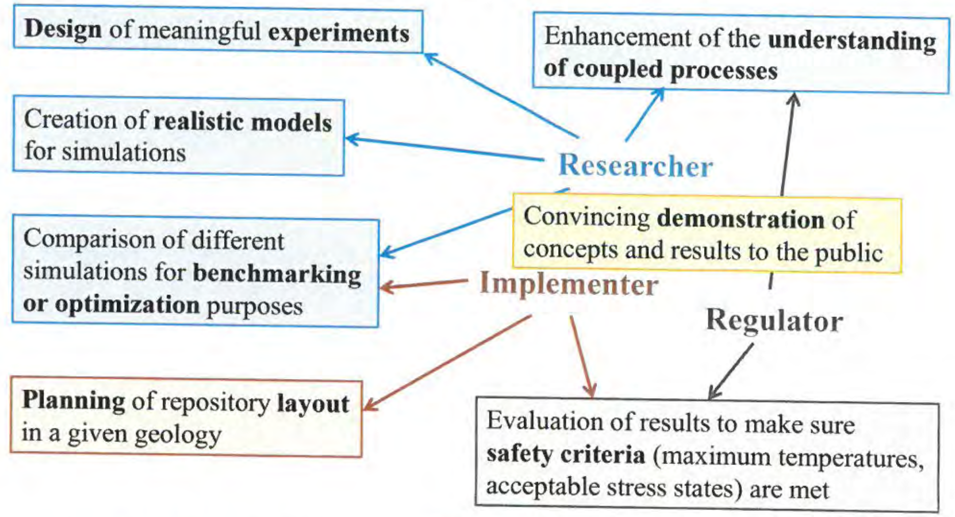
Visualization: Vector





Heat flow in horizontal section:
in container mid-plane (left) - above container plane (right)

Benefits from a Virtual URL



VIRTUS Project Partners

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
- Project management, database (with IFF)

Federal Institute for Geosciences and Natural Resources (BGR)
- Geologic models

DBE Technology GmbH
- Mine layout

GRS/BGR/DBE TEC: Material data evaluation, PLC simulation

Fraunhofer Institut fuer Fabrikbetrieb und –automatisierung (Contractor)
- Software platform
- Visualization

Status and Prospects

- The current phase of the VIRTUS project is ending in October 2014
- The VIRTUS features presented are implemented (testing and improvement is continuing)
- Simulation of three prototypical experiments is continuing
- Tools for model and result evaluation and comparison have not yet been implemented
- VIRTUS has been developed as a virtual URL in salt, but is highly flexible. Little effort is needed to use it with other geologies or other process level codes

Features, Events, and Processes (FEPs) Development Activities

Geoff Freeze[1] and Jens Wolf[2]

[1]Sandia National Laboratories, Albuquerque, NM, USA
[2]Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Germany

Abstract

Feature, event, and process (FEP) analysis and scenario development are an integral part of the iterative performance assessment (PA) process, and are used to inform the construction of post-closure PA models of SNF/HLW repositories. Uncertainty and sensitivity analyses of the results produced by those PA models indicate which FEPs are most important to post-closure repository performance. This information is then used in the next iteration to help refine the set of FEPs and scenarios, and their representation in the PA model.

FEPs have traditionally been organized using a classification scheme developed as part of Nuclear Energy Agency (NEA) International FEP Database. The NEA FEP database uses a hierarchical numbering and classification scheme that is based on two overlapping sets of categories: features (e.g., waste form, waste package, backfill, host rock, etc.) and multi-physics processes (e.g., thermal, chemical, mechanical, hydrologic). The categories are overlapping in the sense that a specific FEP (e.g., flow through the waste package) may be classified both by a feature category (e.g., waste package) and by a process category (e.g., hydrologic). As a result, related FEPs are not always mapped to the same category and it can be difficult to group and/or find all related FEPs within the FEP list. In addition, the overlapping categories sometimes lead to the creation of the same or similar FEPs under different headings.

To better inform PA modeling and safety case development, a new FEP organizational structure, the FEP classification matrix, has been developed that alleviates the issues associated with the overlapping categories and duplicative FEPs in the NEA-based classification scheme. The FEP classification matrix is based on the concept that a FEP is typically a process or event acting upon or within a feature. The FEP matrix provides a two-dimensional organizational structure consisting of a Features axis that defines the “rows” and a Processes/Events axis that defines the “columns”.

The FEP matrix approach is being applied to develop a comprehensive set of FEPs for a generic salt repository, based on the FEP experience and work carried out in the US and Germany. The ultimate goal is to populate an international FEP database for salt repositories that can promote easy searching for FEPs and pertinent information. The populated FEP matrix can be a useful tool for developing a PA model and a robust Safety Case in salt repositories.

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Features, Events, and Processes (FEPs) Development Activities

Geoff Freeze (SNL)
Jens Wolf (GRS)

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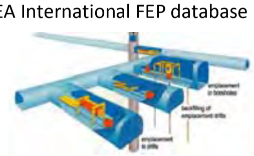
Outline

- Joint U.S.-German Objectives / Motivation
  - SNL: Geoff Freeze, S. David Sevougian, Michael Gross, Christi Leigh
    - DOE Used Fuel Disposition (UFD) Campaign
  - GRS: Jens Wolf, Jörg Mönig, Dieter Buhmann
    - Vorläufige Sicherheitsanalyse Gorleben (VSG)
- Collaborative Results to Date
  - FEP Matrix and Documentation Template
  - New FEPs: bedded salt vs. domal salt FEPs
- Future Work

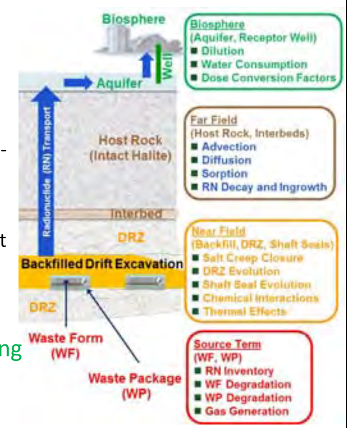
Objectives / Motivation

- U.S. – German collaboration to produce a common FEP list
  - Identify relevant FEPs for disposal of heat-generating waste (SNF and HLW) in salt
    - Applicable to all potential salt concepts and sites
  - Refine existing FEP identification and screening approaches
- Salt Club
  - Produce a FEP Catalogue for use by all NEA Salt Club members
    - Countries with potential interest in salt repositories
    - Documentation of screening decisions
  - Inform the pending update to the NEA International FEP database



FEP Analysis

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



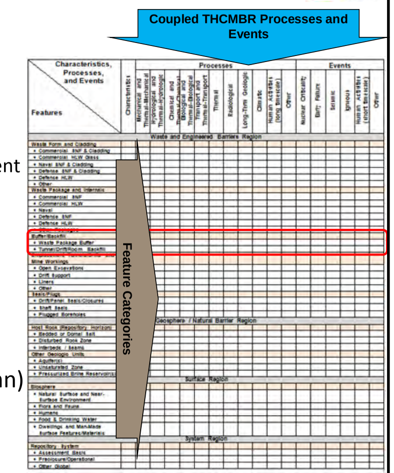
Salt FEP Identification

- US: ~200 UFD Bedded Salt FEPs (Sevougian et al. 2012)
  - Modified from generic FEPs (Freeze et al. 2011) to be more salt-specific
  - Derived from NEA FEP Database (1999, 2006)
  - Cross-checked against WIPP FEP catalogue (DOE 2009)
- Germany: ~100 Gorleben VSG FEPs (Wolf et al. 2012a,b)
  - Derived from NEA FEP Database (1999, 2006)
  - Specific to a salt dome in Northern Germany
- Combined as part of "FEP Matrix" approach (Freeze et al. 2014a,b)
  - Initial US and German FEPs mapped to FEP Matrix to eliminate redundancies
  - 5 example matrix-based FEPs created to test approach

5

FEP Matrix

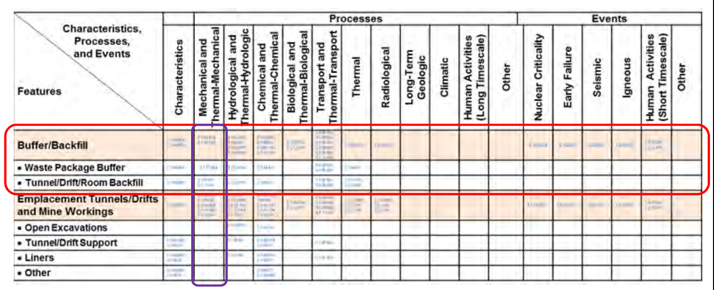
- Two-dimensional FEP organizational structure
  - Matrix Rows = Feature (and component) Categories
  - Matrix Columns = Process and Event Categories
- Matrix Cell contains all FEPs related to the "Process/Event" acting upon or within the "Feature"
- Related FEPs are grouped by Matrix Cell (or by Row or Column)
  - Not distributed among various locations as in the NEA-based hierarchical list



6

FEP Matrix

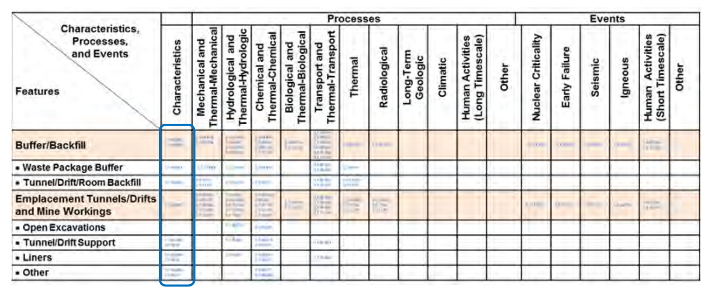
- All FEPs relevant to the Buffer/Backfill "feature"
  - Some are broadly applicable to both
  - Some are specific to the Buffer "component" or Backfill "component"
- All Thermal-Mechanical FEPs relevant to Buffer/Backfill and Emplacement Tunnels/Drifts



7

FEP Matrix

- Characteristic FEPs
  - FEPs containing properties and parameter values that describe a feature or component
    - Only one Characteristic FEP per feature/component
    - No screening for Characteristic FEPs



8

FEP Identification Scheme

- Developed a "numbering" scheme consistent with FEP Matrix
  - Alpha-numeric identifiers indicate where a FEP is mapped in the FEP matrix (e.g., row and column)
    - More descriptive than strictly numeric identifiers
    - Can still be mapped to NEA Database FEP Numbers for traceability
- FEP matrix identifiers have the form: FF.CC.PE.nn

  where:

  FF = Feature

  CC = Component (sub-feature)

  PE = Process or Event category

  nn = sequential tracking number

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FEP Identification Scheme

FF.CC.PE.nn

FF = Features:

- Waste Form: WF
- Waste Package: WP
- Buffer/Backfill: BB
- Mine Workings: MW
- Seals/Plugs: SP
- Host Rock: HR
- Other Geologic Units: OU
- Biosphere BI
- Repository System RS

CC = Components:

- Feature-level: 00
- Component-level (e.g. buffer, backfill, …): 01, 02, 03, ….

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FEP Identification Scheme

FF.CC.PE.nn

PE = Process or Event category:

Processes:

- 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

Events:

- Nuclear Criticality: NC
- Early Failure: EF
- Seismic: SM
- Igneous: IG
- Human Activities (Events): HE
- Other (Events): OE

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FEP Documentation Template

0. FEP Name and Identifier
1. Definition
2. Description and Related FEPs
   - FEP Description may subdivide into "sub-parts" A, B, C, etc.
   - 2.1 General
   - 2.2 Concept Specific (e.g., bedded salt vs. domal salt)
   - 2.3 Properties and Parameter Values
   - 2.4 Related FEPs
3. Screening Decision (by sub-part)
4. Screening Justification (by sub-part)
5. Open Issues
6. References

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FEP Documentation Template

0. FEP Name and Identifier
1. Definition
2. Description and Related FEPs
   - FEP Description may subdivide into "sub-parts" A, B, C, etc.
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   - 2.2 Concept Specific (e.g., bedded salt vs. domal salt)
   - 2.3 Properties and Parameter Values
   - 2.4 Related FEPs
3. Screening Decision (by sub-part)
4. Screening Justification (by sub-part)
5. Open Issues
6. References

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Matrix-Based FEPs – Issues for Bedded vs. Domal Salt

- Filling in the whole matrix with fully described FEPs needs a lot of resources
- "Product" for Salt Club
- Both countries are in a site selection process
- Develop new example matrix-based FEPs that highlight areas where there are differences between bedded salt and domal salt
- Improve template regarding screening decisions and screening justifications

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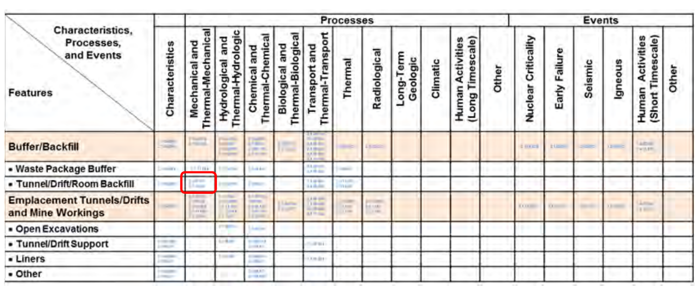
Example Matrix-Based FEP

- BB.02.TM.01 – Mechanical effects on Backfill or from Backfill



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Screening decisions

- Included – FEP is almost certain to be included, independent of the type of salt site or specific site characteristics.
- Excluded – FEP that is almost certain to be screened, independent of the specific salt site
- Site-Specific – FEP requires a substantial amount of detailed information for a specific site evaluation
- Design-Specific – FEP requires detailed information for a specific repository design.
- Evaluate – FEPs are candidates for quantitative sensitivity analyses

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Example Matrix-Based FEP

- BB.02.TM.01 – Mechanical effects on Backfill or from Backfill

ID	Description of Process	Screening Decision	
		Bedded Salt	Domal Salt
A	Compaction or Reconsolidation of Backfill	Included	
	(A_1) An eventual moisture content in backfill may increase the convergence rates		Included
	(A_2) Internal pressure in a segment influences the convergence process		Included
B	Back-Stress from Backfill		
	(B_1) The presence of backfill will generate mechanical loads on the drift walls, slowing convergence of the drifts.	Included	Included
	(B_2) The presence of backfill will generate mechanical loads on drift and borehole liners, and on the waste packages if the packages are placed directly on the floor of the emplacement drifts or	Evaluate	Likely Excluded
	(B_3) The presence of backfill will generate mechanical loads on the tops of waste containers if the containers are placed in short boreholes in the floor or ribs of a drift.	Likely Excluded	Likely Excluded
C	Non-Thermally-Induced Volume Changes		
	(C_1) Swelling of corrosion products	Likely Excluded	Likely Included
	(C_2) Crushing of backfill grains	Evaluate	Evaluate
D	Roof Collapse	Likely Excluded	Likely Excluded

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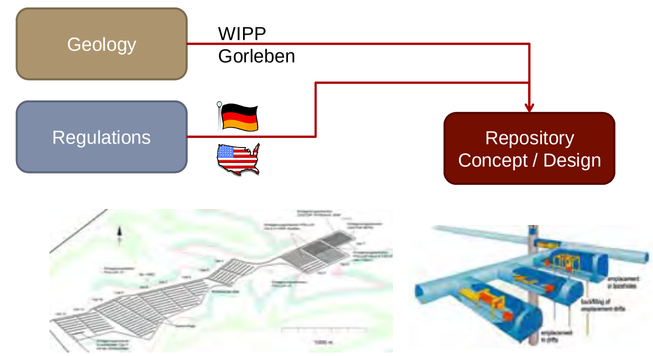
Matrix-Based FEPs – Issues for Bedded vs. Domal Salt



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Matrix-Based FEPs – Issues for Bedded vs. Domal Salt

- 13 new example FEPs
  - HR.01.CP.01 Stratigraphy and Properties of Bedded and Domal Salt
  - HR.02.CP.01 Stratigraphy and Properties of Disturbed Rock Zone
  - HR.03.CP.01 Stratigraphy and Properties of Interbeds and Seams
  - RS.00.CP.01 Repository Design
  - WP.00.TC.01 Gas Generation at Waste Packages
  - MW.00.TH.01 Gas Generation in Emplacement Drifts
  - MW.00.HE.01 Human Intrusion into the Emplacement Drifts
  - SP.02.TM.01 Mechanical Effects on Shaft Sealing
  - HR.02.TM.01 Evolution of the DRZ
  - HR.00.OP.01 Alteration and Evolution of Flow Pathways in Host Rock
  - HR.00.TM.01 Mechanical Effects on Host Rock
  - HR.00.TT.01 Advection of Dissolved Radionuclides in Host Rock
  - HR.00.TT.02 Diffusion/Dispersion of Dissolved Radionuclides in Host Rock

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Example Matrix-Based FEP

- HR.00.TT.01 Advection of Dissolved Radionuclides in Host Rock

ID	Description of Process	Screening Decision	
		Bedded Salt	Domal Salt
A	Advection of Dissolved Radionuclides	Included	Evaluate
B	Transport Through Fractures	Included	Evaluate
C	Channeling Flow	Likely Excluded	Likely Excluded
D	Viscous Fingering	Excluded	Excluded

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Future Work

- Salt FEP Catalogue
  - FEP identification and documentation ongoing
    - Joint U.S.-German collaboration
    - Preamble completed
    - Focus on FEPs where there are differences between bedded and domal salt → Salt Club report
    - Schedule (???-2015?)
  - FEP screening process
    - FEPs vs. scenarios
- Two-Dimensional FEP Matrix Approach
  - Groups related FEPs in a single location (i.e., cell, row, or column)
  - Provides an intuitive alpha-numeric identification scheme
  - Supports safety assessment and safety case development by promoting easy searching of FEP Catalogue to find related issues
  - Present to NEA FEP Working Group in Oct 2014

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Electronic FEP Database

- To be developed (future work?)
- e.g. Qt (C++ GUI library) / Postgres SQL / MySQL

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Acknowledgement

Supported by:

Federal Ministry of Economics and Energy

on the basis of a decision by the German Bundestag

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

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IGD-TP Joint activity: Handling of uncertainties

US-German Workshop on Salt Repository Research
September 7-12, 2014
Santa Fe, New Mexico, USA

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

Abstract

IGD-TP was founded as a technology platform for Implementing Geological Disposal of Radioactive Waste in Europe, in order to co-ordinate R&D activities, demonstrate technology and safety and underpin the development of a common European view on the related issues. Non-European countries are welcome to participate. The IGD-TP Strategic Research Agenda (SRA) defines several topics of specific interest; topic 1.3 specifically addresses sensitivity and uncertainty analysis. According to this demand, a Joint Activity (JA) was defined, titled “Handling of Uncertainties in the Safety Case for Deep Geological Repositories”. To work on this issue, a Technical/Scientific Working Group (TSWG) was founded, currently consisting of 14 organizations from 10 European countries and the USA; further participants are welcome. The work of the TSWG is expected to lead to an EC-co-ordinated international project. The presentation explains the goals of the Joint Activity and its current status.

IGD-TP Joint activity: Handling of uncertainties

Dirk-A. Becker, Ulrich Noseck, GRS

September 9, 2014

2014 US/German Workshop on Salt Repository Research, Design, and Operation

Santa Fe

Background: IGD-TP

Implementing **G**eological **D**isposal of Radioactive Waste – **T**echnology **P**latform

www.igdtp.eu

"Our vision is that by 2025, the first geological disposal facilities for spent fuel, high-level waste and other long-lived radioactive waste will be operating safely in Europe."

Goals

- implementation-oriented R&D activities on all remaining key aspects of deep geological disposal of spent fuel and long-lived radioactive waste
- demonstration on the technologies and safety
- underpin the development of a common European(*) view on the main issues related to the management and disposal of waste

Founded as a European Technology Platform (ETP) to

- provide a framework [...] to define research and development priorities, timeframes and action plans on a number of strategically important issues
- play a key role in ensuring an adequate focus of research funding on areas with a high degree of industrial relevance
- address technological challenges that can potentially contribute to a number of key policy objectives

(*)Non-European countries are welcome to participate!

IGD-TP Strategic Research Agenda (SRA): Key Topics

1. Safety case
   - 1.1 (HP): Increase the confidence in, testing and further refinement of the tools (concepts, definition of scenarios and computer codes) used in licensing safety assessments
   - 1.2 (HP): Improving safety case communication
   - 1.3 (MP): Increase the confidence in and further refinement on how to make sensitivity and uncertainty analyses
2. Waste forms and their behaviour
3. Technical feasibility and long-term performance of repository components
4. Development strategy of the repository
5. Operational Safety
6. Monitoring
7. Governance and Stakeholder involvment

IGD-TP Deployment Plan (DP): Joint Activities (JA)

JA types

- Organizational Working Group (ORWG)
- Technical/Scientific Working Group (TSWG)
  - developing a scientifical or technical Topic
  - preparatory work to generate a possible technical project (TEP)
  - to be initiated when the Topic's subject needs to be analyzed by a group of experts prior to being turned into a Technical Project (TEP)
  - members cover their own costs
- Information Exchange Platform (IEP)
- Technical Project (TEP)
  - activity that covers technical or scientific work on a specific SRA Topic
  - clear RD&D problem definition necessary
  - different funding models
- Technological Transfer (TT)

Both SRA and DP are being being revised and not yet available in final form!

IGD-TP Joint Activity 8

Handling of Uncertainties in the Safety Case for Deep Geological Repositories
(Former title: "Benchmarking" for confidence in long term safety in Safety Cases)

- Adresses mainly SRA topic 1.3
- Contribution to SRA topics 1.1 and 1.2
- TSWG founded

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

- TEP planned to be launched in 2015/2016

2014 US/German Workshop on Salt Repository Research, Design, and Operation 5

History of JA8 in IGD-TP

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

May 2013: 1st Meeting of interested organizations
- Foundation of a TSWG
  - ANDRA, ENRESA, Galson, GRS, JAEA?, NAGRA, NDA, NIRAS-ONDRAF?, NRG, NWMO?, POSIVA, SANDIA, SKB, SURAO, TU-Cl, UJV
- Definition of project contents
- Elaboration of an outline project structure

2014 US/German Workshop on Salt Repository Research, Design, and Operation 6

History of JA8 in IGD-TP (cont.)

July 2013: First draft outline proposal (Dan Galson)
- 8 tasks

August 2013: Second draft outline proposal (GRS)
- 4 WPs with 13 tasks, altogether

September 2013: 2nd Meeting of interested organizations
- Planning of activities of the TSWG
- New title of activity: "Handling of Uncertainties in the Safety Case for Deep Geological Repositories"

2014 US/German Workshop on Salt Repository Research, Design, and Operation 7

Motivation: Uncertainties in the Safety Case

- Are we investigating the right **scenarios**?
  - Are we using the right FEPs?
  - Are our FEP descriptions correct?
  - Do we assign the right probabilities to the FEPs?
- Are we using adequate **models**?
  - Do we model all relevant effects?
  - Are our models suitable for describing these effects?
  - Are the models sufficiently accurate?
- Will the **data** we use lead to reliable results?
  - Is our knowledge of nature good enough to justify the utilized data?
  - Can physically uncertain effects have an influence?

→ Proper handling of uncertainties is an essential part of the Safety Case

2014 US/German Workshop on Salt Repository Research, Design, and Operation 8

Handling of Uncertainties

- Scenario uncertainties
  - Identification of possible influences
  - Proper scenario analysis
- Model uncertainties
  - Identification of possible model uncertainties
  - Application of different model options
- Data uncertainties
- Quantification of data uncertainties
  - Deterministic parameter variations
  - Probabilistic analysis
    - uncertainty analysis
    - sensitivity analysis

Outcome and Recommendations from Former Projects PAMINA and MeSA

- Uncertainty analysis
  - Proposal for a systematic procedure to derive PDFs
  - Protocol to treat model uncertainties
  - These procedures should be further developed and tested in an international framework
  - Use of realistic Safety Cases
  - Experiences shared with other institutions could provide valuable guidance
- Expert judgement
  - Review of approaches was made
  - Necessary to examine such guidelines further
    - to determine whether and when more formal approaches to expert judgement are warranted
    - for system description and scenario derivation
- Probabilistic 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

2nd draft proposal: TEP: 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

Planned contributions of JA8 participants in 2014 and 2015

Work in2014/2015	Active support / provide input
WP 1: Management of uncertainties (Leader: Galson)	
Task 1.1: Strategies for managing uncertainty	NDA, Galson, Andra, SKB, TUC, Posiva
Task 1.2: Management of uncertainties in different time frames of disposal system evolution	NDA, Galson, Andra, SKB, Posiva, GRS
Task 1.3: Regulatory decision-making under uncertainty	Comment: to be done within EC project, in 2 years, when SSM and STUK finalized their reviews
Task 1.4: Communication of uncertainty	NDA (test in stakeholder dialogue), Galson, GRS?, Surao, UJV
WP 2: Uncertainty identification and quantification (Leader: NDA)	
Task 2.1: Expert judgement	NDA, Nagra? BfS?,Surao, Galson
Task 2.2: PDF derivation	NDA, GRS, SKB, Posiva, Andra, NRG(2015), Surao, UJV
Task 2.3: Identification and quantification of correlations	NDA, GRS, 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, UJV

Recent, Current or Planned Work related to WP 3

GRS:

- Compilation of an overview report on methods of sensitivity analysis
- Test and comparison of different methods
  - two generic repository systems in rock salt
- Identification of further methods to overcome identified problems

ANDRA:

- Benchmark tests of sensitivity analysis methods
  - repository system in clay (French concept)

Sandia:

- Detailed sensitivity analysis studies for Yucca Mountain site

Further Procedure and Outlook

Continue co-operation work within the TSWG on own cost until 2015/2016

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

Schedule

- October 2014: IGD-TP Exchange Forum Kalmar (Sweden)
  - Presentation of on-going and planned JA8 work
- Spring 2015: Technical meeting
  - Presentation of results achieved in the working groups
  - Compilation of progress
  - Identification of topics for further international investigation
- September 2015: Description of topics for a potential TEP

Uncertainty and Sensitivity Analysis for Repository Systems in Rock Salt

US-German Workshop on Salt Repository Research

September 7-12, 2014

Santa Fe, New Mexico, USAD.-A. Becker

Gesellschaft fuer Anlagen- und Reaktorsicherheit, Braunschweig, Germany

Abstract

Probabilistic uncertainty and sensitivity analysis of the performance assessment model is an essential part of the safety case for final repositories. Current investigations at GRS and TU Clausthal aim at testing various classical and newly-developed mathematical methods of sensitivity analysis, identifying the typical problems arising with sensitivity analysis of complex final repository models and proposing solutions. The presentation gives an introduction to the general subject as well as an overview of possible approaches and methods and presents some recent results, using the example of a hypothetical repository for low and intermediate-level waste. This system was developed based on the experiences with the model for the German ERAM site.

Uncertainty and Sensitivity Analysis for Repository Systems in Rock Salt

Dirk-A. Becker, GRS

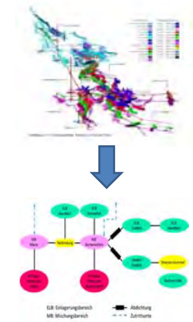
Contributions: Sabine Spiessl and Sebastian Kuhlmann

September 10, 2014

2014 US/German Workshop on Salt Repository Research, Design, and Operation

Santa Fe

Uncertainties in Long-Term Performance Assessment



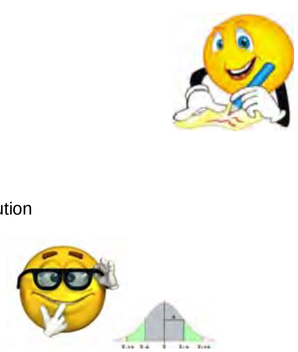
Will the repository be safe now and forever?

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

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

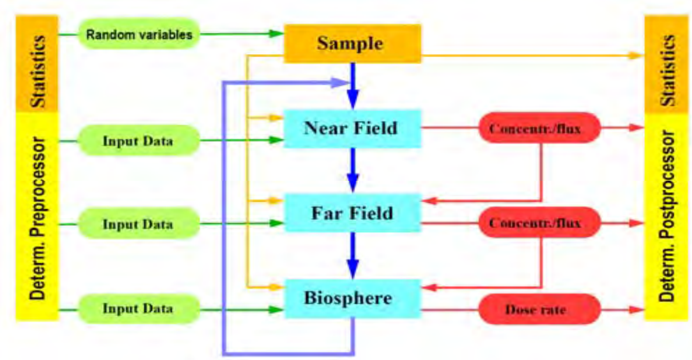
- There are lots of uncertainties: model, scenario, parameters
- Can we trust the model if it says the repository is safe?
- Somehow we have to take the uncertainties into account ...

Handling of Uncertainties in PA



1. Identify the uncertainties
   - Which kind of uncertainty?
   - How can it be handled?
     - Conservative approach
     - Multiple investigations
     - Flexible model
     - Parameter bandwidth and distribution
2. Quantify parameter uncertainties
   - Analyze knowledge
   - Consult experts
   - Parameter dependencies?
   - Assign distributions
3. Perform probabilistic analysis
   - Many model runs with statistically varied parameters
   - Uncertainty analysis: Analyze the uncertainty of the model output
   - Sensitivity analysis: Analyze the model sensitivity to parameter variation

Probabilistic Performance Assessment



Uncertainty and Sensitivity Analysis: Why?

Uncertainty analysis
- Calculate bandwidth of possible model output
- Assess probability of limit exceedance

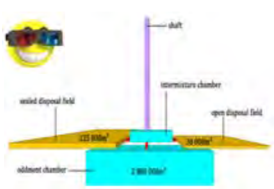
Sensitivity analysis
- Identify “important” , “less important” and “unimportant” parameters
  - “importance” means:
    the parameter value within its bandwidth has a considerable influence to the model output
- Trigger research needs
- Improve model understanding
  - SA provides insight to the model behavior
- Help finding model or data errors
  - SA can disclose implausible model behavior

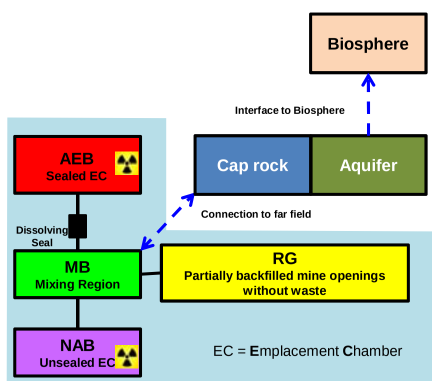
Methods of Sensitivity Analysis

- Graphical methods
  - Give a direct impression of parameter importance
  - Provide visual insight to the model behavior
  - Can disclose sophisticated input-output relationships
- Methods based on linear correlation or regression
  - Provide information on the direction of influence
  - Best adequate for linear or close-to-linear systems
  - Adequate for monotonic systems after application of rank transformation
- Variance-based methods
  - Provide quantitative information on parameter sensitivity
  - Do not provide information on the direction of influence
  - Adequate for all kinds of models
- Non-parametric methods
  - Based on non-parametric statistics (two-sample tests, e.g.)
  - No implicit assumptions on model behavior

Example: Generic Repository for LILW in Rock Salt

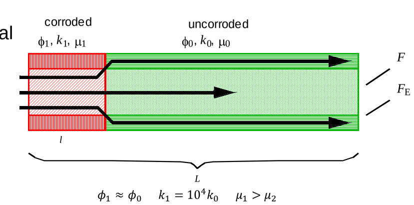
Hypothetical model based on experiences with the ERAM site
GRS-developed software tool: RepoTREND
- near field: LOPOS
- far field: GeoTREND-POSA
- biosphere: BioTREND





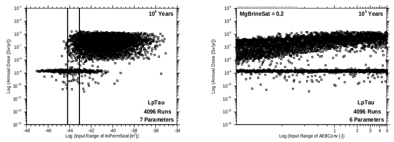
Seal failure

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

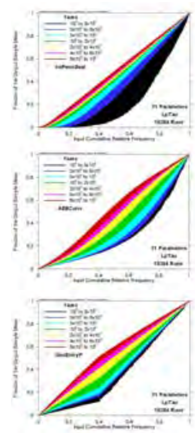


Graphical Methods

Scatterplots

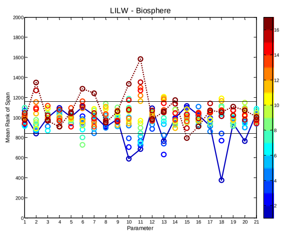


CSM-Plots



Cobweb Plots /
Mean Rank Plots

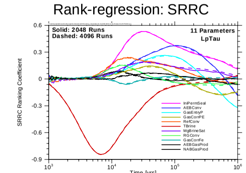
1 – KonvFak
2 – GasEntryP
3 – C14Inv
4 – PorDebris
5 – FacDiffCoeff (Dummy)
6 – IniPermSeal
7 – RefConv
8 – DiffCoeff
9 – MBConv
10 – RGConv
11 – AEBConv
12 – NABConv
13 – GasCorrFe
14 – GasCorrPE
15 – Tbrine
16 – RefPor
17 – BrineMgSat
18 – RGGasProd
19 – AEBGasProd
20 – NABGasProd
21 – FacDisp



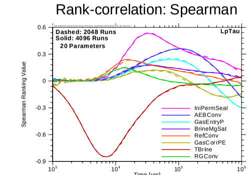
Correlation- and Regression-Based methods

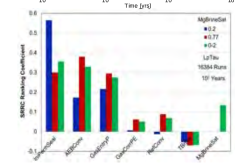
- Rank transformation applied
  - transforms monotonic to linear behavior
  - often improves performance of this type of methods on non-linear systems

Rank-regression: SRRC



Rank-correlation: Spearman





Variance-Based Methods

Calculation of first-order sensitivity indices:

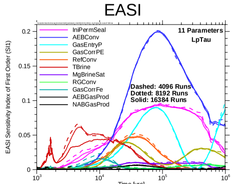
$$\mathrm{SI1}_j = \frac{\mathrm{Var}(\mathrm{E}(Y|X_j))}{\mathrm{Var}(Y)}$$

Y is the entirety of model output values,

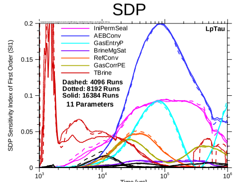
X_j is the entirety of input values for parameter j,

$\mathrm{Var}(\mathrm{E}(Y|X_j))$ is the expectation of Y under the condition that X_j is held constant.

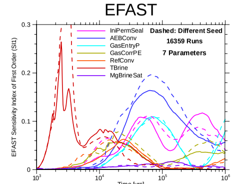
EASI



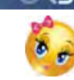
SDP



EFAST



Why is this Important Research?



- Probabilistic performance assessment is an essential part of the safety case
- Sensitivity analysis is a subject of current mathematical interest
  - increasing computer performance
  - permanent development of new methods and techniques
- Sensitivity analysis helps understanding the model behavior and can reveal errors
- Repository models – especially in rock salt – have specific properties
  - discontinuities
  - wide span of possible output values
  - possibility of zero-runs
  - *such models are normally not investigated by theoreticians!*
    - theoretical findings and developments are only partly transferable to repository models
  - application of inadequate SA methods can lead to wrong conclusions
- So far, the work has raised at least as many questions as answered ...

THM-coupled processes in rock salt with special attention to two-phase flow

Benchmark of two different modelling approaches concerning the long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste

Karl-Heinz Lux, Uwe Düsterloh, Ralf Wolters
Clausthal University of Technology (TUC), Clausthal-Zellerfeld, Germany
Jens T. Birkholzer, Jonny Rutqvist, Laura Blanco Martín
Lawrence Berkeley National Laboratory (LBNL), Earth Sciences Division, Berkeley, CA, USA

Abstract

Rock salt is a potential host rock medium for the underground disposal of high-level nuclear waste because it has several assets, in particular its water and gas tightness in the undisturbed state, its ability to heal technically induced fractures and its high thermal conductivity as compared to other shallow-crustal rock types. To comply with the safety requirements of a repository for high-level nuclear waste, the long-term integrity of the geologic as well as geotechnical barriers has to be evaluated. For this purpose, numerical simulations regarding the long-term behaviour of geologic as well as geotechnical barriers of a high-level nuclear waste repository are required, based on state-of-the-art knowledge and using verified and validated numerical simulation tools.

We present an overview on the physical behaviour of rock salt as well as results of two benchmark exercises performed by Clausthal University of Technology and Lawrence Berkeley National Laboratory to validate the numerical simulation tools FLAC-TOUGH (TUC) and TOUGH-FLAC (LBNL) [1]. The first benchmark exercise concerns the TSDE-experiment [2] which has been performed during the 1990s within the German Asse-mine to investigate the compaction behaviour of crushed salt under HLW-disposal conditions in salt rock mass. Thus, this experiment provides excellent data on crushed salt compaction. Moreover, the three-dimensional modelling of the experiment has led to the calibration of some parameters needed to describe the time-dependent response of the natural salt host rock [3], whose determination is difficult in laboratory tests, e.g. due to very low deviatoric stresses resulting in extremely long test durations. The second benchmark exercise concerns the long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste. Therefore, a two-dimensional model of an emplacement drift is investigated, including a heat- and gas-generating waste package and the crushed salt backfill material within the drift. Due to the compaction of the crushed salt and the corrosion-induced gas generation, a gas pressure build-up occurs within the emplacement drift, leading to a pressure-driven fluid infiltration into the surrounding salt rock mass. This infiltration process has to be regarded as a two-phase flow scenario.

The results of the performed benchmark exercises are very satisfactory and increase the credibility of numerical predictions concerning the long-term behaviour of a high-level nuclear waste repository in salt rock mass.

References:

[1] Blanco Martín, L., Rutqvist, J., Birkholzer, J.T., Wolters, R., Rutenberg, M., Zhao, J., Lux, K.-H. Comparison of two modeling procedures to evaluate thermal-hydraulic-mechanical processes in a generic salt repository for high-level nuclear waste. Proceedings of the 48th US Rock Mechanics/Geomechanics Symposium, Minneapolis, June 1-4 2014. Paper 14-7411.

[2] Bechthold, W., Rothfuchs, T., Poley, A., Ghoreychi, M., Heusermann, S., Gens, A., Olivella, S., 1999. Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS Project). European Atomic Energy Community. Report EUR19124 EN.

[3] Wolters, R., Lux, K.-H., Düsterloh, U., 2012. Evaluation of Rock Salt Barriers with Respect to Tightness: Influence of Thermomechanical Damage, Fluid Infiltration and Sealing/Healing. Proceedings of the 7th International Conference on the Mechanical Behavior of Salt (SaltMech7). Paris: Balkema, Rotterdam.

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THM-coupled processes in rock salt with special attention to two-phase flow

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5th US/German workshop on salt repository research, design, and operation
Santa Fe, September 10th 2014

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Contents

- Physical behaviour of rock salt
- Constitutive model *Lux/Wolters*
- Numerical simulation tools *TOUGH-FLAC* and *FLAC-TOUGH*
- Benchmark 1:
  TSDE-experiment within Asse-mine in Germany
- Benchmark 2:
  Long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste
- Conclusions & perspectives

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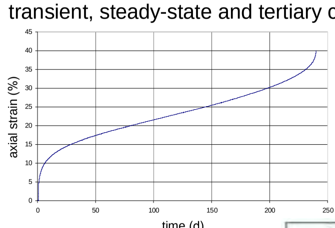
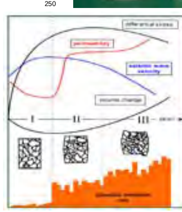
Physical behaviour of rock salt

- Creep behaviour of rock salt under deviatoric stress conditions with transient, steady-state and tertiary creep phase

M



- Damage behaviour of rock salt under deviatoric stress conditions exceeding the damage / dilatancy boundary



Change of properties is used for monitoring and determination of dilatancy / damage

I - compaction
II - damage (micro)
III - rupture (macro)

source: Schulze et al. (2001)

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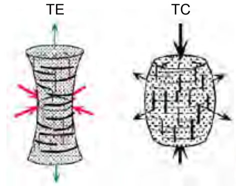
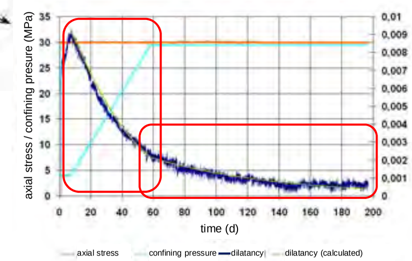
Physical behaviour of rock salt

- Sealing / healing behaviour of rock salt under suitable stress conditions

M



source: Schulze et al. (2001)



source: Lerche (2012)

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Physical behaviour of rock salt

- Creep behaviour of rock salt is dependent on temperature → *Lux (1984)*, *Hampel (2006)*
- Damage behaviour of rock salt is dependent on temperature → *Langer (1980)*, *Hampel et al. (2014)*
- Temperature changes lead to
  - thermally induced deformations
  - thermally induced additional stresses

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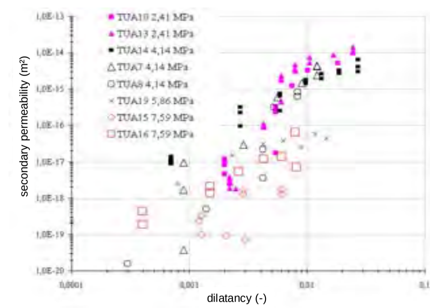
Physical behaviour of rock salt

- Undisturbed rock salt is liquid and gas tight!
- Connection of damage-induced microfissures creates micropathways within the damaged rock salt area → increase of secondary permeability $K^s > 0\, m^2$ and secondary porosity $\phi^s > 0$



source: Stormont (1990)

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Physical behaviour of rock salt

- Damage of rock salt

  ↘ reduction of bulk modulus K

  ↘ increase of *Biot*'s coefficient $\alpha = 1 - \frac{K}{K_S}$
- Lab test results concerning the relationship between dilatancy, secondary permeability and *Biot*'s coefficient are shown in *Kansy (2007)*
- *Biot*'s coefficient is used to calculate effective stresses, if pore pressure occurs

$$\sigma'_{ij} = \sigma_{ij} - \alpha \cdot p_{Fl} \cdot \delta_{ij}$$

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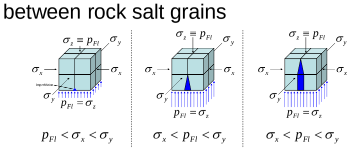
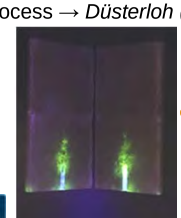
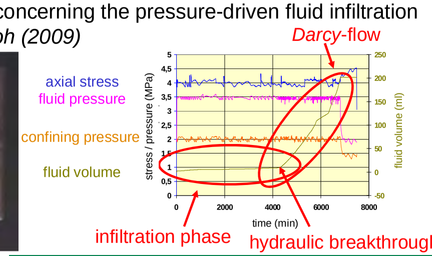
Physical behaviour of rock salt

- Fluid pressure may open grain boundaries between rock salt grains



- Lab investigations concerning the pressure-driven fluid infiltration process → *Düsterloh (2009)*





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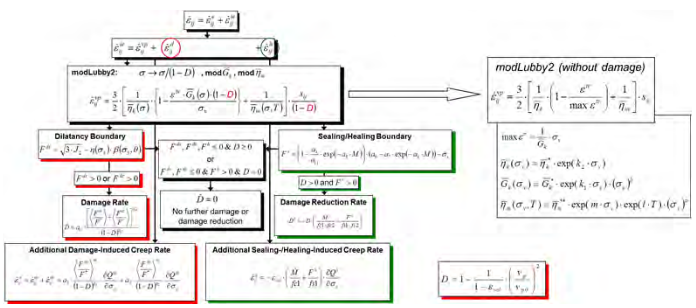
Constitutive model *Lux/Wolters*

- TM-coupled partial model



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Constitutive model *Lux/Wolters*

- HM-coupled partial model
  - thermomechanically induced secondary permeability

$$K_{\parallel}^{s} = K^{*} \cdot \begin{cases} 10^{\lg(K_0)+\left\langle \lg(-\varepsilon_{vol})-\lg(-\varepsilon_{vol,0})+r\cdot\exp(-s\cdot\sigma'_{\perp 2})\cdot\frac{1}{\ln(10)}\cdot\left(Ei(t\cdot\varepsilon_{vol})-Ei(t\cdot\varepsilon_{vol,0})\right)\right\rangle} & \text{if} \quad -\varepsilon_{vol} \geq -\varepsilon_{vol,0} \\ 0 & \text{if} \quad -\varepsilon_{vol} < -\varepsilon_{vol,0} \end{cases}$$

  - hydraulically induced secondary permeability

$$K_{1}^{s} = K^{*} \cdot \begin{cases} 10^{\,i_1+i_2\cdot\arctan\left(i_3\cdot\left(\Delta p_{Fl}-\Delta p_{Fl}^{krit}\right)\right)+i_4\cdot\exp(i_5\cdot\Delta p_{Fl})} & \text{if} \quad \Delta p_{Fl} > \Delta p_{Fl}^{krit} \\ 0 & \text{if} \quad \Delta p_{Fl} \leq \Delta p_{Fl}^{krit} \end{cases} \quad \text{with } \Delta p_{Fl} = p_{Fl} - \min\sigma$$

  - *Biot*'s coefficient

$$\alpha = \begin{cases} \max\left(\frac{D}{D_\alpha};1-\exp\left(m\cdot\sigma_v\cdot\frac{D}{D_\alpha - D}\right)\right) & \text{if} \quad D < D_\alpha \\ 1 & \text{if} \quad D \geq D_\alpha \end{cases}$$

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Numerical simulation tools *TOUGH-FLAC* and *FLAC-TOUGH*

TOUGH-FLAC (Berkeley Lab)

FLAC-TOUGH (TU Clausthal)

Similarities

- Sequentially coupled flow-geomechanics simulators
- Based on same software
  - TOUGH2 (fluid+thermal flow)
  - $FLAC^{3D}$ (geomechanics)
- Material-specific constitutive relationships available
- Can deal with large strains & creep processes

Main difference → Both simulators are based on different numerical schemes

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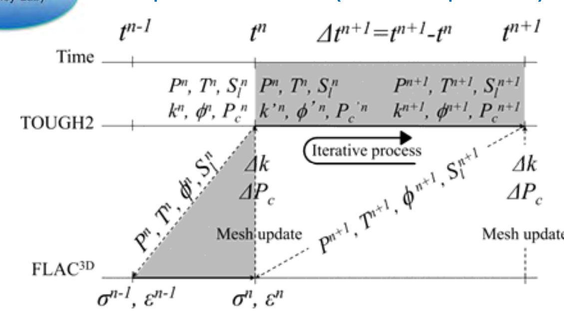
Numerical simulation tools *TOUGH-FLAC* and *FLAC-TOUGH*

TOUGH-FLAC (Berkeley Lab)

Flow problem is solved first (fixed-stress split method)



Legend:

P : pore pressure
T : temperature
S_l : liquid saturation

k : permeability
ϕ : porosity
P_c : capillary pressure

σ : stress
ε : strain
t : time

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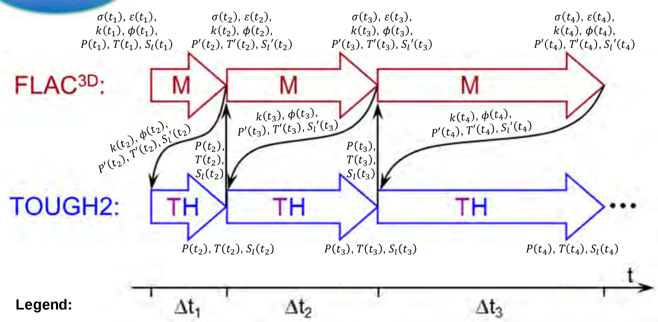
Numerical simulation tools
TOUGH-FLAC and *FLAC-TOUGH*

FLAC-TOUGH (TU Clausthal)

Mechanical problem is solved first (undrained split method)



Legend:

P : pore pressure
T : temperature
S_l : liquid saturation

k : permeability
ϕ : porosity

σ : stress
ε : strain
t : time

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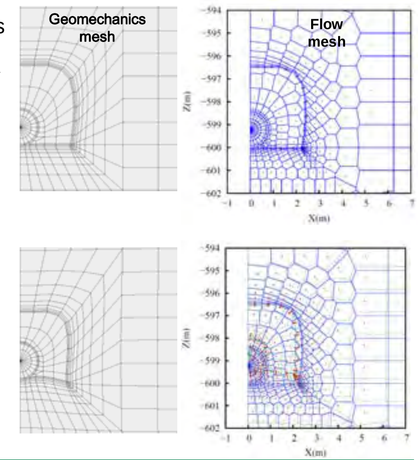
Numerical simulation tools
TOUGH-FLAC and *FLAC-TOUGH*

- Optimum discretizations for geomechanics and flow are not necessarily the same
- TOUGH2 requires a Voronoi discretization, even when the mesh deforms

Flow mesh is updated as geomechanics mesh deforms



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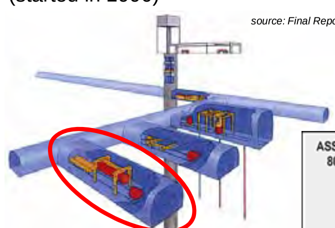
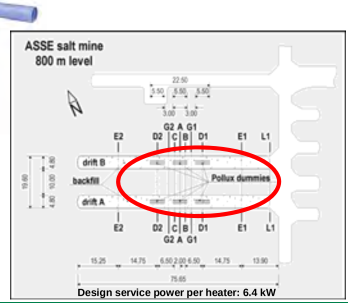
Benchmark 1:
TSDE-experiment within Asse-mine in Germany

- „Thermal Simulation of Drift Emplacement“ experiment (started in 1990)



source: Final Report of BAMBUS I-Project



source: Final Report of BAMBUS I-Project

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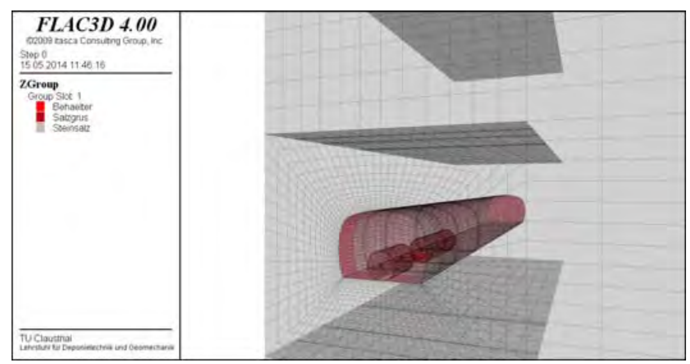
Benchmark 1:
TSDE-experiment within Asse-mine in Germany

- Numerical model



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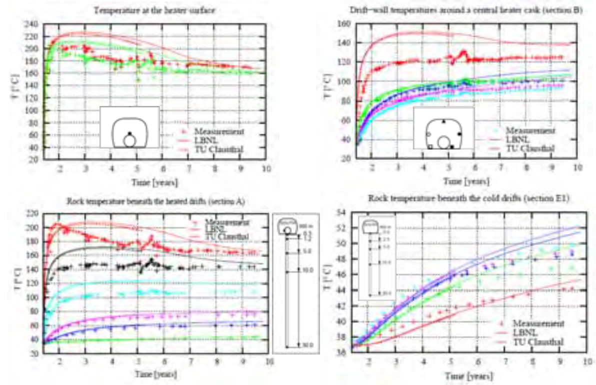
Benchmark 1:
TSDE-experiment within Asse-mine in Germany

- Benchmark results I (comparison of temperature evolution)



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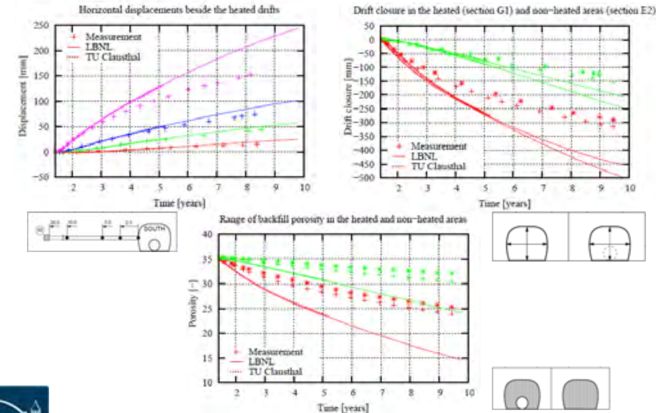
Benchmark 1:
TSDE-experiment within Asse-mine in Germany

- Benchmark results II (comparison of deformation and compaction)



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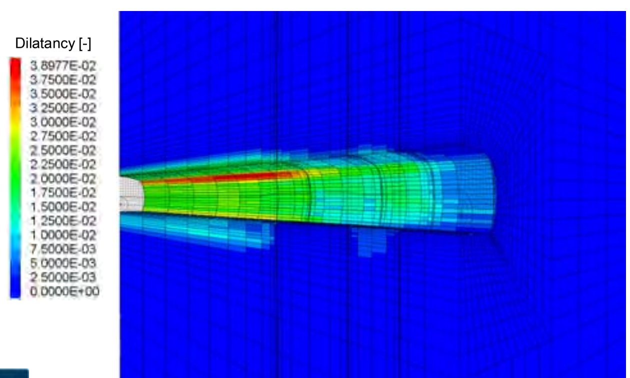
Benchmark 1:
TSDE-experiment within Asse-mine in Germany

- Benchmark results III (dilatancy at t = 8 years after backfilling)



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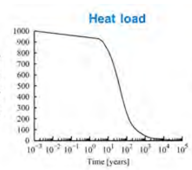
Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste

- Benchmark-scenario: Long-term analysis of a sealed emplacement drift containing a heat and gas generating waste canister and crushed salt backfill material



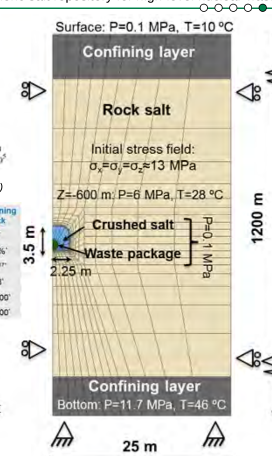
source: Carter et al. (2011)

- Used constitutive models: *Lux/Wolters* for the natural salt and a modified *cwipp* for the crushed salt

	Rock salt	Crushed salt	Confining rock
$S_{l,0}$	0.5	0.02	1*
ϕ_0	0.2 %	30 %	12 %*
k_0 [m²]	0	$3 \cdot 10^{-13}$	10^{-17}*
λ_0 [W/m/K]	4	1	1.8*
K_0 [MPa]	16,650	150	37,900*
G_0 [MPa]	7,690	70	19,500*

*: constant value

- Modelling sequence:
  - primary state
  - excavation of the emplacement drift
  - waste canister emplacement and backfill of the drift
  - post-closure phase (100,000 years)



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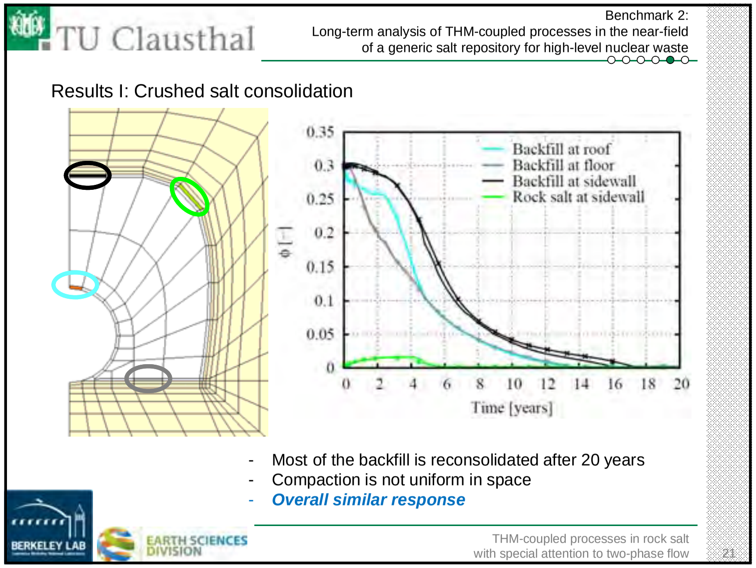
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Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste
Results I: Crushed salt consolidation
ϕ [-]
Time [years]
Backfill at roof
Backfill at floor
Backfill at sidewall
Rock salt at sidewall
- Most of the backfill is reconsolidated after 20 years
- Compaction is not uniform in space
- Overall similar response
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THM-coupled processes in rock salt with special attention to two-phase flow
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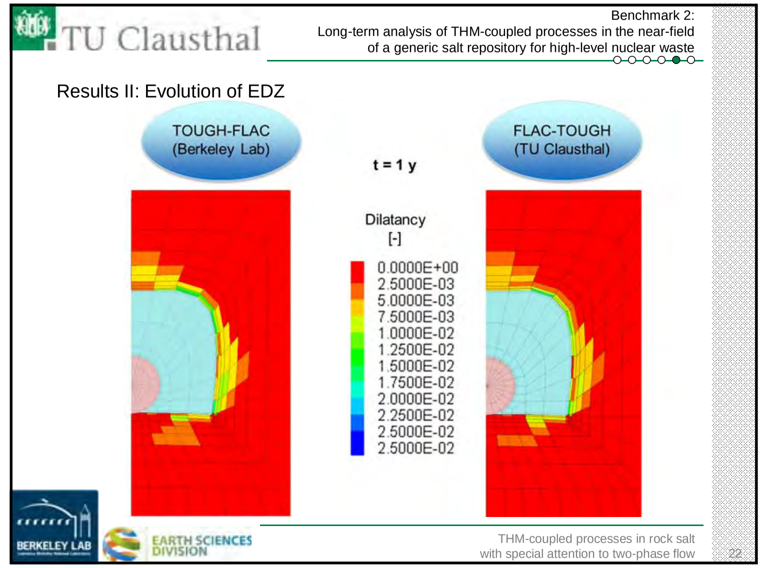
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Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste
Results II: Evolution of EDZ
TOUGH-FLAC (Berkeley Lab)
t = 1 y
FLAC-TOUGH (TU Clausthal)
Dilatancy [-]
0.0000E+00
2.5000E-03
5.0000E-03
7.5000E-03
1.0000E-02
1.2500E-02
1.5000E-02
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BERKELEY LAB
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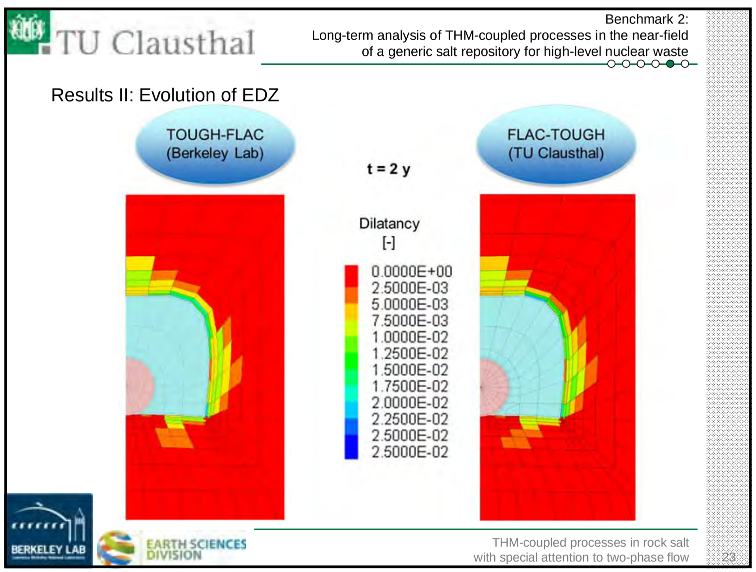
THM-coupled processes in rock salt with special attention to two-phase flow
22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Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste
Results II: Evolution of EDZ
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BERKELEY LAB
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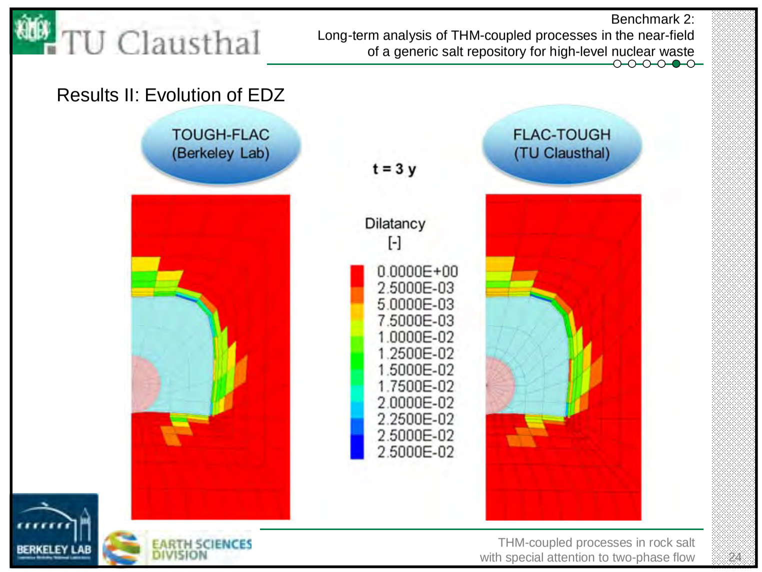
23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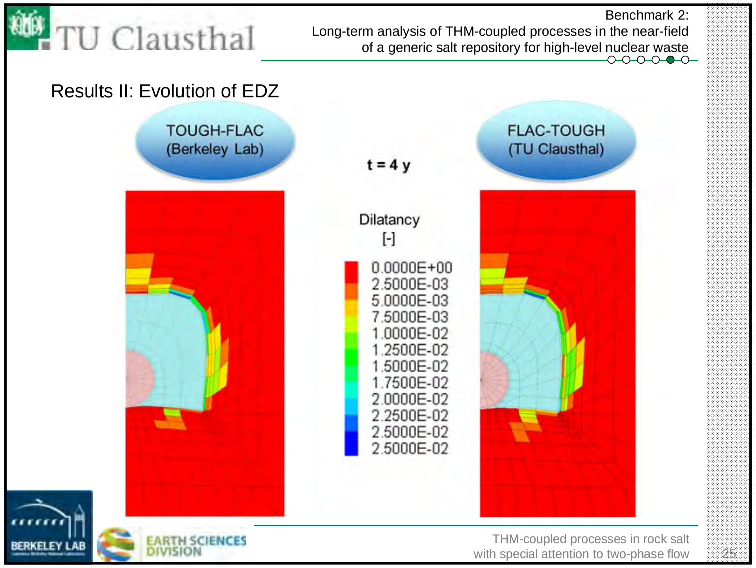
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Long-term analysis of THM-coupled processes in the near-field
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with special attention to two-phase flow
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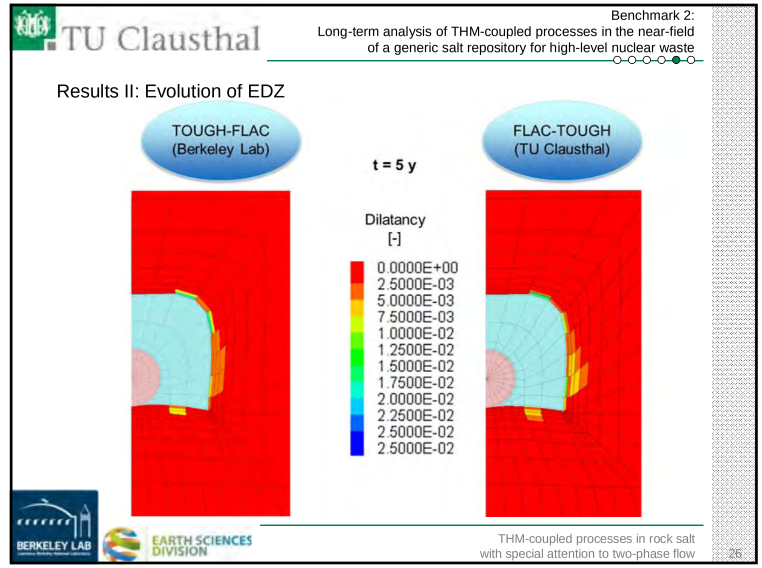
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Results II: Evolution of EDZ
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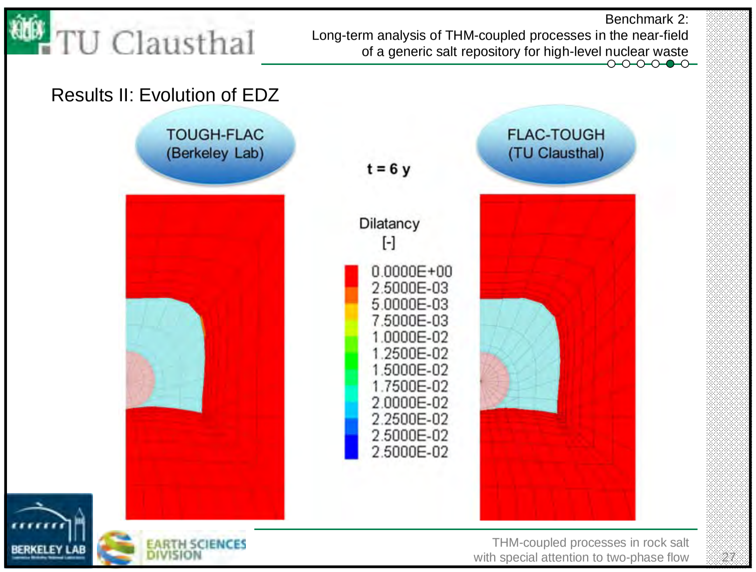
with special attention to two-phase flow
26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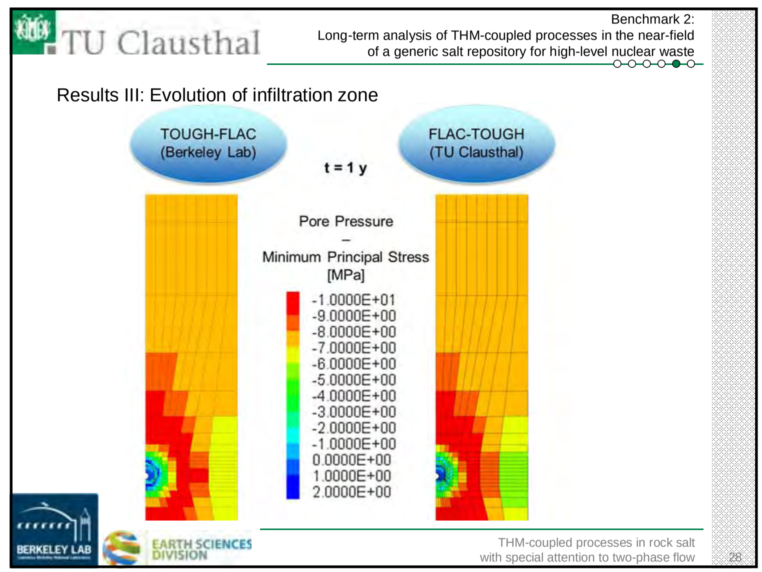
TU Clausthal
Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field
of a generic salt repository for high-level nuclear waste
Results III: Evolution of infiltration zone
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(Berkeley Lab)
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FLAC-TOUGH
(TU Clausthal)
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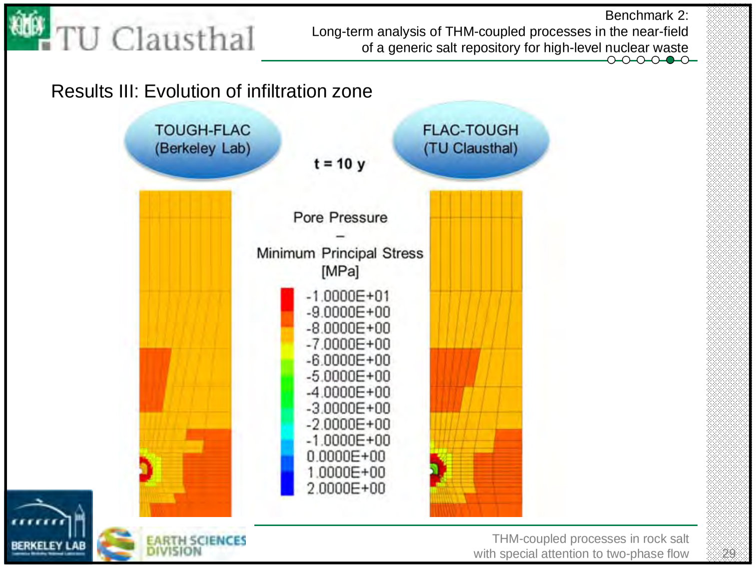
TU Clausthal
Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field
of a generic salt repository for high-level nuclear waste
Results III: Evolution of infiltration zone
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(Berkeley Lab)
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FLAC-TOUGH
(TU Clausthal)
Pore Pressure
–
Minimum Principal Stress
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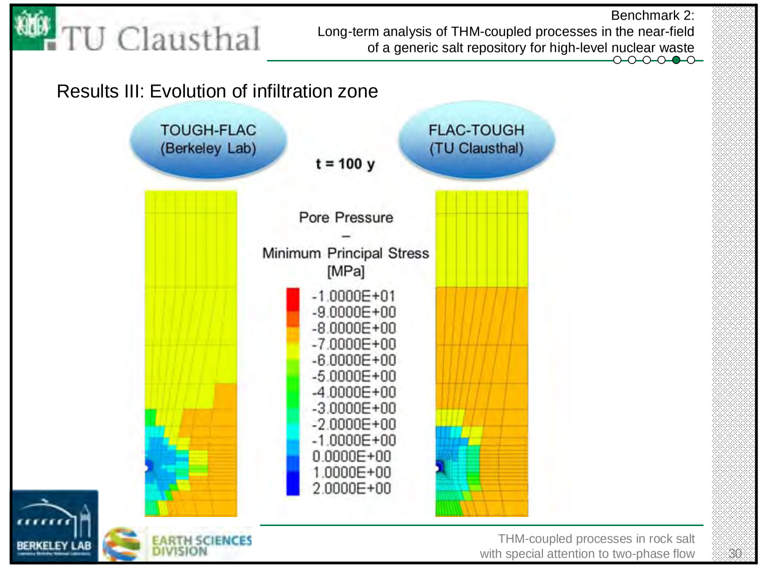
TU Clausthal
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(TU Clausthal)
Pore Pressure
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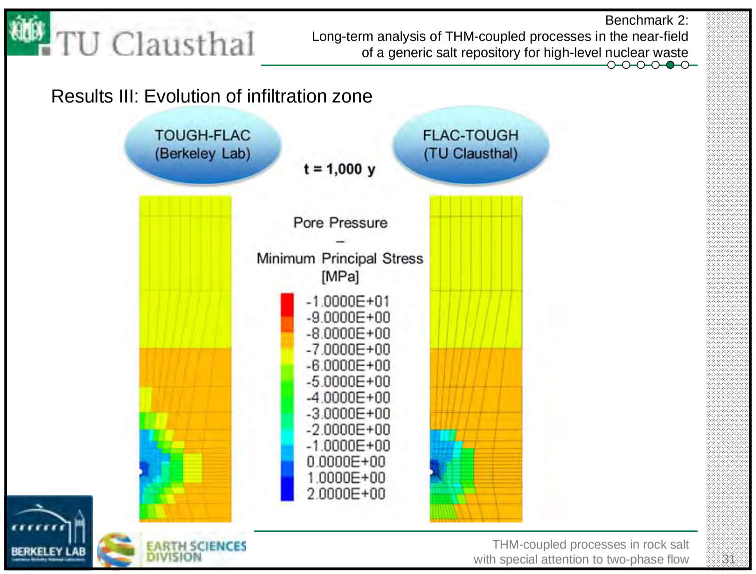
TU Clausthal
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(Berkeley Lab)
t = 1,000 y
FLAC-TOUGH
(TU Clausthal)
Pore Pressure
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Minimum Principal Stress
[MPa]
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with special attention to two-phase flow
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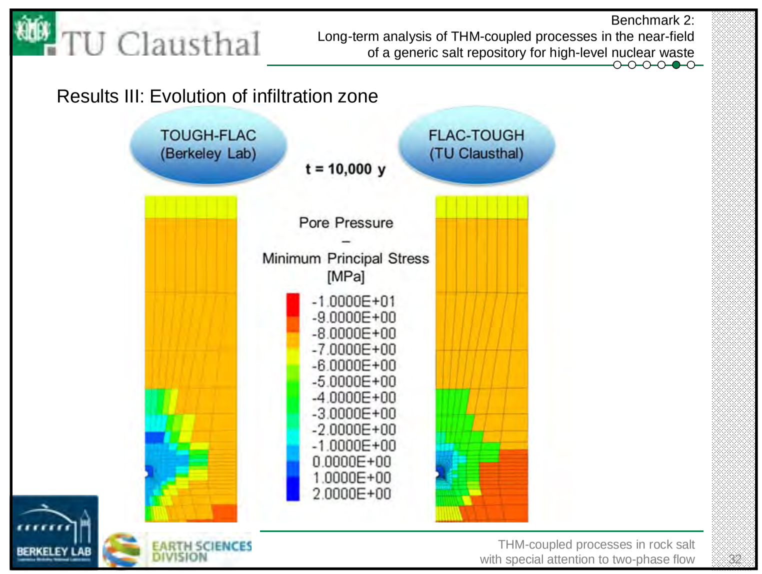
TU Clausthal
Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field
of a generic salt repository for high-level nuclear waste
Results III: Evolution of infiltration zone
TOUGH-FLAC
(Berkeley Lab)
t = 10,000 y
FLAC-TOUGH
(TU Clausthal)
Pore Pressure
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Minimum Principal Stress
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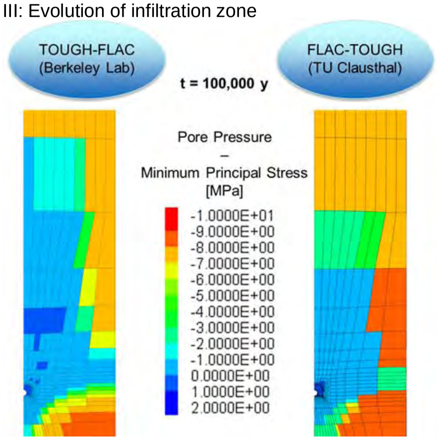
Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste

Results III: Evolution of infiltration zone



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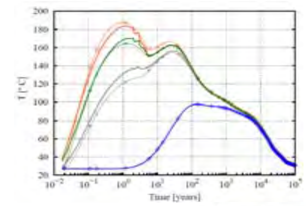
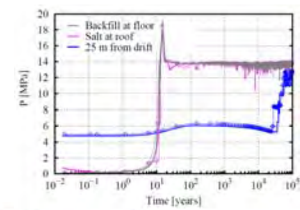
Benchmark 2:
Long-term analysis of THM-coupled processes in the near-field of a generic salt repository for high-level nuclear waste

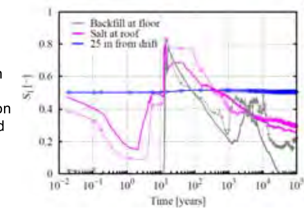
Results IV: Long-term evolution of temperature, pore pressure and saturation





Key aspects well reproduced

- Temperature evolution during compaction
- Pore pressure evolution during compaction and gas propagation
- Saturation evolution



Overall similar response

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Conclusions & perspectives

- Conclusions
  - Numerical analysis of an in situ heater test has been performed using the two different simulation tools *TOUGH-FLAC (LBNL)* and *FLAC-TOUGH (TUC)*
  - Long-term evaluation of a generic salt repository has been performed using the two different simulation tools *TOUGH-FLAC (LBNL)* and *FLAC-TOUGH (TUC)*
  - Simulators *TOUGH-FLAC (LBNL)* and *FLAC-TOUGH (TUC)* include state-of-the-art constitutive models as well as the capability to handle with large strains
  - Results of the benchmark exercises are very satisfying
  - Capabilities of the two simulators to evaluate the barriers integrity over time has been demonstrated including rock mass convergence, backfill compaction, heat production, gas production, 2-phase flow, infiltration (TH2M-coupled processes)
- Perspectives
  - Optimization of the numerical approaches to model larger areas of a repository (3D configuration)

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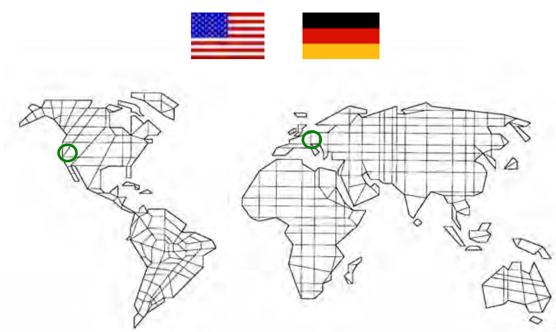
Thank you for your attention!



Thanks for great cooperation in the past.
Hopefully, we can continue this cooperation in the future.

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Exceptional service in the national interest

Sandia National Laboratories

P&T in the Context of Waste Management

Wilhelm Bollingerfehr
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Outline

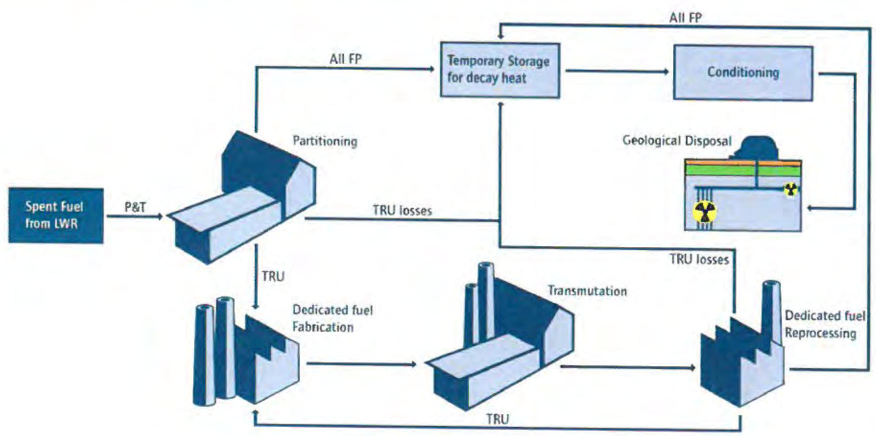
Objectives

- German Ministry for Economic Affairs and Energy (BMWi) and Ministry of Education and Research (BMBF) jointly launched a study on Partitioning and Transmutation (P&T) in summer 2012 to elaborate in detail:
  - ➢ the international state of the art in (P&T) and
  - ➢ the potentials as well as the chances und risks of implementing P&T in Germany
- In this context several social scenarios were derived and the consequences of P&T were compared
- Of particular relevance was an analysis of the implications of P&T on the waste management concept as well as on the disposal of radioactive waste in the light of the phase-out decision in Germany
- DBE TECHNOLOGY GmbH and GRS investigated the consequences of P&T on the repository concepts (footprint) and on the long-term safety

Fundamentals

- P&T processes
- Type and amount of Spent Fuel considered for P&T
- Relevant nuclides in P&T processes

P&T Processes (flow-chart)



source: acatech, Berlin (2014)

Types and Amounts of Waste and SF (Germany)

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

Basis for Data: Phase-out of Nuclear Energy Production until End of 2022

Types and Amounts of Waste and SF (Germany)

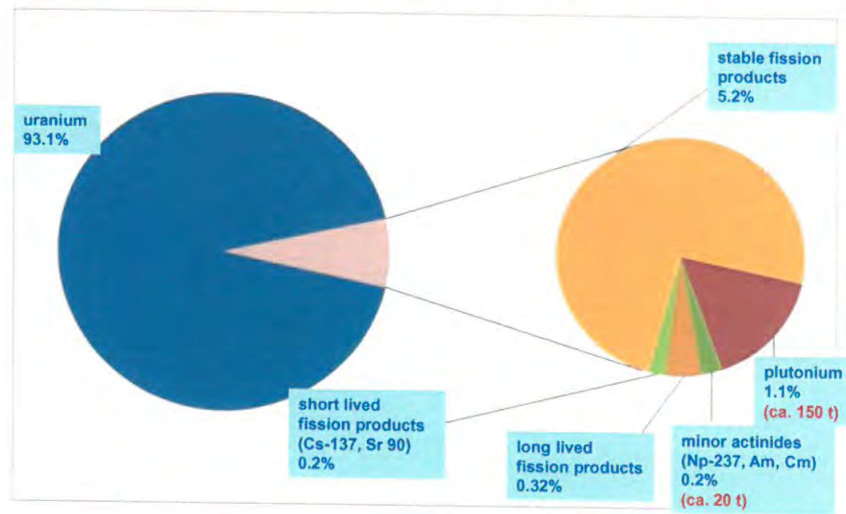
Spent fuel	PWR	UO_2 MOX	12,450 FE 1,530 FE	6,415 765	POLLUX-10	1,398
	BWR	UO_2 MOX	14,350 FE 1,250 FE	2,465 220		520
	WWER-PWR	UO_2	5,050 FE	580		202
	Total	-	-	10,445		2,120

P&T not applicable to:

- Waste from Reprocessing
- Spent Fuel of Prototype and Research Reactors
- Structural Components of Spent Fuel

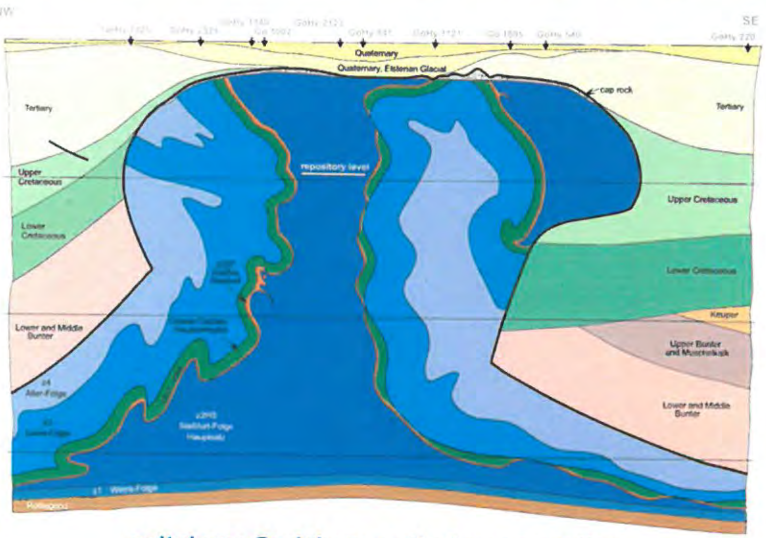
Basis for Data: Phase-out of Nuclear Energy Production until End of 2022

Mass Ratio of Radioactive Elements



➢ Time needed for entire P&T processes: approx. 150 years

Implication of P&T on Repository Footprint

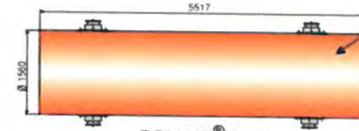


salt dome Gorleben: vertical cross section

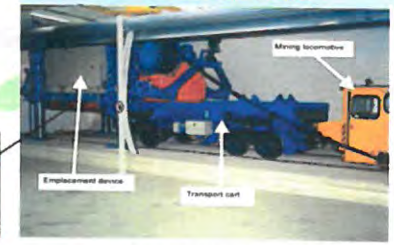
Implication of P&T on Repository Footprint

Drift Disposal Concept

Repository design according to the Preliminary Safety Analysis for the Gorleben site



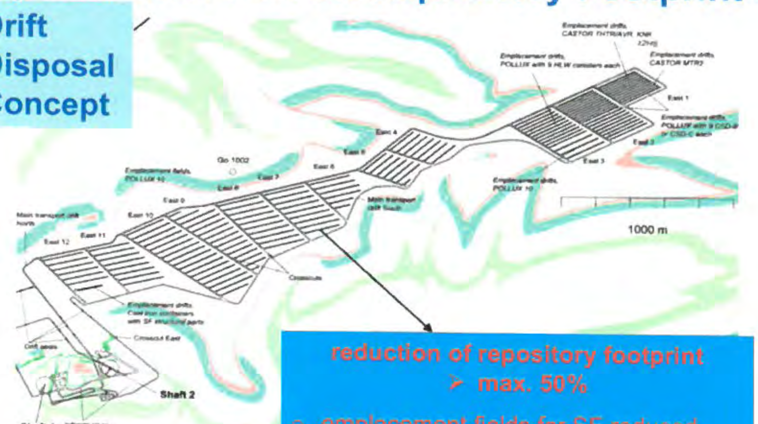
POLLUX® Cask

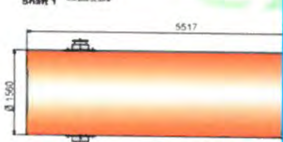


Emplacement tests

Implication of P&T on Repository Footprint

Drift Disposal Concept





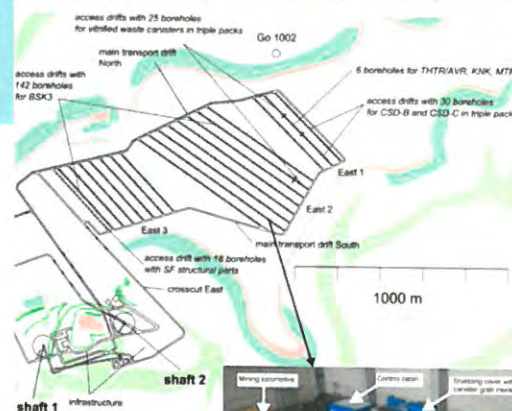
POLLUX® Cask

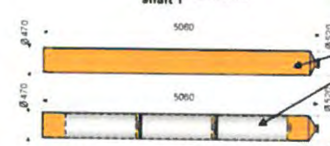
reduction of repository footprint
➢ max. 50%

- ○ emplacement fields for SF reduced
- ✓ emplacement fields for waste from reprocessing remain unchanged
- ✓ emplacement fields for SF from research reactors remain unchanged
- ✓ infrastructure remains unchanged

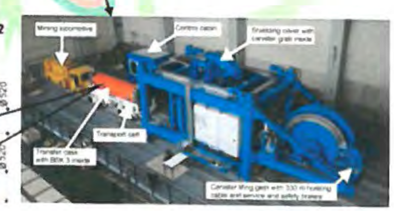
Impact of P&T on repository footprint

Borehole Disposal Concept





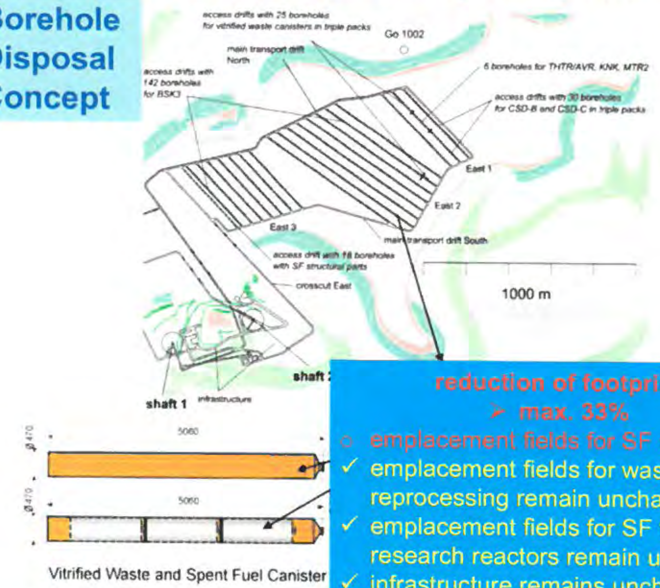
Vitrified Waste and Spent Fuel Canister



Emplacement tests

Impact of P&T on repository footprint

Borehole Disposal Concept



reduction of footprint
- max. 33%

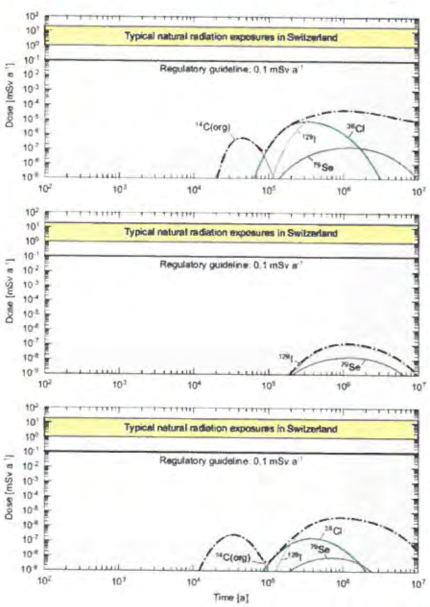
- emplacement fields for SF reduced
- ✓ emplacement fields for waste from reprocessing remain unchanged
- ✓ emplacement fields for SF from research reactors remain unchanged
- ✓ infrastructure remains unchanged

Impact of P&T on repository footprint

"Secondary" waste:

- **waste produced during P&T processes (150 years)**
  - over the total operating period **approx. 100,000 m³** waste with negligible heat production will be produced
- **Konrad repository not available for this waste**
  - waste volume limited to 300,000 m³
- **consequently an additional repository required**
  - Size: one third of Konrad repository volume

Impact of P&T on long-term safety



Potential radiation exposure in a repository in Opalinusclay

- **direct disposal of SF**
  (relevant nuclides: C-14, I-129, Se-79, Cl-36)
- **vitrified waste**
  (relevant nuclides: I-129, Se-79)
- **medium active waste**
  (relevant nuclides: C-14, I-129, Se-79, Cl-36)

(source: Nagra)

Summary and Conclusions 1/2

- **Even in case P&T were applied in Germany, a repository for heat-generating waste is needed for:**
  - already existing heat-generating waste from reprocessing
  - spent fuel from research- and prototype nuclear power stations and research reactors
  - heat-generating waste from reprocessing plants needed for P&T processes
- **One half of the original repository footprint remains unchanged (drift disposal concept); two thirds of the footprint in case of borehole disposal concept**
- **One additional repository is needed for the disposal of the 100,000 m³ of secondary waste**

Summary and Conclusions 2/2

- Model calculations (brine pathway) in the course of the preliminary safety analysis Gorleben did not show any relevant release of radionuclides;
  - ➢ thus, P&T cannot provide any advantage in this regard
- Applying P&T mainly leads to a transmutation of radionuclides which have been shown in transport calculations as less relevant for the long-term safety of repositories.
- The amounts of fission and activating products relevant to the safety case will not be reduced by applying P&T, but rather increased.

Acknowledgements

Many thanks

- to my colleague and the colleagues of GRS:
  - ✓ Wolfgang Filbert
  - ✓ Dieter Buhmann
  - ✓ Jörg Mönig

  for their contributions to the report on the *Consequences of P&T on Repository Design and Long-Term Safety*
- to the Federal Ministry for Economic Affairs and Energy (BMWi) and the Project Management Agency Karlsruhe (PTKA) of the Karlsruhe Institute of Technology (KIT) for funding the R&D project of DBE TECHNOLOGY and GRS on P&T

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PTKA
ENERGY
NNSA

NEA salt club update

Jörg Mönig
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Theodor-Heuss-Str. 4
38122 Braunschweig, Germany

Housekeeping

Meetings

- Kick-off meeting, Apr. 20, 2012, Paris (15 participants)
- 1st meeting Dec. 4, 2012, Paris (25 participants)
- 2nd meeting, Sept. 16, 2013, Berlin (32 participants)
- 3rd meeting, Mar 18, 2014, Paris (20 participants)
- next meeting Feb. 26, 2015, Paris (*to be confirmed*)

Current mandate terminates end of 2015

- Renewal at annual IGSC meeting fall 2015

Membership

SNL
LANL
US DoE EM, CFO
Respec
WIPP

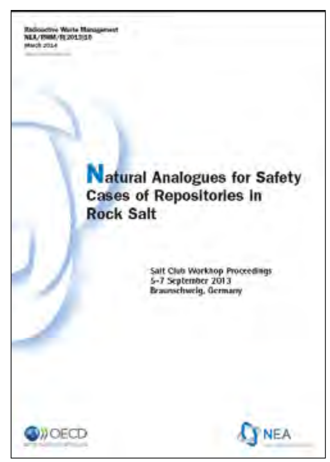
BGR
DBE Technology
GRS
HZDR

IfG
KIT
TUC
TUBS

Ministry of Economics

COVRA
NRG

Accomplishments



Programme of Work until 2015 (I)

Common FEP catalogue for a HLW repository in domal / bedded rock salt

Salt Knowledge Archive

Mechanical Behaviour of rock salt
- Re-consolidation of rock salt
- Creep of rock salt at low deviatoric stresses
- Dilatant behaviour of rock salt

Thermodynamic aspects of brine chemistry
- ABC Salt Workshops
- Joint International Pitzer Database

Programme of Work until 2015 (II)

Microbial activities in rock salt
- Report on existing data for microbial ecology in a salt repository
- Identification of future work with potential relevance to safety case development

Natural and anthropogenic analogues issues in rock salt

Concluding Remarks

Salt Club is alive and active
- already remarkable results achievd
- ambitious work programme ahead

Success depends on personal/institutional „devotion“
- sometimes challenging to endure (budget constraints)

Concentrate work
- try to provide tangible results

Focus on scientific issues with impact on the safety case development for a repository in salt rock