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2nd US/German Workshop on Salt Repository Research, Design and Operation

Meeting Venue Hotel Schönau
Peiner Straβe 17, 31228 Peine Germany
November 9-10, 2011

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CHAPTER ONE PROCEEDINGS
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Foreword

This report includes the slides and abstracts presented at the 2nd US/German Workshop on Salt Repository Research, Design and Operation. The subject matter for the 2nd US/German workshop was selected primarily by the three authors of this report based on recommendations from the 1st Workshop (www.sandia.gov/SALT/SALT_Home.html). In some technical areas, collaboration has progressed positively and such efforts will be more or less highlighted in proceedings of the 2nd US/German workshop. Open discussion of collaborative research topics followed formal presentations and are aligned in this report in the same order as the workshop agenda, which is attached as Appendix A. This **Foreword** section presents a synopsis of the 2nd US/German workshop. The workshop focused on a few key topics that build on content and discussion of the 1st US/German workshop and references to work completed thereafter, including the proceedings of the first workshop *US/German Workshop on Salt Repository Research, Design, and Operation* (KIT, 2011) and a state-of-the-art report *Salt Disposal of Heat-Generating Nuclear Waste* (Hansen and Leigh, 2011).

Recent developments in Germany and the United States have renewed interest in salt repository investigations and the authors of this report took the action to renew collaborations and cooperation on overall salt repository science and engineering. As a result of policy decisions, an arising issue in the United States concerns renewed high-level waste (HLW) disposal research in various geological media, including salt. The research agenda between our two countries leverages collective efforts for the benefit of our respective programs. Fundamentally, these workshops are concerned with salt repositories for HLW, which drives the nature of the expected thermomechanical response.

The initial purpose of the renewed US/German salt repository workshops was to assemble invited key investigators in salt repository science and engineering and to identify a coordinated research agenda that participants can agree in principle to pursue individually or in concert with others. This aim has now been complemented by creation of the Salt Club under the aegis of the Nuclear Energy Agency. The Salt Club concept was discussed at length in the 1990s and early 2000s, during a period of fruitful collaborations between the German research centers, Sandia, RESPEC and the US Department of Energy (DOE). The objectives of the 2nd US/German workshop are to continue collaborative research activities, to build upon the research agenda, and to renew working relationships at the institutional and individual levels. The Salt Club wishes to optimize the use of individual resources for the mutual benefit of each program.

Participants are experts in certain aspects of salt repository research, design and operation. A list of participants and observers is included in Appendix B. An overall salt research and development (R&D) program is recognized to be much larger than this specialty workshop. For example, many participants in the 2nd US/German workshop also contribute to the Solution Mining Research Institute (www.solutionmining.org) and the ongoing Mechanical Behavior of Salt Symposia (www.saltmech7.com). Therefore the R&D undertaken here is focused and selected to address a limited number of key topics in salt repository research, design and operation. This summary is created to document the proceedings, with a goal to both provide a discussion report and establish direction for research into HLW disposal in salt. These proceedings are expected to enhance our collaborative research by identifying future topics beneficial to all participants.

These workshop proceedings examine the state of salt repository science and review selected technical issues pertaining to salt disposal of high-temperature nuclear waste. Workshop activities are expected to further bolster the already solid performance expectation for salt disposal. This workshop's scientific agenda covers a breadth of topics, which sometimes naturally overlap, but presentations and discussion retain their original organization. This agenda recognized that research must begin with a safety case, including performance assessment. After presenting the introductory safety cases from the German and US perspectives, we address the crucial topics of sealing systems, demonstrations, and field testing. Discussion of seal systems and their components takes a central role in this workshop. We feature virtual repository visualization R&D activities in the opening session. The potential to better visualize the repository setting and its evolution should facilitate conveyance of technical information to stakeholders.

This workshop focuses on mechanical, thermal and to a lesser extent hydrological aspects of HLW disposal in salt. The crucial elements of sealing the repository are covered in some detail. There is a strong technical basis for salt disposal, including compelling evidence that the materials disposed in salt will be entombed. Thermal, hydrologic, and geochemical considerations suggest that radionuclides in a salt repository for HLW would not migrate from the disposal horizon (Hansen and Leigh 2011). Therefore, topics of this workshop examine how well we can seal shafts and drifts and how well we understand thermal effects on mechanical deformation.

Details pertinent to HLW disposal in salt are presented in the subsequent session, including backfill, crushed salt behavior, testing, modeling and microprocesses. Next, the discussions turn to the topic of rock salt deformation and healing, specifically the creation and mitigation of the disturbed rock zone. Subsequently, presentations are given on the modeling state-of-the art for these processes, focusing on collaboration between several German research institutions and Sandia National Laboratories. The last formal topic of the 2nd US/German workshop discusses analogues for a qualitative safety demonstration of salt HLW disposal. Each topical area is addressed by subject matter experts; followed by a brief question-and-answer period. At the end of the formal presentations, the research agenda is discussed in an open forum. Through open discussion we were able to identify the most productive near-future collaborations to further the scientific basis for salt HLW disposal. This report includes key elements of discussion and some general conclusions in appropriate sections, summarized in concluding remarks.

After concluding debate and deliberation of the 2nd US/German workshop R&D elements, a Salt Club roundtable discussion was undertaken. Elements of the Salt Club discussion are included in these proceedings because its implementation provides additional sponsorship of the salt repository agenda. The Salt Club is in a formative stage, so its immediate future goals concern near-term organizational strategy.

These proceedings provide summaries of the work undertaken at the 2nd US/German workshop, including the safety case; testing in the laboratory and field; seal systems demonstration and performance; principles of salt behavior; potential for fracture damage and its mitigation; advanced modeling capabilities; and near-future developments and contemplation of international collaboration through the Salt Club or other groups. A clear R&D agenda supporting HLW waste disposal in salt is defined through mutual experiences elaborated upon during the 2nd US/German workshop, including seal system design, coupled process simulation, and application of performance assessment methodology.

This summary is divided by session as follows:

- Session 1: Safety Analysis/Safety Case
- Session 2: Sealing System for Repositories in Salt
- Session 3: Backfill
- Session 4: Rock – Salt
  - Deformation and Healing
  - Coupled Modeling
- Session 5: Miscellaneous Topics
  - Natural Analogues
  - Technology Platform
- Session 6: Discussion of R&D Issues
- Session 7: Salt Club
- Session 8: Concluding Remarks

The open-forum discussion in Session 6 (Discussion of R&D Issues) revisited topics identified in the 1st US/German workshop (KIT, 2011), which allowed discussion of follow-up, progress achieved and a path toward addressing the R&D agenda. Topics addressed at this workshop were those previously identified as vitally important to international salt repository collaboration between German and US researchers. This workshop proceedings document records the progress achieved and indicates avenues for further progress.

Session 1: Safety Analysis/Safety Case

Disposal of heat-generating waste in a suitable salt formation is attractive because intact natural salt is essentially impermeable, self-sealing and thermally conductive. Through time, several processes create a salt repository environment that severely limits the possibility of radionuclide movement. A salt repository could potentially achieve total containment, with no releases to the environment in undisturbed scenarios. As an example, the post-closure safety concept at Gorleben involves safe containment of the emplaced waste in a repository system where there is at most an insignificant radionuclide release from the containment-providing rock zone (CPRZ, sometimes also called the isolating rock zone) during the demonstration period of 1 million years. Complete containment is the most stringent form of safe containment. This occurs when there is no contact between intruding solution and waste or when there are no radionuclide releases from the CPRZ. In all other cases, radionuclide fluxes from the CPRZ are contained in a small defined volume of surrounding geology. The preliminary Gorleben site safety assessment is currently predicated on a detailed site-specific catalogue of features, events and processes (FEPs).

Very similar performance is achieved at the licensed Waste Isolation Pilot Plant (WIPP) repository. Even using very conservative models, there is no radionuclide pathway out of the ambient-temperature salt repository except through diffusion. The only potential releases from WIPP are human intrusion scenarios where repository flooding and pressure increases lead to surface releases through boreholes. HLW isolation is expected to be similarly robust in a repository that is appropriately sited, constructed, and operated. Temperature effects on salt deformation are dramatic, as shown by laboratory tests on natural salt specimens and field experiments at full scale. Deformation in a salt repository will be enhanced by elevated temperature upon placement of the heat-generating waste. Elevated temperatures and deviatoric stress states near the waste are likely to enhance dry-out and promote encapsulation.

Participants in the 2nd US/German workshop agreed that a near-term focus of our collaborations and Salt Club initiatives could result in an integrated FEPs list. Within the German program described by J. Mönig, a comprehensive documented FEPs catalogue was created. Site-specific FEPs were integrated with the preliminary safety analysis for Gorleben. A FEPs list has been assembled for salt disposal at WIPP (Hansen and Leigh, 2011). A FEPs screening table for salt disposal of heat-generating waste would need to be created if the US moves forward with a performance assessment for salt HLW disposal. Although there is no current regulatory guidance for such an analysis in the US, the Salt Club identified the collaborative goal of creating a mutually acceptable FEPs list between the US and Germany for salt disposal of heat-generating waste.

Given the advanced state of knowledge regarding disposal of heat-generating waste in salt, it would be constructive for the US to develop the safety case for salt disposal of Defense High-Level Waste (DHLW). Most of the temperature effects expected for DHLW have been evaluated by research in Germany and the US. A possible second collaborative goal is the organization of the existing scientific arguments for DHLW disposal in salt. The compilation of existing research results will further refine the remaining research agenda.

Using existing knowledge, a reasonable expectation of heated disposal room evolution is:

- The damaged zones around the disposal room release accessible moisture through flow down the stress gradient.
- Room closure will be accelerated by thermal activation of crystal plasticity (flow without damage).
- If used, granular salt backfill will reconsolidate.
- Stress differences will diminish and fractures will heal in the process.
- Healed salt and highly reconsolidated granular salt will develop permeability similar to that of undisturbed halite.
- Response of the modified disposal system is improved regarding future human-initiated borehole intrusion because through time there is less moisture available, and lower permeability around the emplaced waste.

Based on the above expectations, an undisturbed salt repository containing heat-generating waste is expected to be extremely robust.

Session 2: Sealing System for Repositories in Salt

In some manner, the banner of *Sealing Systems* overarches nearly all the other specific R&D activities. Long-term isolation often rests upon the seal system design and demonstration. The license to open a repository is likely contingent upon demonstration of the ability to close it. Therefore, sealing systems components and their interaction with the native salt are absolutely vital to the discourse at the 2nd US/German Workshop on Salt Repository Research, Design and Operation.

N. Müller-Hoeppe noted that sealing systems are installed to supplement a tight geological barrier, in order to seal fluid access routes into the repository. Shaft and drift seals play a significant role in long-term repository safety. As geotechnical structures, drift and shaft seals have to be designed in accordance with applicable regulatory and technical guidelines. In many cases, successful demonstration of shaft and drift seal effectiveness has already been accomplished. However, sealing system efficacy will be scrutinized in the licensing process.

In Germany, prototype construction is demonstrated and short-term safety functions are verified by in situ testing. To show reliability of short-term safety functions, two steps are recommended. First, in situ test results are compared to the results of blind predictions. Usually, deviations arise and knowledge gaps become evident. As a consequence, the second step involves improving process understanding, reducing knowledge gaps and improving predictive tools.

R. Mauke provided a recent demonstration of drift seals located in rock salt at the Morsleben facility. The trial construction consists of three system components: the sealing body (i.e., 25-30 meters of salt concrete), the contact zone between the seal body and the surrounding rock salt and the rock salt excavation damaged zone (EDZ). All these components were observed during the in situ investigation. Geotechnical measurements of stress, strain, displacement, temperature, and pore pressure were carried out in the contact zone, the sealing body and the surrounding rock salt. Seal construction using salt-based concrete took place in December 2010 over approximately 20 hours. Injection of the contact zone between the seal body and the surrounding rock salt was carried out in February 2011. The success of the in situ trial was demonstrated in excavation, prominent construction phases and significant preliminary measurement results. These types of full-scale, high-performance demonstrations are of great value for salt HLW disposal.

P. Kamlot described some of the real-time sealing analyses and demonstrations associated with the Asse II mine. An emergency sealing concept has been developed and construction of drift sealing elements is a main element of the emergency plan. The presentation included the most important elements for performance assessment of the drift seal's functionality. Specialty cement was developed, similar to what might be specified for other salt formations. Constructability characteristics and engineering properties are critical to concrete drift seal performance. The geotechnical nature of disturbed rock and its attendant permeability must be taken into account to achieve a tight drift plug. For this work at the Asse II mine, a viscoelastic-plastic constitutive law for calculation of softening and dilatancy was developed and calibrated using a dilatancy-permeability relation. These relations were then applied with great success. The in situ experiment lasted 7.5 years and revealed that it is possible to construct sufficiently functional drift sealing elements even under the complicated site conditions of the Asse II mine.

Taken together, these demonstrations of construction and high functionality provide pronounced confidence for salt repository sealing programs. The design bases in each case will identify a set of guidelines incorporating repository and seal system performance, and a commitment that the seal system design would implement accepted engineering principles and practices. Design guidance is based on primary goals to:

- limit hazardous constituents reaching regulatory boundaries;
- restrict groundwater flow through the seal system;
- use materials possessing mechanical and chemical compatibility;
- protect against structural failure of system components;
- limit subsidence and prevent accidental entry; and
- utilize available construction methods and materials.

An established Quality Assurance program that includes review by independent, qualified experts is essential to assure appropriate information is provided to the regulatory authority. Sealing system performance plays a crucial role in overall system performance because open shafts hydraulically connect the surface, water-bearing units and the repository horizon. Uncertainty in engineering material properties is addressed through selective use of low-permeability materials. Emphasis is given to permeability characteristics and mechanical properties when selecting engineered materials. To enhance long-term performance, the materials must also be chemically and physically compatible with the host formations. Plugging and sealing a salt repository will continue to be of interest to the US/German collaborations.

R. Nelson presented a new initiative called Salt Disposal Investigations (SDI), with an emphasis on field test elements. Recent US policy decisions have helped renew interest in US research on geologic disposal of HLW and spent nuclear fuel in various geologic media. Given both historic salt research and a successfully operating WIPP facility, salt disposal is well ahead of many other disposal options in the US. The SDI comprises a series of research topics for heat-generating waste disposal predicated on compilation of previous and ongoing salt research and identifying additional science necessary to fill gaps and extend our current understanding. The primary basis for proposed SDI work derives from the Hansen and Leigh (2011) summary report, using a disposal concept that builds upon the WIPP experience. The Hansen and Leigh summary drew heavily from the 1st US/German Workshop on Salt Repository Research, Design and Operation.

The SDI studies include laboratory tests on dry granular salt at elevated temperature to evaluate reconsolidation processes, including the functional relations between permeability and density and thermal conductivity and porosity. The SDI scope includes updating the hardware and software for repository-class analyses. These proceedings repeatedly discuss a strategy to continue and enhance international collaboration on salt modeling. The SDI envisions field demonstrations of a proof-of-principle disposal plan for high-heat generating waste. The disposal concept has some similarity to BAMBUS II (Bechthold et al., 2004), where simulated heat-generating waste was covered with crushed salt, then measurements and modeling were carried out on granular salt reconsolidation, elevated temperature creep, coupon corrosion, and heat transfer. The temperatures anticipated in the SDI disposal concept are substantially above previous field tests at the WIPP or Asse. An SDI field-test plan had not been developed at the time of 2nd US/German Workshop on Salt Repository Research, Design and Operation. Different possible uses of new underground space at the WIPP are being considered at this stage. Alternatives to the very high temperature field demonstration could include more modest heat-generation rates associated with US HLW.

The proof-of-principle field demonstration/test proposed at the WIPP is still in the conceptual phase. The SDI research group is seeking review and suggestions from our international colleagues who have experience in field-scale salt testing, laboratory experimental salt deformation and salt constitutive modeling. *International Collaboration* is a specific element of the SDI proposal. Several key workshop discussion topics are embodied in the SDI, notably granular salt testing at elevated temperature and benchmarking of coupled process models. The viability of an SDI field demonstration/test will be enhanced by progress in these research elements.

W. Bollingerfehr explained the difference between technical barriers and geotechnical barriers. The waste containers as technical barriers isolate the radioactive waste and ensure that handling processes are safe during repository operation. Geotechnical barriers will be designed to close and seal the man-made openings (i.e., drifts and shafts) of the repository. Shaft seals are of utmost importance, because these barriers seal the only potential pathway for fluid intrusion into the repository. Information is available on shaft seals that were developed, constructed and tested for a German hazardous waste repository. The shaft-seal concept for the US transuranic waste repository at the WIPP has been designed for a bedded salt formation. In Germany, components of a shaft sealing system have been demonstrated. However, a published concept for the eventual sealing of the shafts of a German repository for heat-generating radioactive waste does not yet exist. For this reason, BMWi (German Federal Ministry of Economics and Technology) launched a three-phase research project called ELSA.

The Research, Development and Demonstration (RD&D) project ELSA is divided into three phases, and is developed more completely in the presentation by W. Bollingerfehr in Chapter 2. Phase 1 studies include research on the state of the art, compilation of boundary conditions, and requirements for shaft seals for HLW repositories. Phase 2 concerns the development of technical concepts for shaft seals that provide safe long-term sealing of HLW repositories. According to current considerations, the concepts should be modular so that the geologic situations and hydromechanical boundary conditions at the respective sites can be taken into account. Phase 3 involves the construction and testing of the functional components of the shaft seals on a large scale. Discussions are planned with interested international partners, because of the international significance of this project. These workshops provide an opportunity to continue the dialogue.

F. Hansen's presentation summarizes the science and engineering of the shaft seal system used in WIPP compliance certification. The experience of developing and licensing a shaft seal system provides a clear and successful precedent. Design details are fully published in journals and technical reports (e.g., Hansen and Knowles, 1999). Shaft seal system functions entail material characteristics, construction, performance and verification. Functional requirements could include low fluid permeability, stable chemistry, robust mechanical properties and constructability. The WIPP design approach applied redundancy to functional elements and used multiple, common, low-permeability materials to ensure reliable performance. Laboratory and field measurements of component properties and performance provided the basis for the design and related evaluations. Hydrologic, mechanical, thermal and physical features of the system were evaluated in a series of calculations. Assurance that the shaft seal design can be constructed is achieved by use or adaptation of existing technology for seal construction combined with the use of commonly available materials. A well-designed salt repository requires minimal engineered barriers. However, if licensing or public assurance requires seals to be placed in drifts or shafts, many participants at the 2nd US/German Workshop on Salt Repository Research, Design and Operation believe that the technical bases to permanently seal a salt repository exist today.

K.-H. Lux provided some basic, compelling investigations into barrier integrity investigations, which are included in this report. His contributions are provided in two parts: first, development of short-term seal elements using shaped salt blocks; and second, pressure driven infiltration. Laboratory-scale experiments compared porosity and permeability of crushed salt and shaped blocks. Shaped blocks can be constructed with a porosity of less than 10%, similar to highly compacted mine-run salt (Hansen and Ahrens, 1999). The Lux experiments showed that permeability was effectively eliminated in the shaped-block experiments. Petrofabric observations showed native salt structure was reestablished, although the stresses in these laboratory investigations were very high relative to repository applications. The second series of laboratory/modeling investigated pressure-driven infiltration, with application to mechanical and hydrological integrity of natural salt.

Project VIRTUS is a visualization tool that will provide 3D-visualization of safety relevant processes investigated and predicted by numerical simulations. T. Rothfuchs provided an overview of this powerful means of communication and demonstration. In particular, VIRTUS will furnish research and waste management organizations with an innovative instrument for the analysis of repository processes and for the development of repository concepts and designs. The idea of a virtual Underground Research Laboratory (URL)/repository was launched in late 2010 as a joint project of GRS, BGR and DBE TEC. The VIRTUS Software platform will provide an influential instrument for the analysis and visualization of the very complex processes taking place in an URL/repository and its capability may be of great use to many of the international partners. It is therefore highly appropriate and advantageous to have this work presented at the 2^{nd} US/German Workshop on Salt Repository Research, Design and Operation.

Session 3: Backfill

Reconsolidation of crushed salt may play an important role in salt repository evolution and long-term performance if it is used for backfilling or sealing system elements. In the US, crushed salt behavior under ambient conditions was studied extensively as part of the shaft seal system at WIPP. Physical processes and a functional relationship between permeability and density were developed, reviewed and approved in the WIPP compliance certification shaft seal design (Hansen and Knowles, 1999). Today we hope to extend this foundation of knowledge to the potential application of crushed salt as a barrier element in a HLW repository, which is being addressed by laboratory investigations at elevated temperature.

Previous investigations show that ambient reconsolidation of crushed salt occurs rapidly at modest pressure. Because natural bedded salt from the WIPP has a small amount of accessible brine, the processes of pressure solution and re-precipitation govern salt reconsolidation. However, an elevated-temperature HLW repository environment may dry the salt and limit the processes observed during reconsolidation at ambient temperatures. An experimental program is underway at Sandia National Laboratories to explore this possibility using post-consolidation observational microscopy. These experiments are beginning under the auspices of the Used Fuel Disposition Campaign (DOE, 2011). Workshop participants will be given an opportunity to critically review this research and participate in evaluation of the findings.

The topic of reconsolidation of granular salt, particularly under dry conditions, was acknowledged as a topic of mutual and current interest by researchers at the 2^{nd} US/German workshop. To this end, the 2^{nd} US/German workshop brought together some of the foremost experts on this topic. G. Callahan presented a constitutive model that he developed to capture the major deformation components of crushed salt. The constitutive model used to describe the reconsolidation of crushed salt includes two mechanisms – dislocation creep and grain boundary diffusional pressure solution. The constitutive model is generalized to represent three-dimensional states of stress. Parameter values for the model were determined through nonlinear least-squares model fitting to an experimental database of shear and isostatic pressure consolidation tests. Using fitted parameter values, the constitutive model was validated against constant strain-rate tests, following a load path outside of the laboratory experimental database. The model appears to capture the creep-consolidation behavior of crushed salt reasonably well, based on fitting statistics and the ability of the model to predict test data, particularly the ability to predict load paths and test data outside of the fitted database. Analysis results of a shaft seal problem were presented to demonstrate model-predicted consolidation of the shaft seal crushed-salt component. Current work is exploring the capability of the model to represent dry granular salt consolidation at elevated temperature.

D. Stührenberg presented numerous results from compaction and permeability experiments he has conducted over the past twenty years. These results include samples with various quantities of Ca-bentonite. His test results illustrate that backfill resistance increases with decreasing void ratio (porosity) and decreases with decreasing compaction rates. When compaction rate is held constant, backfill resistance decreases with increasing temperature. As noted by other researchers, small amounts of water added to consolidating granular salt dramatically reduce backfill resistance. Backfill resistance decreased considerably when 10-15% Ca-bentonite by weight was added to consolidation tests at room temperature.

C. Lerch and K. Wiezorek further emphasized the importance of backfilling to minimize open cavities and transport heat away from disposed waste. Both of these physical contributions to the long-term safety case hinge on experimental investigations and constitutive models developed for crushed salt. A prerequisite for process-level code calculation is the description of all relevant crushed salt behavior processes using material models and defensible model parameters developed from reliable data. Presentations by C. Lerch and K. Wiezorek emphasized the material models of the process-level codes and the availability of experimental data as a basis for these material models. Pertinent research areas include reconsolidation processes for granular salt, healing mechanisms for damaged native salt and two-phase flow considerations in hydraulic behavior. Consistent with other subject matter experts, these presentations emphasized the important effects associated with the presence of moisture in coupling the thermal, mechanical and hydrological regimes.

Compaction and consolidation behavior is further acknowledged as a key sub-process for salt disposal. These processes were extensively investigated and documented, providing confidence in their validity. Current open questions are not related to fundamental understanding of ambient-temperature consolidation, but instead to the transferability from different test methods and differences in test procedures at labs. Heat conduction in reconsolidating salt warrants collaboration and further research, particularly into heat transfer at the beginning of compaction when porosity is highest. Elastic parameters and other material characteristics can be more completely documented through additional laboratory testing. Given this identified research area, Sandia National Laboratories will examine their current test plans to address this need through an extended test matrix.

To advance the discussion above, it was agreed that the existing Sandia test plan would be sent to J. Mönig and G. Callahan for their considerations and recommendations. This was done November 21, 2011 via email. The granular salt compaction and consolidation work at Sandia is expected to continue through 2012, culminating in a technical report. With specific input from other subject matter experts, Sandia could optimize the test matrix and maximize return on investment. Test Plan SNL-FCT-TP-11-0001 was approved for use in May 2011. The primary purpose of these experiments is to quantitatively evaluate dry salt consolidation as a function of stress and temperature. A secondary purpose is to establish the deformational processes by which the salt reconsolidates. Test techniques for these elevated temperatures have been developed but remain burdened with technical difficulty. Through the mechanical data and observational work, Sandia intends to evaluate the applicability of the ambient model (Callahan, 1999), which accounts for the effects of moisture through pressure solution and dislocation creep.

Drying and possible change of consolidation mechanisms are hypotheses pertaining to crushed salt in a heat-generating salt repository. Related experimental work was identified to be of great interest to domestic and international salt repository programs during the 1st US/German workshop (KIT, 2011; Hansen and Leigh, 2011). Extensive discussion occurred regarding granular salt consolidation after formal presentations at the 2nd US/German Workshop on Salt Repository Research, Design and Operation. A considerable body of laboratory results, large-scale demonstrations and industry analogues exists among the several research entities participating in the 2nd US/German workshop. This existing information can be reexamined for the purpose of creating a collaborative review paper.

Session 4: Rock Salt - Deformation and Healing

Deformation and healing concerns the evolution and mitigation of the disturbed rock zone; it is named the DRZ in the US and excavation disturbed zone (EDZ) in most other countries. One of the key attributes of salt for disposal involves the reversal of the excavation damage in the EDZ, whereby fractures heal as the stress differences diminish. Healing arises when the magnitude of the deviatoric stress decreases relative to the magnitude of the mean stress. Salt healing processes include microfracture closure and bonding of fracture surfaces. Microfracture closure is a mechanical response to increased compressive stress applied normal to the fractures, while bonding of fracture surfaces occurs either through the relatively slow process of crystal plasticity, or the relatively rapid process of pressure solution and re-deposition. The presentation by Grupa et al. contains an introduction to spontaneous healing. Confirmation of healing has been obtained in laboratory experiments, small-scale tests and natural analogue observations.

The properties of the EDZ control a significant portion of the brine that is postulated to flow into waste rooms at the WIPP. EDZ properties also control potential transport pathways along seal systems that must be diminished to acceptable levels or eliminated entirely. Permeability is the most important EDZ characteristic. Damage-associated volumetric strain gives rise to increased permeability. The evolution and healing processes are therefore fundamentally important to seal system design considerations. Collaborators at the 2nd US/German workshop discussed laboratory testing, in situ testing and real-world analogues needed to build on existing information. The EDZ is often explicitly implemented in design analyses and performance assessment process models and will therefore be an important module for benchmarking the computational capabilities. Subsequent benchmark discussions can be found in Session 4.

EDZ response was identified as a key interest area at the 1st US/German Workshop on Salt Repository Research, Design and Operation. The approach taken to incorporate EDZ response to combined thermal and mechanical effects was through validation of the constitutive model, including permeability as a function of damage. To this end, the 2nd US/German workshop discussed mutual progress in terms of field experience and system design. Thermal and mechanical effects on the EDZ remain an important salt repository concern, particularly regarding heat-generating waste disposal.

J. Grupa from Nuclear Research and consultancy Group (NRG) and his colleagues from the HPT Laboratory at Utrecht University presented information on NRG´s capacities and the author's extensive experience and contributions in modeling salt rock deformation. Their research was often advanced in various international research projects (EC-Framework Programs) and has contributed substantially to the state of knowledge enjoyed by the salt repository community today. Their ongoing research includes plastic salt flow at elevated temperatures and dislocation creep influence and effects for describing phenomena using both experimental and modeling approaches. The microphysical plastic flow mechanism of dislocation motion at 100-200 degrees Celsius continues to be a fundamental question regarding plastic deformation of intact salt. They also explored spontaneous crack healing and mechanical crack healing in a confining stress field. Spontaneous healing is caused by transport of salt ions through a hygroscopic water layer. Pore water salt ion concentration in larger cracks is higher than the salt concentration in small cracks, due to the effects of surface tension. This difference drives diffusion of ions from large cracks to smaller cracks, resulting in dissolution of solid salt in large cracks and deposition of salt in small cracks. Through this process, crack inter-connection is lost; the EDZ reduces and eventually becomes impermeable.

D. Stührenberg and O. Schultze provided persuasive evidence for deformation and healing of both the EDZ and crushed salt. For many salt disposal concepts, these processes operate in tandem: as the crushed salt backfill consolidates it eventually develops structural competence and creates backstress on the country rock, which thereby effectively drives the stress state toward conditions favorable to healing the EDZ. Laboratory measurements have been made of porosity and permeability of crushed salt and the EDZ. The presented data generally show the strong effects of moisture, promoting both the healing and consolidation processes. Interestingly, salt continued to exhibit high permeability at porosities $<5\%$ when reconsolidated under dry conditions. The micromechanics explaining these results will be published at MECHSALT VII (www.saltmech7.com).

W. Minkley's presentations provided several analogues from extensive real-world experience and observations (gas break-out) that were explained in terms of the fundamental physical processes of fracture creation and propagation. The examples indicated saliferous barrier impermeability will be lost quickly if either the minimum stress or dilatancy criteria is violated. The minimum stress criterion is the most critical consideration for barrier integrity, because the importance of the dilatancy criterion is limited to the EDZ. Long-term warranty of an impermeable state depends on the stress state in the geologic salt barrier (both convergence and thermomechanical stresses) not violating the dilatancy or the minimum stress criteria. Effects of convergence-induced stresses on geological barriers was exemplified by the performance of the Asse mine, where geomechanical calculations illustrated a significant stress relaxation of the rock salt barrier and damage in the vicinity of the upper level. The Bokeloh salt dome represents an example of an actual rock mechanical situation where the minimum stress criterion was violated and a passage of fluids became possible. After reduction of fluid pressure at the dome flank, there was a significant decrease of inflow in the mine. Percolation of saturated brine was stopped when the fluid pressure fell below the minimal principal stress and a salt barrier sealing process began. Additional analogues included recovery of barrier integrity in the salt mass after a dynamically induced gas fracture, further demonstrating the self-healing capacity of rock salt.

Open discussion contemplated healing of the EDZ, including the great enhancement of healing by the presence of moisture. The fracture-healing process is attributed to pressure solution processes, the same mechanism that increases consolidation rates in granular salt. It is currently difficult to ascribe reduced permeability to "permanent" healing or to mechanical effects in practice. If moisture is present, fracture healing is likely to be permanent, and if the near field is dry, mechanical response could result in reduced permeability. Damage and healing of the EDZ in salt is also an important issue in hydrocarbon storage applications.

Session 4: Rock Salt - Coupled Modeling

Salt repository science, engineering, operations, and expected performance for HLW disposal have a strong foundation, including decades of large-scale or full-scale field tests, supporting intermediate-scale test results and significant laboratory data bases. Several advanced experimental and theoretical geomechanical models exist in the community (see A. Hampel and L. Arguello presentations in this workshop). Today, Sandia National Laboratories and German colleagues are examining the state of the art in computational mechanics as applied to heat-generating nuclear waste salt repositories. Several advanced constitutive models are being evaluated for design and long-term performance in salt formations. A. Hampel's presentation recounted the German Federal Ministry of Education and Research sponsorship of modeling collaboration for this purpose. The third phase of these studies *Priorities of Future R&D Work on the Final Disposal of Radioactive Wastes* is being continued in a joint project (2010–2014) with collaboration between Sandia National Laboratories and German partners:

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

Project objectives are to document and use benchmark calculations to compare constitutive models and modeling procedures. In this manner, the models and modeling procedures can be validated, which enhances the confidence in numerical simulations performed with the models.

The current phase of the project concentrates on thermomechanical damage and healing behavior. Two field tests are being modeled: a heated borehole and permeability measurements behind an 85-year old rigid bulkhead. Both tests were conducted in the 1990s at the Asse Mine in Germany. The creation of damage zones and healing processes in salt remain important technical issues for salt repositories. Approaches to modeling will include using field test information, laboratory results, and micromechanical processes. Both US and German researchers have made significant contributions on this active research topic. This work brings together a range of technical approaches including use of analogues from industrial salt mine sealing experience, large-scale testing, theoretical treatment of the damage function, micromechanics, permeability measurements, and numerical modeling.

Sandia National Laboratories (see L.Arguello presentation) has performed many verification and validation calculations of thermal-structural interaction tests conducted at WIPP from the 1980s to the 1990s. No further thermomechanical field tests were conducted at WIPP since then, but there have been software and hardware advances over this period. Thus, salt repository analyses have the potential to use the *next generation* of coupled massively parallel multi-physics capability being developed under a single computational framework at Sandia, known as SIERRA Mechanics. These tools are being applied to the benchmark collaborations described in A. Hampel's presentation by an internal Sandia initiative.

US/German collaborations have acknowledged salt repository benchmarking as a key topic, both to reexamine constitutive models and take advantage of newer, more powerful computational frameworks. This benchmark exercise will use codes that are appropriate for application to salt repository calculations, with appropriateness determined by a track record of published reports for similar calculations, demonstrated Quality Assurance, and other objective validation of the appropriate capability. Examples of SIERRA Mechanics application include Stone et al. (2010) and Arguello et al. (2011). As the US/German collaborations press onward in this area, Sandia proposes to model and thereby benchmark an appropriate thermomechanical field test from the WIPP underground testing era.

There were three full-scale, heated tests at WIPP that may serve as benchmarks for simulation. Sandia is currently examining an axisymmetric heated pillar test (Room H) and a Defense HLW heater test (Room B), as shown in Figure 1. An ambient temperature version of the Defense HLW test in Room B was conducted in Room D; thus, the Room B/Room D pair provides additional code validation possibilities. A collaborative benchmark aligned with a WIPP field test would necessitate various modelers to fit their constitutive models to WIPP data and make predictions against the selected in situ experiment. In principle, the WIPP benchmark could be added as a joint calculation under the Joint Project III collaboration.

Figure 1. Room H Heated Pillar and Room B Defense HLW Tests.

From the US salt repository perspective, a benchmark calculation would also help validate the requisite tools for modeling any future field demonstration or test. For test plan development, modeling could play an important role in instrument placement and in establishing the data quality objectives for the main test parameters. Looking forward, a benchmark modeling effort will assess the current capabilities of the thermomechanical computational codes available. The results of this work will establish the modeling framework for HLW repository design, possible demonstration or testing, and of course performance assessment when the salt repository program has progressed to that stage.

Session 5: Miscellaneous Topics - Natural Analogues

The 2nd US/German workshop addressed several R&D activities that can be pursued by laboratory testing, by field demonstrations or testing, and by way of computational modeling. One largely underutilized argument for permanent disposal in salt can be found in natural analogues as exemplified by W. Minkley's substantial presentation in Session 4, which provided several real-world analogues to salt repository performance. Natural analogues provide qualitative information in the context of performance assessment, which can be crucial to a safety case. Many anthropogenic and geologic analogues provide important insight into processes and system behavior for permanent nuclear waste disposal in salt. The organizers arranged for discussion of analogues at the 2nd US/German workshop, recognizing their power for conveying images of permanent encapsulation in salt. The German work includes identification and application of analogues to a safety case for a HLW rock salt repository (see the presentation by U. Noseck). N. Rempe makes a similarly persuasive case in his considerations of extreme-case analogues. Motivated by common interests and relevance to the qualitative safety case, the group identified the near-term goal of publishing a collaborative document on this topic.

Presentation material at the 2nd US/German workshop included bounding cases that demonstrate long-term robustness of salt disposal. Analogues are observable and tangible and understandable to the lay stakeholder, providing valuable information in the public eye. Anthropogenic evidence draws from mining experience, as well as some special cases of nuclear detonations in salt. Anthropogenic evidence associated with vast and pertinent mining experience provides important qualitative assessments of preserved artifacts. The geologic analogue of salt penetrated by volcanic dikes shows the transient high-temperature processes to be very limited; nature showcases the encapsulating ability of salt formations over long timescales.

Some of the analogue evidence is obvious: the current-day existence of the salt formation provides evidence for integrity against subrosion and diapirism, the impermeability of salt, and the mechanical and structural stability of the salt formation. The integrity of the geotechnical barriers also borrows from analogues, including EDZ healing around existing closure systems.

The most dramatic man-made analogues are nuclear detonations; they are considered beyond-worst-case analogues. Detonations were discussed by N. Rempe at the 2nd US/German workshop. The US has detonated three nuclear devices in geologic salt: one at the Gnome Site near WIPP and two at the Salmon Site at Tatum Dome in Mississippi. The 3.1 kiloton Gnome shot unintentionally breached drift closures and sent radioactive steam up the shaft; the site was cleaned up by dumping the surface material down the shaft. No migration has been detected outside the Gnome experiment boundary for more than a half century. The Tatum tests involved two sequential devices; the second was detonated in the cavity created by the first. Monitoring results indicate radioisotopes are confined to the test cavity. Salt formations have been shown to seal and confine nuclear detonations.

Geologic analogues also supply strong evidence of the confining nature of salt formations. Examples were presented of salt formations intersected by magmatic dikes at the 2nd US/German workshop. Despite the severe nature of such magmatic intrusions, there are only very thin alteration zones at the contact between the high-temperature igneous intrusion and the salt. No evidence of significant fluid (inclusion) migration toward the heat source has been reported from field observations.

Analogues involving massively disruptive events within a salt formation create palpable evidence of salt containment over very large distances and long times. These analogues are tantamount to qualitative performance assessment arguments for complete containment of nuclear waste disposal in salt. Obviously, there are no engineered barriers involved with the entombment and isolation demonstrated by analogues. Properties of salt allow the geological formation to absorb, naturally seal and encapsulate the intrusion.

Session 5: Miscellaneous Topics – Implementing Geological Disposal – Technology Platform

On November 12, 2009, Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) was officially launched. IGD-TP's Vision Statement is: *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.* At the time of this workshop, the platform had 91 participants that embrace the Vision Statement. W. Brewitz, W. Steininger, and S. Köster (BMWi) provided an overview at this workshop.

The first goal of the platform was based upon the state of the art, which involves a systematic approach to identification of research development and demonstration (RD&D) issues. These goals have matured into a strategic research agenda (SRA) comprising key topics, as well as topics of common interest necessary to fulfill the vision. Furthermore, the SRA articulates the stepwise procedure in prioritization of the topics in terms of importance and urgency. The implementation of topics will be followed by a deployment plan.

While the overarching goals include broad aims, some of the identified research focus areas are precisely the same goals established for the 2nd US/German Workshop on Salt Repository Research, Design and Operation, specifically the safety case and sealing systems. Therefore, it seems the goals and aspirations for repository programs in the US can follow the template provided by the IGD-TP to obtain positive results.

Session 6: Discussion of R&D Issues

In the summaries of each session above, certain *must-have* future activities were identified. Mutual identification of a coordinated research agenda is one of the tangible benefits of these workshops. Principal investigators at the 2nd US/German workshop agreed on several future goals.

Backfill. J. Mönig and others would like to elaborate on the compaction process at very low porosity, because this condition could theoretically create a pore-pressure situation and limit attainment of very low permeability. Participants in the 2nd US/German workshop include several researchers who have contributed significantly to our collective understanding of reconsolidation processes. The general consensus is that salt compaction is quite well understood, but some points need additional clarification. A small task force of the participants in this workshop has been encouraged to bring clarity to this issue as part of the ongoing collaborations. It seems the technical community has a multitude of laboratory results on this topic, including substantial demonstration underpinning the WIPP shaft seal system and industry experience. The ultimate natural analogue could be considered to be the undeformed natural Permian Basin salt with 1-3% porosity, which is saturated and impermeable.

Heated dry granular salt could behave differently if there is no moisture to activate pressure solution. Research described at the 2nd US/German workshop is evaluating whether heated dry consolidation can be represented by existing models (e.g., Callahan, 1996). Additional collaboration is encouraged to examine the considerable data available from D. Stührenberg. In particular, consensus is desired on representation of thermal conductivity as a function of porosity. Participants agree that salt consolidation is an important topic for continued research, particularly in a dry environment.

<u>Seal Systems.</u> It was clear from the several informative presentations and ensuing discussions that seal systems in salt repositories remain a crucial focus of the German repository programs. Seal systems comprise both distinct concerns, addressable by focused research and collaborations, and concerns regarding composite functionality, which can be addressed at a systems level. Seal systems are built of differing elements and verification of function can be achieved in several ways. Both the US and German programs have demonstrated performance of seal system components to various degrees. In the US program, the WIPP shaft seal system was found to be acceptable to the regulatory authority. The WIPP shaft seal system includes salt-based concrete, compacted bentonite clay and a column of reconsolidating granular salt. The DOE has submitted a change request to the WIPP regulator to change the drift closure systems at WIPP from a large-volume salt-concrete plug to a relatively long horizontal placement of mine-run salt. This is another application where it is essential to have a firm understanding of the governing parameters and properties of salt consolidation as a function of porosity.

German salt repository groups continue to develop and demonstrate construction and evaluate performance measures. Documentation of the WIPP shaft seal system and case studies of seals in salt environments have been shared among researchers. Collaboration will be continued on the use of natural and anthropogenic analogues for the qualitative case for long-term isolation in salt, since this was identified as useful to performance arguments. Under the aegis of seal systems investigations, fruitful collaborations regarding modeling, laboratory data and field demonstration results endure as future workshop topics.

<u>Benchmark Modeling Studies.</u> Today's computational environment enjoys enormous capabilities that can be brought to repository-class analyses. As discussed in Session 4, carefully controlled underground field experiments at WIPP could serve as benchmark modeling opportunities to assess these computational capabilities. The Salt Disposal Investigations (SDI) proposal in the US includes an activity to benchmark thermomechanical codes and models. Benchmarking computational capability is common practice and was done previously in the WIPP program, on an international parallel calculations exercise and most recently by the EU consortium for calculations on the BAMBUS II experiment (Bechthold et al., 2004). At the 2nd US/German workshop, ongoing benchmarking calculations were discussed at some length. A case study covering WIPP field tests has been proposed; it is likely Sandia National Laboratories will soon benchmark the SIERRA mechanics code against a selected WIPP field test.

In the Sandia benchmark calculation of the selected WIPP field test, many of the parameters will have already been established because the field tests were modeled in the 1980s and 1990s. The modeling structure and parameter values are documented. However, there are differences in the constitutive models adapted for the state-of-the-art codes and at this time there is a possibility to capture some of advanced concepts in the modeling. After the benchmarking exercise is completed, the US program will have powerful tools to perform forward calculations that would be useful for disposal concept demonstrations, possible test layout design and of course performance assessment for HLW disposal in salt. Hopefully, several of the most developed constitutive models for thermomechanical behavior of salt, such as the Günther/Salzer model (Günther and Salzer, 2007; Günther et al., 2010), can be brought to the benchmark studies through proposed international collaborations.

The capability to model thermomechanical coupled processes in salt is reasonably represented in several programs. These capabilities are being further developed in the Hampel consortium calculations, as described in the respective presentations in Chapter 2 of this report. Parties at the 2nd US/Germany workshop discussed the possibility of extending these benchmark exercises to an existing data set developed from a field-scale test conducted at WIPP. Although the WIPP experiments were conducted 25 years ago or more, the tests were carefully controlled, well defined and transparently executed under a well-established Quality Assurance program. A significant database of experimental results has been assembled for WIPP salt. The dataset of RESPEC tests was made available to A. Hampel while at the 2nd US/German workshop. These data are discussed and plotted in a Sandia report (Pfeifle, 1997). Interested partners could fit their respective models to the data set and run a well-defined benchmark calculation against field test results. If an agreement can be reached, the first step would involve fitting existing laboratory test data to the individual partner models. Sandia and IfG have also been exploring the possibility of collaboration regarding use of the Günther/Salzer law for calculations within SIERRA Mechanics.

Excavation Damage Zone. Salt damage modeling in the US has not included constitutive models that have a verified temporal healing function for the EDZ evolution and devolution. The WIPP compliance certification asserts that EDZ healing for drift and shaft sealing is sufficiently rapid to be time independent or considered instantaneous for design purposes. This conclusion is predicated on several studies including analogues and anecdotal information. Discussion at the 2nd US/German workshop on laboratory, modeling and field testing of the EDZ helped reinforce collaborations toward modeling the healing zone behind an 85-year old rigid bulkhead at the Asse Mine in Germany.

Technology Development—Visualization Tools. The VIRTUS visualization of geology at Gorleben and the geometry in the underground openings provides a potentially valuable tool for display of process level codes as realized in a repository setting.

Availability and Movement of Brine. Sandia National Laboratories will address this computationally using the SIERRA mechanics simulation platform. If a full-scale SDI field test is undertaken (outlined by R. Nelson in this workshop), accessible brine and vapor transport will be key considerations. It is possible to perform initial research on this topic in the laboratory, and it was proposed to create a joint laboratory testing program. O. Schultze emphasized that we must be careful to assure complete understanding of flow and differentiate single-phase flow from two-phase flow. The fundamental parameter during salt reconsolidation is not just permeability; it should include porosity and the nature of the pore structure. Examination of porosity and substructural features using optical and electron microscopy can be difficult because of the large grain size found in natural rock salt.

As R. Nelson described in the SDI disposal concept for heat-generating waste, future R&D goals include a firm understanding of the evolutionary processes involved with consolidation of heated crushed salt and vapor transport. Vapor-phase removal of accessible moisture from the local system is expected to occur when the salt heats up. The underlying question is whether the vapor is completely removed from the system by ventilation or does the vapor condense at some point "downstream". This question is entirely consistent with the scope of the proposed laboratory tests and the next generation of modeling. Based on evidence available to date, it is expected the vapor-transport effects on reconsolidation processes are nominal and acceptable in terms of performance consequences.

The original SDI concept has led to mining new underground space at WIPP. This new space is a *de facto* underground research laboratory (URL), which delivers potential for a wide range of salt science investigations. Opportunity exists to demonstrate a proof-of-principle disposal concept as well as URL space to be advantageously used to help further the salt repository agenda. The URL could potentially host a wide assortment of tests to confirm our collective knowledge on the technical basis for salt disposal. Consistent with our goals of collaboration, the URL space could be used to underwrite internationally significant science and engineering R&D, such as sealing elements and the EDZ. An ongoing performance confirmation program would be essential for regulatory approval of nearly any repository. Performance confirmation would also be necessary within the safety case arguments made for HLW in salt, similar to the experiences at WIPP and Yucca Mountain. Ongoing science made available by a salt URL could reassure societal and political stakeholders that confirmation of expected performance will be transparent. Due diligence also demands ongoing scientific research to confirm the licensing bases, although the safety case for a salt repository is robust and well substantiated.

Session 7: Salt Club

The goals and objectives established by the organizers of the 2nd US/German Workshop on Salt Repository Research, Design and Operation have now been supplemented by recognition of the IGSC-Salt Club by the Nuclear Energy Agency. Hopefully, the Salt Club will help build upon the objectives of the US/German workshops: to continue collaborative research activities, to build upon the research agenda and to renew working relationships at the institutional and individual levels. For this to be successful, *Rules of Engagement* for the Salt Club need to be established and a charter needs to be created and agreed upon. After some discussion, T. Rothfuchs was declared Salt Club Chairman by fiat, and he subsequently volunteered to draft a Salt Club Mandate. As these formative issues are being addressed, it is hoped that the kickoff meeting for the Salt Club can be held within the next six months.

A core group (Steering Committee) was nominated for the member nations of the Salt Club:

- Germany (E. Biurrun/DBE TEC, S. Köster/BMWi, and T. Rothfuchs/GRS/Chair).

- United States (F. Hansen/Sandia and A. van Luik/DOE)
- Poland (TBD)
- Netherlands (TBD/COVRA)

Salt Club undertakings are responsive to the NEA/IGSC goals and therefore reach a wider distribution and more extensive applicability. It was acknowledged that genuine advancement of the salt repository science will still be accomplished by small, dedicated groups

Several suggestions were discussed for initial Salt Club activities:

- A topical report on salt deposits throughout the world
- A FEPs catalog—consistent with the conclusions of the 2nd US/German workshop participants
- A salt knowledge archive and a safety case archive, the scope and definition to be determined
- A natural analogue workshop
- A technical statement about vapor/brine transport in HLW salt repository

These topics will be considered in due time after the Salt Club establishes operational protocol.

Activities of specific interest such as the agreement between Los Alamos and KIT on actinide solubility and the Sandia agreement with the German consortium for benchmarking are expected to continue under the auspices of existing Memoranda of Understanding.

Session 8: Concluding Remarks

The 2nd US/German Workshop on Salt Repository Research, Design and Operation allowed participants to explore a subset of issues important to HLW disposal in salt. National nuclear policy has impacted the repository options in both countries. The research agenda being pursued by our respective countries leverages collective efforts for the benefit of both programs. The US/German salt repository collaborations align well with the findings of the US Blue Ribbon Commission and are consistent with the aspirations of the IGD-TP. Disposal concepts have been developed in the US for salt, shale, volcanic rock, granite, and deep boreholes. Sandia National Laboratories has recently published in-depth technical reports on the performance of conceptual high-level waste repositories in shale, salt, granite, and deep boreholes. The position of overall US repository programs is similar in many respects to the goals of the IGD-TP.

From the perspective of the US repository programs, international collaboration has been attracting more support since the demise of the Yucca Mountain Project. Given suitable operational designs, there is substantial confidence that compliance with regulatory standards for human and environmental protection can be demonstrated for several geologic venues. The US repository experience and RD&D in salt far surpasses any other disposal option. Salt disposal has the greatest amount of previous research, by far the most practical mining experience, and is the option that makes the shortest bridge to a realized US repository. Favorable aspects of salt include ease of mining, multiple concepts of operations, and minimal engineered barriers.

Through these workshops, the primary salt repository researchers from Germany and the US have further advanced the technical basis for salt disposal. Within each session, concrete ideas about the direction forward were discussed and summarized. We agreed in principle to pursue these possibilities:

- Integrate a FEPs catalogue for HLW in salt.
- Write a document that establishes the safety case for HLW in salt.
- Provide international review of the Salt Disposal Investigations field demonstration.
- Enhance the test matrix of the Sandia National Laboratories salt compaction test plan.
- Write a review paper on reconsolidation of granular salt.
- Collaborate on benchmark modeling to assess the state-of-the art.
- Publish a collaborative paper on natural and anthropogenic analogues.

The realization of these specific goals depends on the initiative and resolve of the principal investigators.

Participants agreed to arrange the next workshop in the United States with a target date of May 2012. In the interim period, some of the collaborations noted above will be advanced, while others continue to be formed. The shape of repository policy in the US may change and interest in salt may increase in response to findings and recommendations of the US Blue Ribbon Commission. As stated earlier, the path forward for US repository science has much in common with the IGD-TP.

A formal R&D effort is needed to support shifts in strategy and to be responsive to regulatory expectations and requirements. One constructive approach being considered is to develop the technical case for HLW disposal in salt, based on the considerable amount of information available from previous studies in the US and Germany. In the process of developing the safety case, furtherance of R&D efforts will likely become clearer and help prioritize collaborations. Some of the relevant R&D topics for HLW disposal have been identified and discussed in the US/German workshops, as recorded here.

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Appendix A. Agenda

Wednesday, November 9

08:30-09:00	**WELCOME ADDRESSES**
	S. Köster, BMWi, A. Orrell, SNL, E. Biurrun, DBE TEC
09:00-10:00	SESSION 1: SAFETY ANALYSIS/SAFETY CASE
	J. Mönig, GRS, Chr. Leigh, SNL
10:00-10:10	Break
10:10-11:30	**SESSION 2: SEALING SYSTEMS FOR REPOSITORIES IN SALT I**
	N. Müller-Hoeppe, DBE TEC R. Mauke, BfS P. Kamlot, IfG
11:30-12:00	*Salt Disposal Investigation*
	W. Bollingerfehr, DEB TEC F. D. Hansen, SNL
12:00-13:00	**Lunch**
13:00-13:45	**SESSION 2: SEALING SYSTEMS FOR REPOSITORIES IN SALT II**
13:45-14:00	*Project Virtus+*
	T. Rothfuchs, GRS
14:00-14:45	**Discussion and summary of sessions**
14:15-1500	**Break**
15:00-16:00	**SESSION 3: BACKFILL**
	G. Callahan, RESPEC D. Stührenberg, BGR, Chr. Lerch, DBE TEC K. Wieczorek, GRS
16:00-16:30	**Discussion and summary of sessions**
16:30	Adjourn
17:00	**DEB Headquarter Evening of Science and Culture**
	Lecture by Prof. Kepplinger, Uni Mainz, “Media Opinions, Political Power” (in German)
18:00	Dinner hosted by DBE TEC and cultural event

Thursday November 10

08:30-09:30 **SESSION 4: ROCK SALT–Deformation and Healing**

J. Grupa, NRG, Chr. Spiers, Univ. Utrecht
O. Schultze, BGR
W. Minkley, IfG

09:30-10-30 *TM(H) Modeling – Benchmark*

A. Hampel, Hampel Consulting
L. Argüello, SNL

10:30-11:00 **Break**

11:00-12:00 **SESSION 5: MISCELLANEOUS TOPICS**

Natural Analogues
U. Noseck, GRS
N.T. Rempe, WIPP

Technology Platform IGD-TP

12:00-12:30 **Discussion and summary of sessions**

12:30-13:30 **Lunch**

13:30-14:30 **SESSION 6: DISCUSSION ON OPEN RD&D ISSUES**

Must-haves for the programs, identification of future joint activities

14:30 **End of workshop**

15:00-16:30 **SALT CLUB–ROUND TABLE**

Chairs: A. van Luik, DOE-WIPP
Klaus-J. Röhlig, TU Clausthal

Appendix B. List of Participants and Observers

2nd - US-German Workshop on Salt Repository Research, Design and Operation

Peine, Germany,

November 9 – 10, 2011

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Acronyms

BGR	Federal Institute of Geosciences and Natural Resources, Hannover
BfS	Bundesamt für Strahlenschutz (BfS), Salzgitter
BMU	Federal Ministry Environment, Nature Conservation and Nuclear Safety
BMWi	German Federal Ministry of Economics and Technology
CPRZ	Containment Providing Rock Zone (isolating rock zone)
DBE TEC	DBE TECHNOLOGY Gmbh
DHLW	Defense High-Level Waste
DOE	Department of Energy, US
EDZ	Excavation Disturbed Zone
ELSA	Schachtverschlüsse für Endlager für hochradioaktive Abfälle
FEP	Features Events and Processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH
HLW	High-level Waste
IGD-TP	Implementing Geological Disposal-Technology Platform
IfG	Institut für Gebirgsmechanik GmbH, Leipzig, Germany
KIT	Karlsruhe Institute of Technology, Germany
LUB-IUB	Leibniz Universität Hannover Germany
MECHSALT VII	Seventh Conference on the Mechanical Behavior of Salt
NRG	Nuclear Research and Consultancy Group, The Netherlands
R&D	Research and Development
RD&D	Research, Development and Demonstration
SDI	Salt Disposal Investigations
SNL	Sandia National Laboratories, Albuquerque US
TU BS	Technische Universität Braunschweig, Germany

TU C	Technische Universität Clausthal, Clausthal-Zellerfeld, Germany
URL	Underground Research Laboratory
US	United States
VIRTUS	Virtual Underground Research Laboratory in Salt
WIPP	Waste Isolation Pilot Plant, United States

Table 1. Areas of interest and possible assessment methods

Area of Interest	Specific Data / Information Need	Assessment Methods
Response of the DRZ to combined thermal and mechanical effects	• Validation of constitutive model • Permeability as a function of damage • Field demonstrations • Seal system design	• Laboratory testing • In situ testing • Model development • Analogue comparisons • International collaborations
Consolidation of backfill materials	• Thermal conductivity as a function of porosity • Consolidation constitutive model with temperature dependence	• Laboratory testing • In situ testing • Microscopy
Availability and movement of brine	• 3-D coupled analysis tools • Field test measurements and validation	• Literature review • Historic field measurements • Code capability development • In situ testing • International collaboration
Vapor phase transport mechanisms	• Further development of theory • Module development for coupled codes • Field test validation	• Viability of conceptual model workshop • Code capability development • Laboratory testing • In situ testing • International collaboration
Radionuclide solubility controls	• Establish viability of scenario for radionuclide solubility studies	• International collaboration • Laboratory testing

Area of Interest	Specific Data / Information Need	Assessment Methods
Potential radionuclide transport mechanisms	• Establish viability for transport mechanisms	• Theory development • International collaboration
Waste degradation	• Evolution of the disposal room • Source term	• Literature research • International collaboration • Analogue comparisons
Gas generation and pressure buildup	• Source term • Ensure seal system function	• International collaboration • Analogue comparisons
Buoyancy of waste packages	• Consensus from international peers	• Literature review • Workshop with consensus report
Plugging and Sealing	• Proof-of-Concept • Performance of system elements	• Demonstration experiments (large / full scale) • Accompanying laboratory experiments (material behavior) • Modeling (process level, PA) • Conceptual issues (state-of-the-art, review, etc.) • International collaboration
Radiolysis of waste materials, waste packages, and salt	• Establish the basis • Review application to HLW repository in salt	• Workshop with consensus report
Climate change	• Local climate scenarios • Coupled analysis tools for thermal-hydrologic-mechanical simulation of long-term processes	• Literature research • Analogue comparisons • Numerical site studies • International collaboration

Area of Interest	Specific Data / Information Need	Assessment Methods
	• Numerical studies of long-term evolution	•

CHAPTER TWO
AGENDA

Wednesday, November 9, 2011

Session 1

Preliminary Safety Assessment Gorleben

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

Abstract

The objectives of the preliminary safety assessment Gorleben (Vorläufige Sicherheitsanalyse Gorleben – VSG) are to assess, based on a preliminary safety case, the aptitude of the Gorleben site to host a HLW repository. The work includes, inter alia, safety analyses, the development of a repository concept and the identification of future needs with respect to R&D and site investigations. The project is conducted by leading German institutions with GRS being the main contractor. Started on Juli 2010, the project VSG will continue to December 2012 with an ensuing international peer review. The assessment is guided by the safety requirements for disposing high-level radioactive waste published by the German Ministry of Environment, Nature Conservation and Radiation Protection in October 2010. This first application of the new safety requirements, which contain detailed requirements in 8 topics, will aid to identify areas where future refinements of the safety requirements are desirable or where additional regulatory guidelines are necessary.

The work of the VSG project is organized in work packages. Owing to the ongoing status of the project, only an outline is presented with some initial results. Site investigations in the past have provided a wealth of information which is summarized in several publicly available reports by the Federal Geological Survey (BGR). Based on this information the future evolution of the site was predicted. The amount of the HLW waste to be emplaced was estimated on the basis of the recent German decision to phase out the use of nuclear energy until 2022. This embraces about 37.000 PWR spent fuel elements, about 3.700 canisters with vitrified high level waste and about 4.000 canisters with compacted reprocessing waste. Additionally, an optional disposal of some low-level waste is considered. An outline of the safety concept and the concept for demonstrating safety was established. The post-closure safety concept focusses on the safe containment of the emplaced waste, which 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 (CPRZ, sometimes also called isolating rock zone) during the demonstration period of 1 million years.

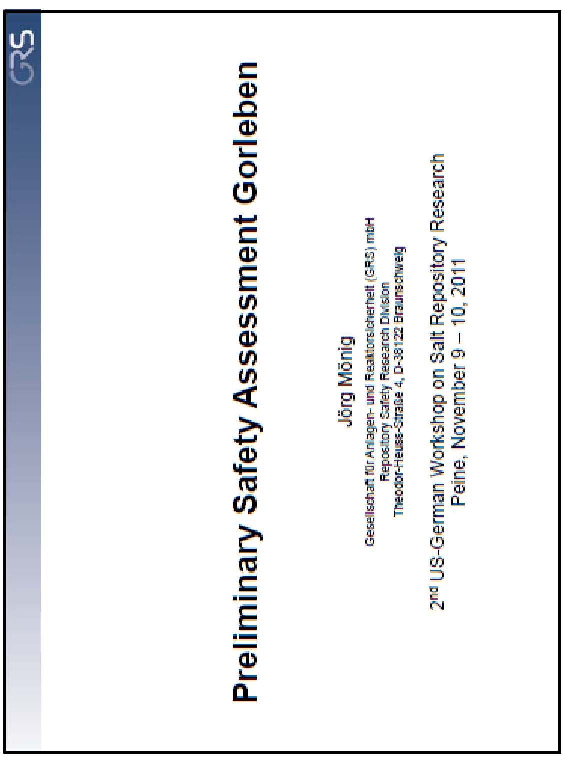
A repository concept was developed by DBE Technology, which involves drift disposal of the waste in thick-walled canisters. In addition, a borehole concept will be developed. The safety requirements demand that all high-level waste can be handled and retrieved safely during the repository's operational phase and can be recovered post-closure up to 500 a.

A site-specific catalogue of features, events and processes was derived, which contains detailed information concerning the various FEP. In particular, the interdependencies of the FEP are identified, the time windows of action, and whether the FEP impairs the function of so-called containment-providing barriers. Using the FEP catalogue future evolutions of the site were identified in a systematic way starting from FEP leading to an impairment of the function of primary containment-providing barriers. All evolutions are considered which involve a contact of solutions with the waste canisters and the mobilisation of radionuclides from the waste.

The proof of safe containment is a staged assessment with quantitative and qualitative arguments. Complete containment is regarded as the most stringent form of safe containment. Complete containment is given when no contact between intruding solution and waste occurs or when no radionuclides are released from the CPRZ, respectively. In all other cases, the calculated annual radionuclide fluxes from the CPRZ are taken up in a defined low volume of groundwater. Using a stylised exposure scenario, radiation exposures are calculated and related to a limit value of 0.1 mSv/a. As long as the resulting value is below 1, the radionuclide releases from the CPRZ can safely be considered to be radiologically insignificant.

(INSERT Jörg Mönig: Preliminary Safety Assessment Gorleben PRESENATIONS)

Jörg Mönig



Preliminary Safety Assessment Gorleben
Jörg Mönig
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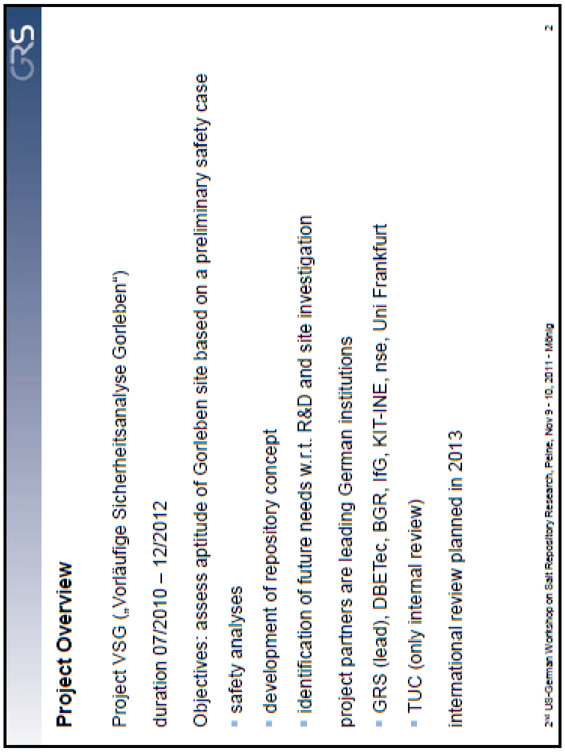
Repository Safety Research Division
Theodor-Heuss-Straße 4, D-38122 Braunschweig
2nd US-German Workshop on Salt Repository Research
Peine, November 9 – 10, 2011



Project Overview
Project VSG („Vorläufige Sicherheitsanalyse Gorleben")
duration 07/2010 – 12/2012
Objectives: assess aptitude of Gorleben site based on a preliminary safety case
safety analyses
development of repository concept
identification of future needs w.r.t. R&D and site investigation
project partners are leading German institutions
GRS (lead), DBETec, BGR, IfG, KIT-INE, nse, Uni Frankfurt
TUC (only internal review)
international review planned in 2013
2nd US-German Workshop on Salt Repository Research, Peine, Nov 9 - 10, 2011 - Mönig
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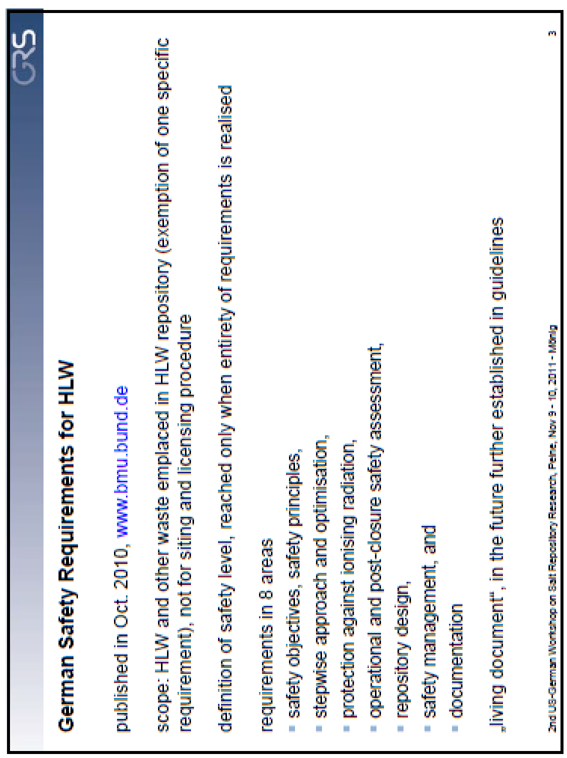

German Safety Requirements for HLW
published in Oct. 2010, www.bmu.bund.de
scope: HLW and other waste emplaced in HLW repository (exemption of one specific requirement), not for siting and licensing procedure
definition of safety level, reached only when entirety of requirements is realised
requirements in 8 areas
safety objectives, safety principles,
stepwise approach and optimisation,
protection against ionising radiation,
operational and post-closure safety assessment,
repository design,
safety management, and
documentation
„living document", in the future further established in guidelines
2nd US-German Workshop on Salt Repository Research, Peine, Nov 9 - 10, 2011 - Mönig
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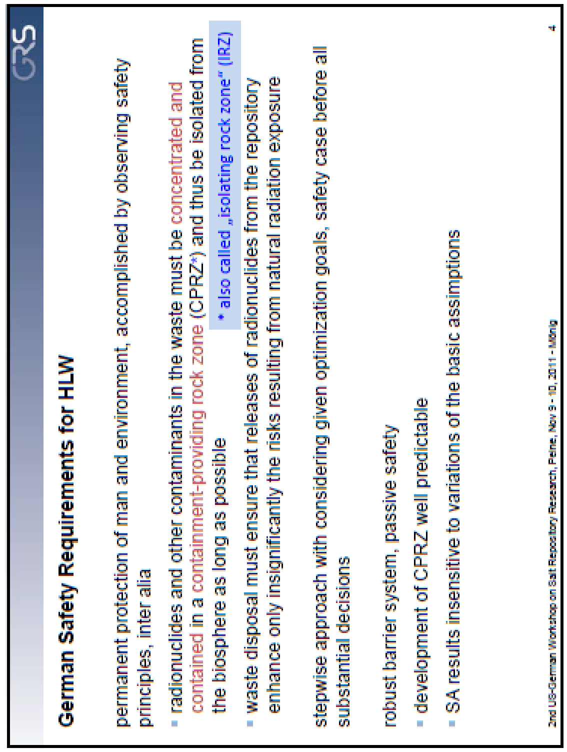

German Safety Requirements for HLW
permanent protection of man and environment, accomplished by observing safety principles, inter alia
radionuclides and other contaminants in the waste must be concentrated and contained in a containment-providing rock zone (CPRZ*) and thus be isolated from the biosphere as long as possible
* also called „isolating rock zone" (IRZ)
waste disposal must ensure that releases of radionuclides from the repository enhance only insignificantly the risks resulting from natural radiation exposure
stepwise approach with considering given optimization goals, safety case before all substantial decisions
robust barrier system, passive safety
development of CPRZ well predictable
SA results insensitive to variations of the basic assimptions
2nd US-German Workshop on Salt Repository Research, Peine, Nov 9 - 10, 2011 - Mönig
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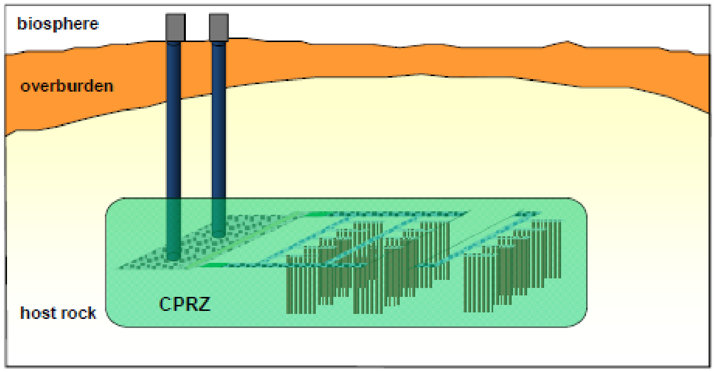
Containment-Providing Rock Zone (CPRZ)



German Safety Requirements – Key Issues

Demonstration of
- integrity of CPRZ
- integrity of geotechnical barriers (shaft and drift seals)

for likely evolutions of the repository system

requirements concerning waste canisters
- retrievable during operational phase
- recoverable up to 500 a post-closure, no release of aerosols

calculated exposures or radiation risks are indicators, permissible additional effective radiation exposure in the biosphere
- 0.01 mSv/a for likely evolutions
- 0.1 mSv/a for less likely evolutions

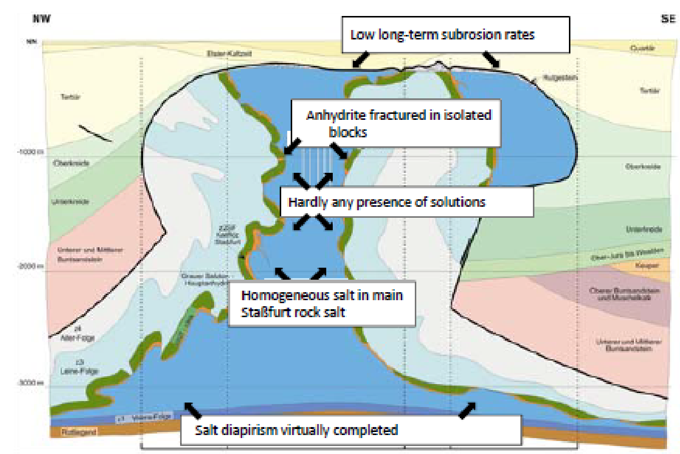
simplified radiological long-term prediction

VSG Project Plan

Basics		
site characterisation and long-term prediction	waste characterisation and quantity	safety concept 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 during the demonstration period
- An **insignificant release** from the CPRZ is a release whose radiological consequences calculated by a biosphere model are below permissible limits and thus pose no risk to subjects of protection

Features of Gorleben Site



Post-Closure Safety Concept Objectives

rapid enclosure of waste canisters by the salt rock

CPRZ remains preserved during demonstration period, its barrier function is not impaired by external and internal processes and events

influx of only very small quantities of solution to the waste canisters in likely system evolutions, influx of small quantities of solution in less likely evolutions

gas generation and gas pressure increase rate is constrained to prevent any frac of the salt rock

transport of radionuclides and release from the CPRZ is retarded by chemical and physical processes

no criticality at any time

requirements are derived from these objectives with respect to

- positioning, design and mining of repository
- technical measures

VSG Project Plan

Basics

site characterisation and long-term prediction | waste characterisation and quantity | safety concept and demonstration concept

waste to be emplaced (based on phase-out of nuclear energy use until 2022)

- spent fuel elements
  - PWR, BWR, VVER - ~ 37.000 (8 % MOX)
  - various research reactors
- reprocessing waste
  - vitrified waste (~ 3.700 CSD-V)
  - compacted waste (~ 4.000 CSD-C)
- other (low-level) waste not to be emplaced in Konrad repository, e.g.
  - tails from uranium enrichment plant (35.000 m^3)
  - various other LLW (15.000 m^3)

VSG Project Plan

Basics

site characterisation and long-term prediction | waste characterisation and quantity | safety concept and demonstration concept

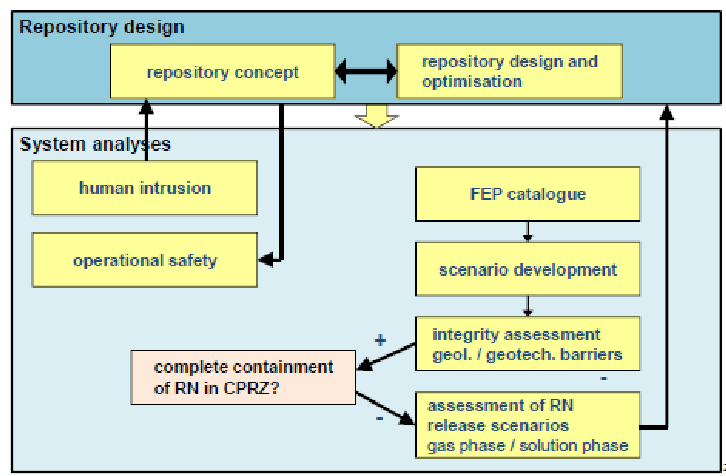
Repository design

repository concept ↔ repository design and optimisation

repository concepts considered

- emplacement of HLW
  - drift emplacement in thick-walled casks (Pollux and Castor)
  - emplacement in boreholes with steel liners
- emplacement of LLW iin dedicated waste packages in chambers and drifts

VSG Project Plan



Scenario development

based on comprehensive Gorleben-specific FEP catalogue

possible (and plausible) future evolutions (scenarios) of the repository system are derived in a systematic way

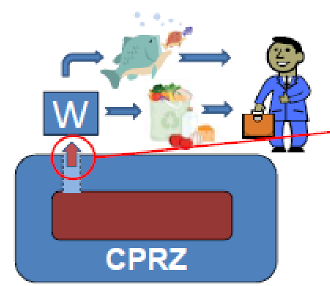
main starting point are FEPs that lead to an impairment of the function of primary containment-providing barriers

- geological barrier (salt)
- shaft and drift seals
- canisters for spent fuel and vitrified waste

all evolutions are considered which involve

- contact of solutions with the waste canisters
- mobilisation of radionuclides from the waste

Demonstration of Radiological Insignificance of RN release



activity fluxes [Bq/a] dose conversion factors

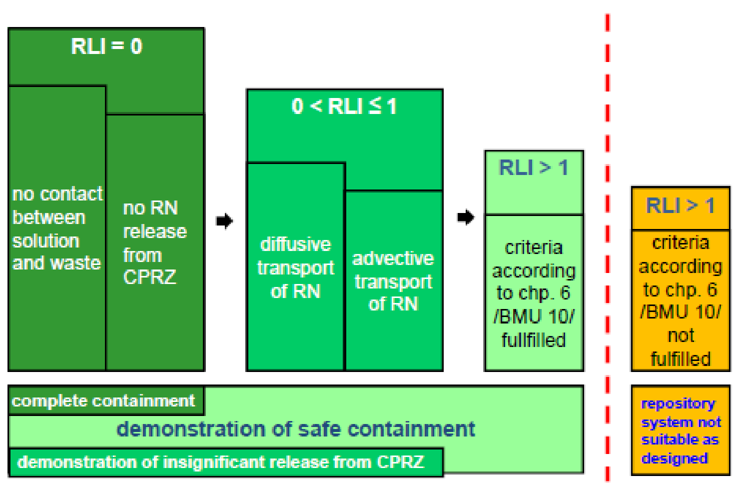
$$RLI = \frac{\sum_i S_i \cdot DCF_i}{W \cdot K_{RLI}}$$

5000 m³/a inspection level: 0.1 mSv/a

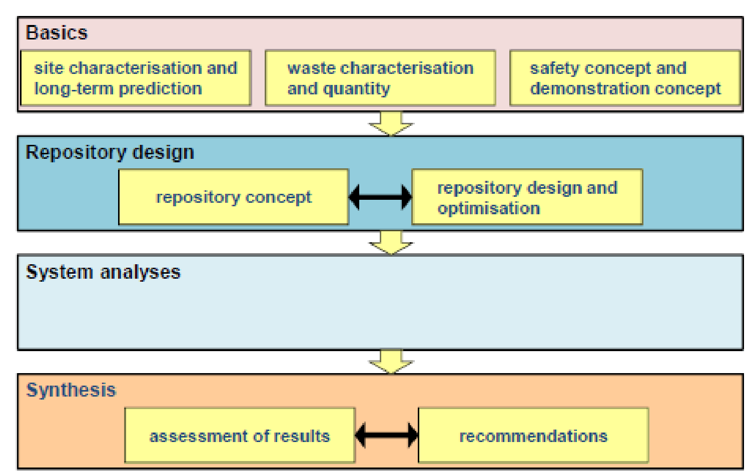
- stylised exposure scenario is used
- comparison with radiation exposure in biosphere

⇨ Proof of Safe Containment is a staged assessment with quantitative and qualitative arguments

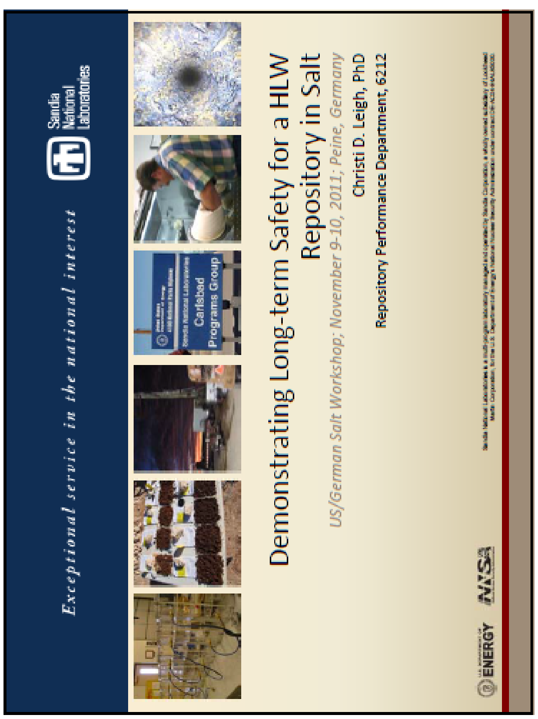
Assessment Scheme for Scenarios

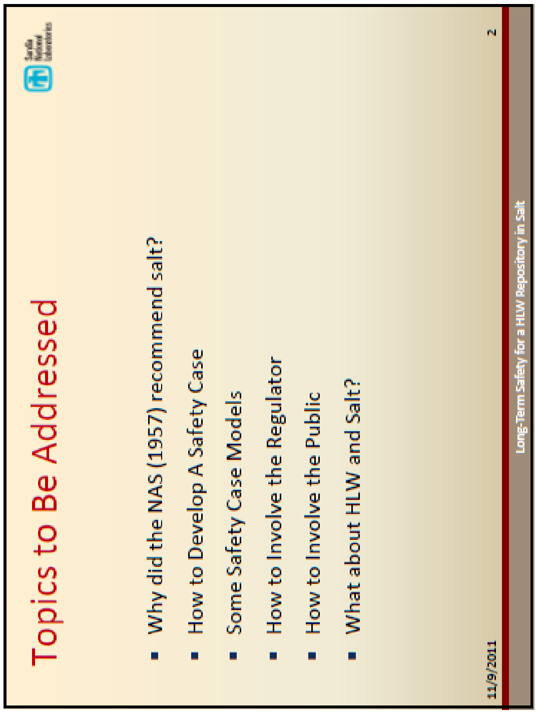


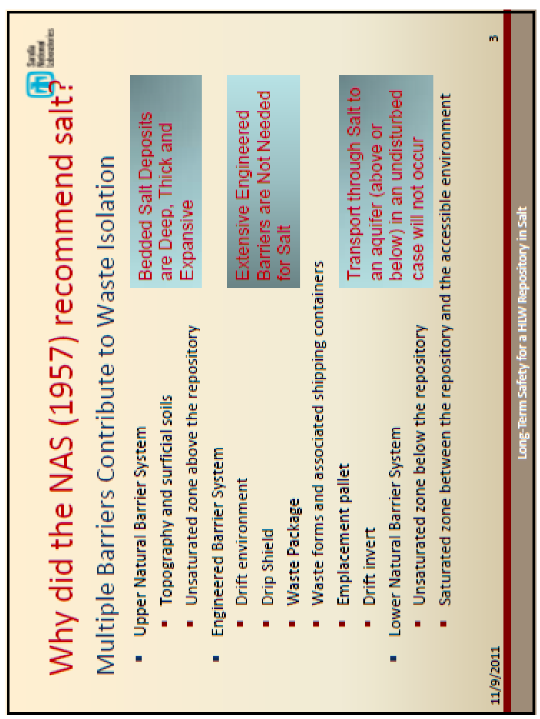
VSG Project Plan

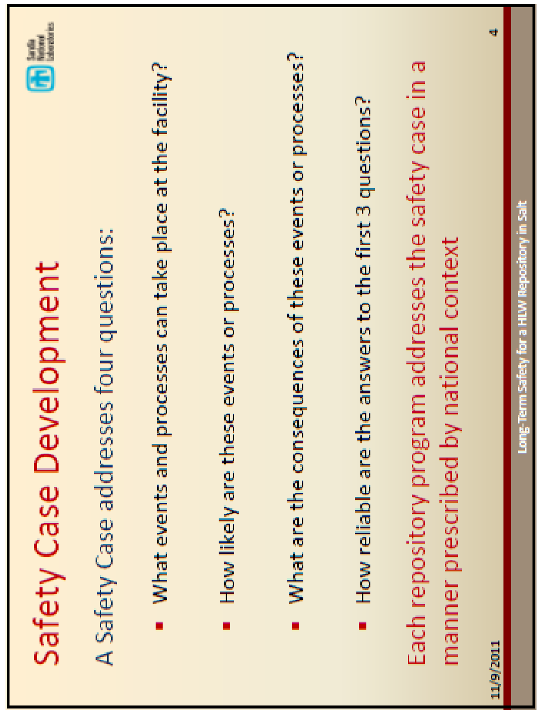


Christi Leigh: Demonstrating Long-Term Safety for a HLW Repository in Salt (No Abstract)









What events and processes can take place at the facility?

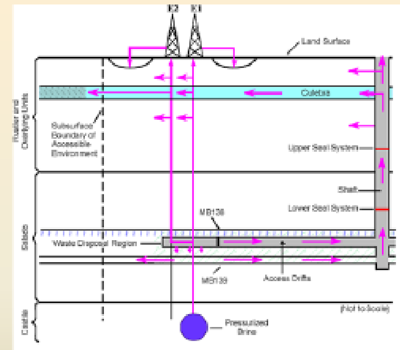
Identification begins with a large list of FEPs:

- Use is made of existing FEPs lists
- USA programs have used the international list for salt and volcanic tuff
- Our collaborations could develop a FEPs list for HLW in salt and serve as a foundation for analyses

Some possible FEPs for a HLW repository in salt: Response of the DRZ to combined thermal and mechanical forces, Consolidation of backfill materials, Availability and movement of brine, Vapor phase transport mechanisms, Radionuclide solubility controls, Potential radionuclide transport mechanisms, Waste form and/or waste package degradation, Gas generated and pressure buildup, Buoyancy of waste package, Radiolysis of waste materials, waste packages, and salt.

How likely are these events or processes?

FEPs are evaluated and scenarios are formed given the waste type, proposed repository location and geologic medium, and the concept of design



A scenario for an anticlinal salt formation or a salt dome would be different than a bedded salt—these depend on geology. Human intrusion and the possibility of mineral extraction (drilling?) also depend on geology. All of the Yucca Mountain scenarios are built around the geology: e.g., seismic or volcanism.

What are the consequences of these events or processes?

Consequences are estimated based on:

- Conceptual Models – conceptually, how will the system behave?
- Mathematical Models – how can the conceptual model be implemented mathematically?
- Computer Models – how can the mathematical model be solved using computing resources?

The international community is greatly advanced in its ability to estimate consequences related to a salt repository for HLW.

How reliable are the answers to the first 3 questions?

Epistemic uncertainty incorporated through Latin hypercube sampling of cumulative distribution functions and Monte Carlo simulation with multiple realizations

Aleatory uncertainty incorporated through the design of the analysis

- Incomplete data
  - for example, limited hydrologic data from test wells
- Spatial variability and scaling issues
  - data may be available from small volumes (for example, porosity measurements from core samples), but may be used in the models to represent large volumes
- Measurement error
  - usually only a very minor source of uncertainty
- Lack of knowledge about the future state of the system
  - probabilities of disruptive events
- Alternative conceptual models

All analyses must be conducted within a Quality Assurance Framework

Some Safety Case Examples

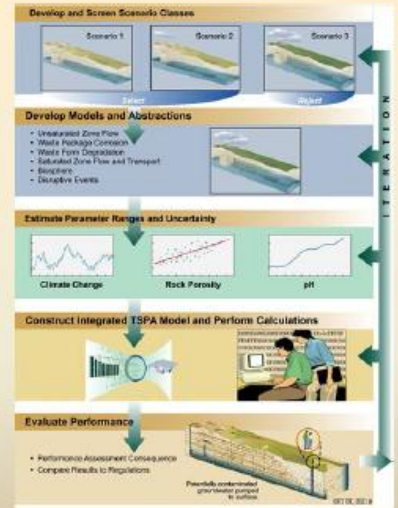
The U.S. Paradigm

- Screen FEPs and develop scenario classes
- Develop models and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes
- Evaluate uncertainty in models and parameters
- Construct integrated TSPA model using all retained FEPs and perform calculations for the scenario classes and "modeling cases" within scenario classes
- Evaluate total-system performance; incorporating uncertainty through Monte Carlo simulation

11/9/2011 9

Long-Term Safety for a HLW Repository in Salt

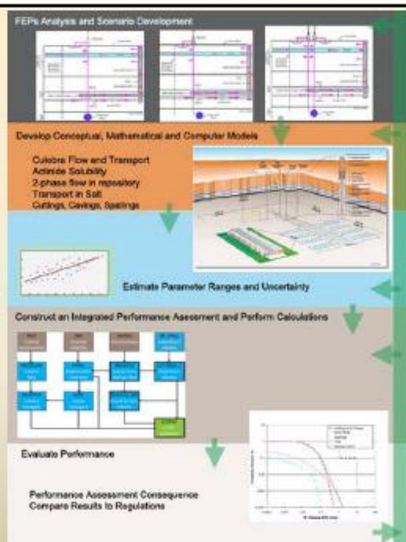
Yucca Mountain



11/9/2011 10

Long-Term Safety for a HLW Repository in Salt

Waste Isolation Pilot Plant



11/9/2011 11

Long-Term Safety for a HLW Repository in Salt

An Example from Belgium

(NOCA 2009. *Long-Term Testing and Monitoring Strategy—Final Report.*) Issue No. 1 3641390//SNL-URS

There is confidence that the safety concept and the design of the proposed disposal system show sufficient promise to proceed to the next program stage

DS The proposed disposal system is properly defined and its development has been guided by a well-defined and rational step-by-step safety strategy	SS The proposed disposal system will provide passive long-term safety if implemented according to design specifications	FS The proposed disposal system is feasible	US The residual uncertainties related to the proposed disposal system can be adequately dealt with in future program stages
DS 1 The waste to be disposed of, including its conditioning characteristics, is adequately known	SS 1 The assessment basis provides evidence that the safety functions will be fulfilled as described by the safety concept	FS 1 The assessment basis and feasibility assessment provide evidence of the engineering practicality of the disposal system	US 1 There are no uncertainties that call into question the capacity of the system to fulfil the requirements
DS 2 The application of the safety strategy takes proper account of the boundary conditions of the B&C program and of the available science and technology	SS 2 Results from long-term safety evaluations confirm the safety of the disposal system	FS 2 Operational safety, as evaluated in feasibility assessment, will be provided, taking into account all relevant uncertainties	US 2 There are good prospects that it will be possible to incorporate reserve FEPs in future safety models, thereby leading to higher calculated safety margins
	SS 3 Quality assurance procedures have been applied that favor confidence in assessment basis development and in the findings of long-term safety assessment	FS 3 Costs for the construction, operation and closure of the repository, as calculated in feasibility assessment, can be covered with the current funding mechanism	US 3 There are good prospects that future RD&D will enable relevant non-critical uncertainties to be reduced or even avoided
		FS 4 Quality assurance procedures have been applied that favor confidence in assessment basis development and in the findings of feasibility assessment	

11/9/2011 12

Long-Term Safety for a HLW Repository in Salt

What about HLW and Salt?

- Each repository program addresses the safety case in a manner prescribed by national context
- Collaboration on a FEPs list for HLW may be a useful engagement. Each program could build and streamline from such a compendium
- FEPs are evaluated and scenarios are formed given the waste type, proposed repository location, geologic medium, and the concept of design
- The international community is greatly advanced in its ability to estimate consequences related to a salt repository
- All analyses must be conducted within a Quality Assurance Framework

Session 2

SEALING SYSTEMS FOR REPOSITORIES IN SALT I

N. Müller-Hoeppe

DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine, Germany

When closing a final repository in rock salt, sealing systems are installed to supplement the tight geological barrier in order to seal the access routes into the repository. These sealing systems – shaft and drift seals – play a significant role in long-term repository safety. Shaft and drift seals are considered to be geotechnical structures. Therefore, they have to be designed in accordance with the applicable regulatory and technical guidelines. Shaft and drift seals have been constructed either as a prototype or as a sealing system for usage. The drift seals are situated in the Asse repository /1/ and the Morsleben repository /2/, the shaft seals in the Salzdetfurth mine /3/. In the case of the Asse and the Morsleben repository LLIL-radioactive waste has to be separated from biosphere, in Salzdetfurth long-term dry closure of a salt mine was required. As a consequence in all these cases long-term aspects had to be considered.

When licensing sealing systems for repositories their constructability and safety functions must be verified and the reliability has to be confirmed. Additionally, they are treated as geotechnical structures and therefore it has to be confirmed to what extent it is possible or rather necessary to apply the European Standard in civil (geotechnical) engineering /4/.

Typically, constructability is demonstrated by prototype construction. Some short-term safety functions can be verified by in situ testing. To show reliability of short-term safety functions two steps are recommended. First, in situ test results are compared to the results of blind predictions. Usually, deviations arise and knowledge gaps become evident. As a consequence process understanding is improved and knowledge gaps closed e.g. using back analyses of in situ test results. Finally, the tools used for predictions are improved. If predictions cover tests results adequately, in a second step it is confirmed whether the predictions show the level of reliability required by applicable technical standards.

To show long-term reliability in terms of civil engineering standards – although the standards do cover long-term processes - advanced approaches have to be applied. As a first step the following procedure has been established applying in principle the method of partial factor design. Actions acting on the sealing systems as well as the resistances are classified. As a result it was found that a large number of actions and resistances do not depend on time. In other cases time can be eliminated by state variables used in standard engineering procedures. Thus, short-term and long-term proofs show the same procedural method even though the quantities may differ when taking into account very long functional life of geotechnical structures.

As a second step it was examined whether actions exist that are neglected in short-term proofs which may become important in the long-term. Comparison of technical guidelines and FEP–lists were suitable to perform this step. Results indicated that actions related to geochemical conditions (e.g. corrosion processes) are mostly neglected in short-term considerations but may have significant influence in the long term. The scientific procedure to handle this problem is well established. Short-term data are created and predictions are made using geochemical calculations for extrapolation purposes. Natural analogues – if available – are used to underpin the predicted results. Adequate engineering procedures still have to be established. For that reason the actions induced by geochemical conditions acting on seals were identified. Fluids (gas and brine) were identified to define the geochemical action on sealing systems potentially at elevated temperatures in the case of HLW/SF disposal. Next the amount of brine was checked to define the main action. In this context it turned out that brine intruding from the overburden is recognized to constitute the main action as the brine reservoir is unlimited. Thus, the corrosion potential is assumed to be at a maximum. The type of brine depends on the potential pathways being considered. For instance unsaturated brines from upper groundwater levels may migrate towards the shaft seals, NaCl saturated brine containing sulphates may originate from the cap rock, and $MgCl_2$ saturated brine from $MgCl_2$ deposits (e.g. potash) on discrete pathways.

The Asse repository serves as an example of $MgCl_2$ saturated brine due to large amounts of potash available along potential pathways. In the case of the Morsleben repository both NaCl saturated brine as well as $MgCl_2$ rich brine may occur depending on individual pathways that cannot be predicted in advance. In the case of the Gorleben exploration site, however, the shafts are assumed to form the only pathways. Close to the top of the salt the amount of $MgCl_2$ available is small. Growing $MgCl_2$ enrichment, however, cannot be excluded with increasing depth.

Regarding resistances it is stated that Magnesium oxycloride concrete shows high chemical stability and durability against $MgCl_2$-rich brines. Thus, after prototype testing the material was selected for constructing drift seals in the Asse repository. In an NaCl-rich environment Ca-based salt concrete shows high chemical stability/durability. Drift seals made of salt concrete are mainly planned to seal the emplacement areas in the Morsleben repository. A prototype drift seal made of salt concrete was erected and in-situ testing is currently ongoing. At the Gorleben exploration site both materials are assimilated along the pathways of saturation. Additionally, a sealing element made of bentonite is planned at time close to the overburden interface, comparable to that which was tested at the Salzdetfurth mine. Although the second step to prove resistance of sealing systems against chemical actions reliably is still ongoing, progress has been made indentifying main actions and resistances /4/ of long-term corrosion processes.

In the context of prototype in situ testing it became evident the EDZ/contact zone acted as a preferred pathways showing localized flow /5/. By in situ investigations it was determined that flow takes place using a small zone of about 1 cm thickness. Measurements indicate that in the small damaged zone flow depends on the differential stress $\Delta p = \sigma_{min} - p_{fl}$ even though the level of permeability is about 2 – 3 orders higher than in intact rock salt /6/. To check plausibility of this result the levels of permeability measured in this small zone were compared to levels of permeability that were measured in EDZs. It turned out that the same range is covered.

As a result it can be stated that progress was made treating long-term processes in the context of the European Standards. Geochemical conditions were analysed and used for designing sealing systems. The data basis on contact zones was improved leading to a better understanding of hydro-mechanical behaviour.

ACKNOWLEDGMENTS

The work referred to in this paper was made in cooperation with colleagues from Asse GMbH (former GSF/HMGU), BGR, BfS, DBE, GRS , IfG, IBeWa and TU Clausthal. Many thanks to them for their excellent collaboration.

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N. Müller-Hoeppe

SEALING SYSTEMS FOR REPOSITORIES IN SALT I

Nina Müller-Hoeppe
DBE TECHNOLOGY GmbH

2nd US-GERMAN WORKSHOP ON SALT REPOSITORY RESEARCH, DESIGN, AND OPERATION
November 9 -10, 2011
PEINE, GERMANY

Conclusions from US-German Workshop 2010

Applying the European Standard to a repository in rock salt helps

- to link "long-term SA" and the proof of safety function of saeling systems
- to derive and apply adequate technical specifications and procedures
- to indicate issues that cannot reliably be proven at present

Agreeing with the European Standard in civil engineering is fundamental for licensing

The European Standard is an excellent tool to identify the most urgent R&D

Next steps (from the viewpoint of 2010)

- Investigations to check to consequences of different working lives for sealing systems barriers required in "long-term SA" and European Standards
- Coupling of the risk based engineering approach to prove safety function and the dose based approach to prove radiological safety

Basic Questions

When constructing seals the following questions must be answered:

- How is constructability, safety function, and reliability proved?
- In what extent is it possible to apply the European Standard in civil (geotechnical) engineering?

Standard Answers and Procedures

Constructability → Prototype construction

Safety function (short – term) → In-situ testing

Reliability (short – term, 1. step) → Back analysis of in-situ tests´ results and comparison with blind predictions
→ Analysing deviations and knowledge gaps

Improvement of process understanding and closure of knowledge gaps
→ Improvement of tools used for predictions

Reliability (short – term, 2. step) → Applying the required level of reliability according to technical standards to sealing systems

Advanced Answers and Procedures

Reliability (long – term, 1. step) → Classification of actions acting on sealing systems and their resistances (i. e. method of partial factor design in principle)

A lot of actions/resistances do not depend on time or time can be eliminated by classical state variables
→ no difference between short-term and long-term proofs

Reliability (long - term, 2. step) → Check the existence of actions that are neglected in short-term proofs which may become important the long-term (FEPs)

Actions related to geochemical conditions (e.g. corrosion processes) may be of significant influence the long-term
→ Applying the classical scientific procedure: Creation of short-term data, prediction by extrapolation, use of natural analogues

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Example: Asse Repository

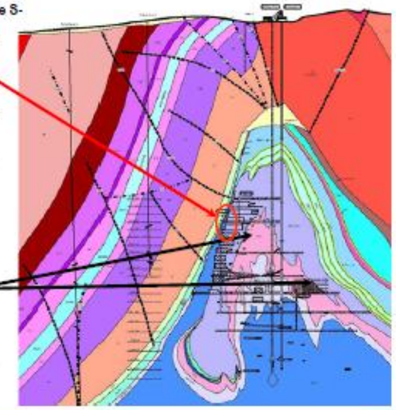
Brine intrusion (12 m³/d): since 1988 at the S-flank via the disintegrated salt barrier

Brine changed from $MgCl_2$ rich brine and is now saturated at NaCl and $CaSO_4$ but poor in $MgCl_2$

Exposed carnallitite layers

Dissolution or disintegration of the carnallite by interaction with the intruding $MgCl_2$-poor brine during the post operation period
➢ Destruction of large amounts of carnallitite and destabilization of the underground facilities
➢ Risk of rock breaking and collapse of the underground facilities

Note: The $MgCl_2$ reservoir was consumed, evidently



Source: GSF

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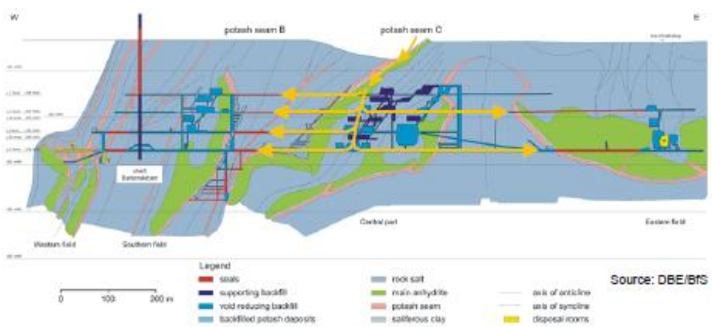
Example: Morsleben Repository

Brine intrusion (11 m³/a): Pathways connected to overburden far from emplacement areas



Source: DBE/BfS

Several brine types are possible as intruding brine may pass or bypass potash seams. Additionally, $MgCl_2$ consuming salt concrete backfill is also available.

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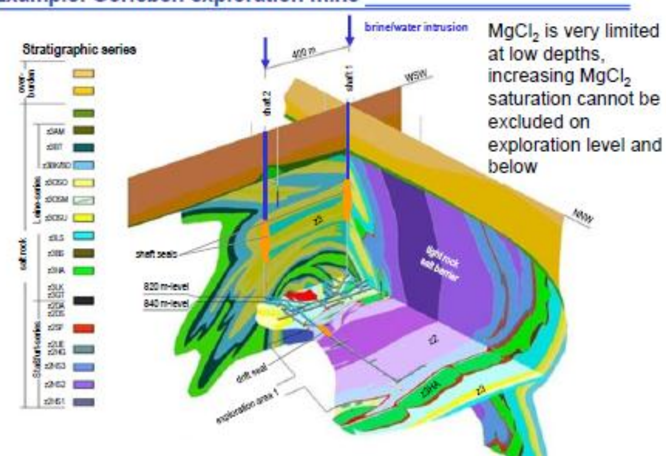
Example: Gorleben exploration mine



$MgCl_2$ is very limited at low depths, increasing $MgCl_2$ saturation cannot be excluded on exploration level and below

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Engineering Approach

What is the main action induced by geochemical conditions affecting the seals?

- Fluid phases (brine and gas) and temperature rise in the case of HLW/SF disposal
- With respect to seals brine intruding from the overburden is recognized as the main action as the brine reservoir is unlimited
- Brine saturation depends on existing or potential pathways
  - Unsaturated brine from upper groundwater levels (Rain water serial)
  - NaCl saturated brine containing sulphates, e.g. $CaSO_4$ (Cap rock serial)
  - $MgCl_2$ saturated brine (Depending on available $MgCl_2$ on pathway)
- Brine at nearly constant temperature is assumed

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Long-term Stability/Durability of Materials

$MgCl_2$-rich environment → Magnesium oxycloride concrete (Sorel-concrete) shows high chemical stability/durability

NaCl-rich environment → Ca-based salt concrete shows high chemical stability/durability

as a consequence

→ Asse: Drift seals made of magnesium oxychloride concrete are under construction

→ Morsleben: Drift seals made of salt concrete are mainly planned, prototype construction is finished. Presently, in-situ testing is going on

→ Gorleben: Both materials are under discussion following the pathways of saturation (shafts are assumed to be the only possible pathways)

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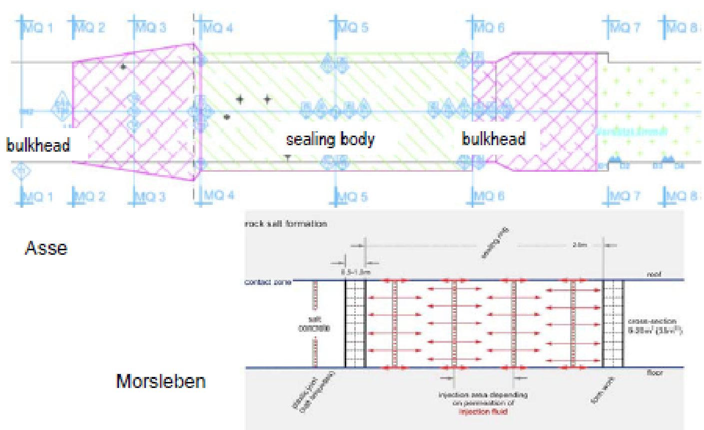
Drift Seal Concepts - Realised Prototypes



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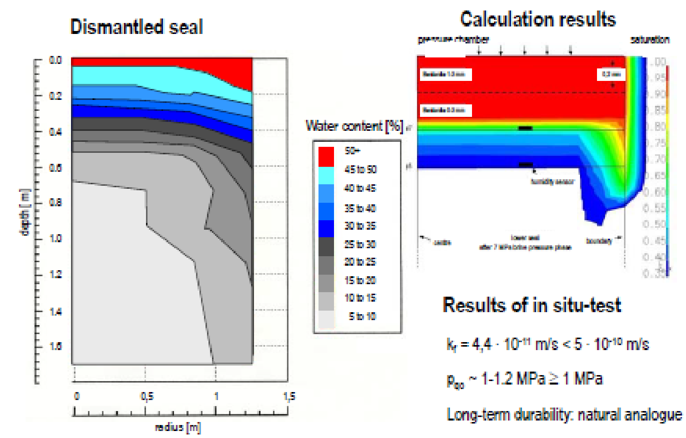
Shaft Seal Salzdetfurth– Saturation of Bentonite Prototype Seal



Results of in situ-test

$k_f = 4{,}4 \cdot 10^{-11}$ m/s < $5 \cdot 10^{-10}$ m/s

p_{ao} ~ 1-1.2 MPa ≥ 1 MPa

Long-term durability: natural analogue

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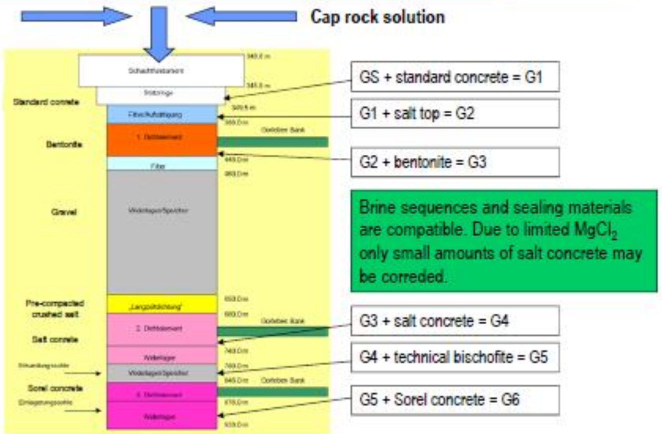
Shaft Seal Concept – Based on Realised Prototypes



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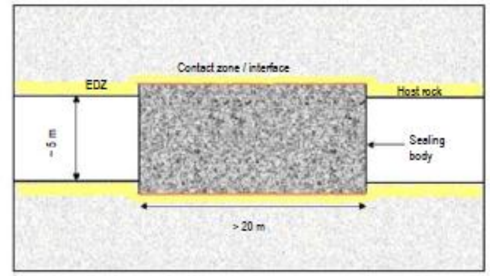
Elements of a sealing system

Hydraulically effective elements of seal acting in parallel



Prototype testing →EDZ and/or contact zone are higher permeable

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Example: Asse Prototype Test PSB A2

Source: HMGU

Observation: Localized flow via EDZ/contact zone

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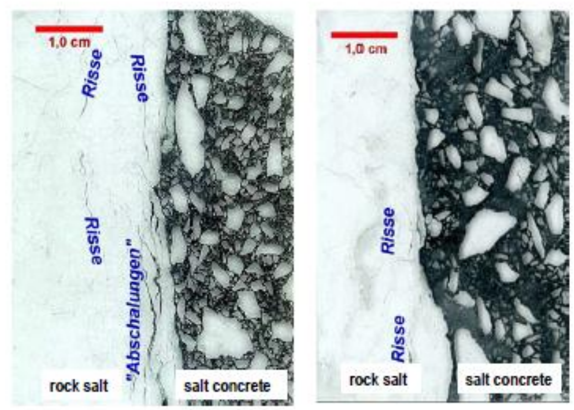
Example: Asse Seal (Asse-Vordamm)



Translation

Risse = cracks

„Abschalungen"

= „spalling"

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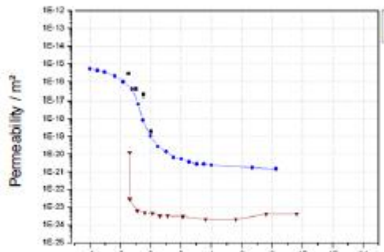
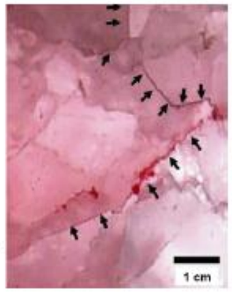
Permeability of Intact Rock Salt

Source: IfG



Widening of grain boundaries →

$p_{fluid} \approx p_{tot}$



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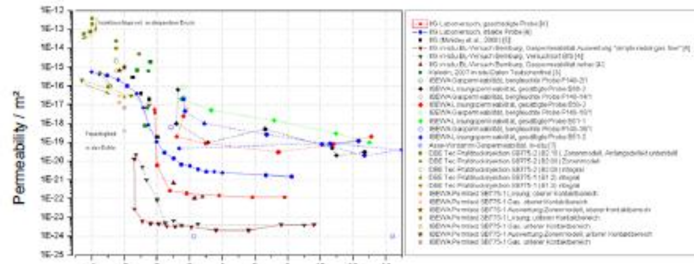
Permeability of Intact Rock Salt and Contact Zones



→ Better understanding of hydromechanical behavior of EDZ / contact zones (around 1 cm width after re-ripping)

→ Hydrochemical behavior of contact zones is still open, natural and technical analogues indicate minor influence

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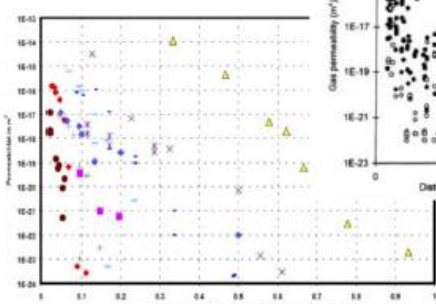
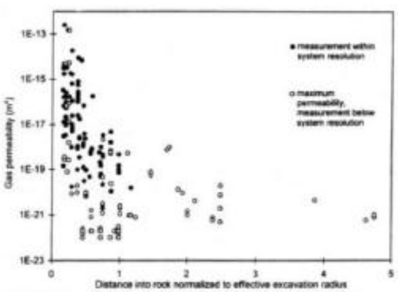
Comparison: Range of Permeabilities In-Situ (Open Drift)



Häfner et al.



Stormont

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Sealing Systems I – Summary and Conclusions

Progress has been made

- Assessing the consequences of different working lives for sealing systems required in "long-term SA" and European Standards by decoupling actions and resistances in "short-term" and "long-term" processes
- As a result geochemical conditions were analysed and used for designing of sealing systems
- The data basis on contact zones was improved leading to a better understanding of hydro-mechanical behavior

Next Steps

- Coupling of the risk based engineering approach to prove safety function to exclude failure modes of sealing systems
- Assessing the influence of hydro-chemical coupling in contact zones

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BfS

DBE

GRS

IfG

IBeWa

TU Clausthal

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

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

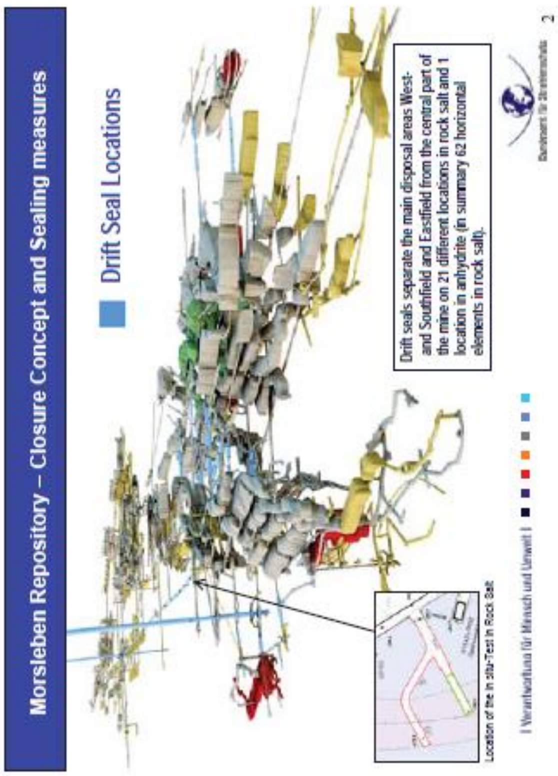
Seals are to be erected in the repository for radioactive waste Morsleben (ERAM). These will form a partition between the repository areas in which the radioactive waste is emplaced and the remaining mine workings into which a solution inflow can not be ruled out. The seals should prevent the penetration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

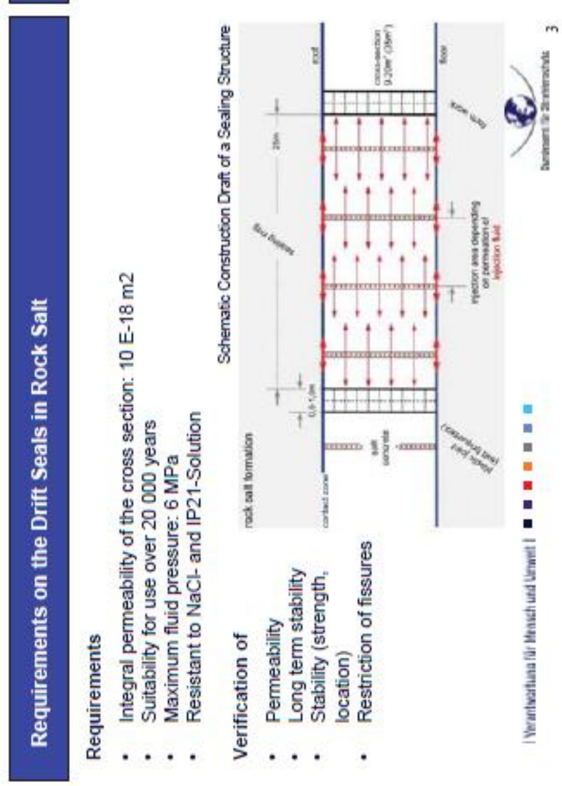
The drift seals located in rock salt are made up of one or more segments of salt concrete in lengths between 25 and 30 m. A succession of several segments will be separated from each other by plastic joints to prevent the occurrence of restraint stresses. Injection of the contact joint between the sealing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

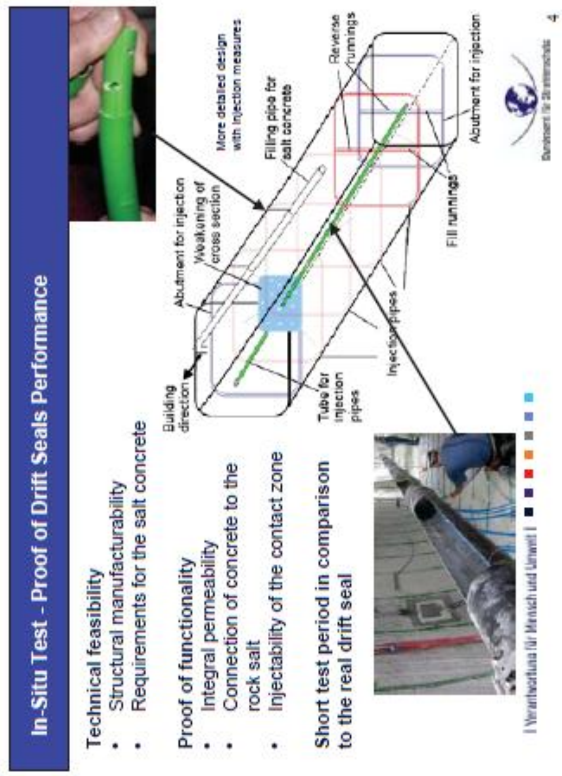
A test drift and an accompanying parallel drift have been newly excavated for the experiment. Boreholes for the measurement cables have been drilled from the gently rising parallel drift. Also emanating from the parallel drift hydraulic pressurisation tests could be performed by using the pressure chamber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

Besides implementing the construction draft for a seal segment, the manufacture of the trial construction also comprised geotechnical instrumentation for stress, strain, displacement, temperature and pore pressure measurements that are carried out in the contact zone, the sealing body and the surrounding rock salt. Additionally, a comprehensive site investigation programme has been carried out, in particular with regard to the stress state and the convergence behaviour of the surrounding rock salt. In addition to the in situ measurements, test specimens from different areas of the construction have been drilled. Laboratory tests of strength and permeability, as well as in situ permeability measurements are planned for these drillings. Starting from the excavation, the prominent construction phases and significant preliminary measurement results are presented in this article. All presently available results indicate that the in situ trial was successful.

<u>**Nina Müller-Hoeppe, Ralf Mauke**</u>







In-Situ Test – Construction Design and Geotechnical Measurements

Measurements on in-situ test

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

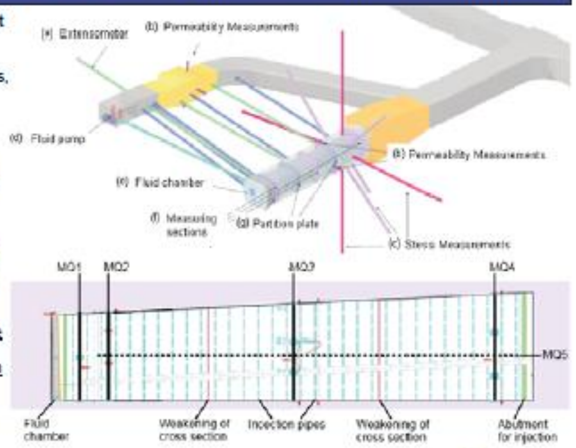
Connection of concrete to the rock salt (e. g. Cores from the contact zone)

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

Injectability of the contact zone

Mechanical Stability of location

Prediction of stresses and deformations with calibrated numerical analysis

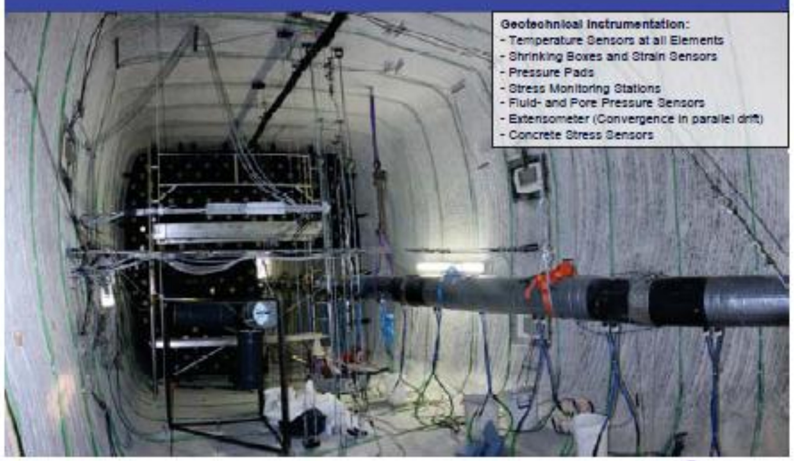


Investigation and monitoring program - Site Investigation

Measurements for Site Investigation

- 3D-Laserscanning
- Stress measurements (Hydrofrac and BGR overbore method)
- Determination of Permeabilities in the exploration areas (conventional borehole packers and new mobile surface packers)
- Deformation measurements (Convergence, Extensometer)
- Climate- and Temperature measurements for the calibration of the results
- Video Endoscopy
- Geological mapping

In-Situ Test - Impressions of Construction - Instrumentation



In-Situ Test - Impressions of Construction - Concreting

Concreting of the Drift Seal (484 m³ - fresh in fresh, Construction Time: 20 h – 15./16. Dez. 2010)

In-Situ Test - Impressions of Construction – Grouting

Injection of the Contact Zone (on 23rd February 2011):

- 2 Colloid grout mixer
- 7 Injection pumps
- Beam with Intake- and Outtake Pipes for 34 Ring Pipes
- 1st and 2nd Step: Ultrafin 12 with 90% NaCl-Solution
- 3rd and 4th Step: Ultrafin 12 with 30% NaCl-Solution
- Grouting Quantity: 1.150 Liter (3-Shift Operation, 24 h)

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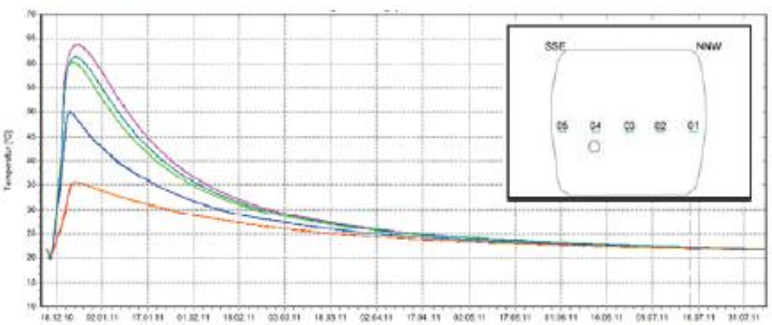
Selected Results – in situ Experiment - Temperature

Temperature Measurements inside the Drift Seal (MQ 3, horizontal Temperature Chain)
The maximum temperatures were approx. 65 ° C in mid-structure and 40 ° C in the contact zone. Meanwhile, the temperatures are lowered to the level of normal surroundings conditions (approximately 21° C).



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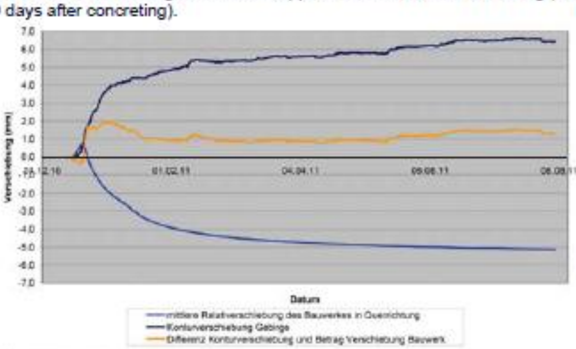
Selected Results – in situ Experiment - Deformation

Deformation Measurements: The contraction of the structure was compensated by the convergence. The deformations and the shift of the contour of the rock salt are in the same order of magnitude. The structural deformations are mainly due to the autogenous shrinkage behavior of the salt concrete (from 0.5 to 0.7 mm / m) and the cooling of the building. Shrinkage deformations are no longer detectable approx. 2,5 Month after concreting (date of grouting was 70 days after concreting).



MQ 2, Analysis of Deformations

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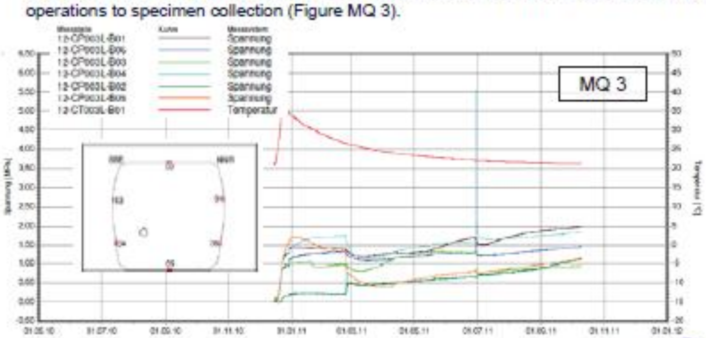
Selected Results – in situ Experiment - Stress Measurement

Stress Measurements (22 Pressure Pads in the Contact Zone)
The current increase of the normal stresses in the contact zone are between 0.1 MPa and 1.5 MPa at MQ1 and MQ2 (near the pressure chamber), between 0.9 MPa and 2.0 MPa near the middle of the structure (MQ3) and between 1.5 MPa and 4.0 MPa at MQ4 (MP4 near the air-side is largely determined by a cross-sectional expansion of the drift for necessary drilling operations to specimen collection (Figure MQ 3).



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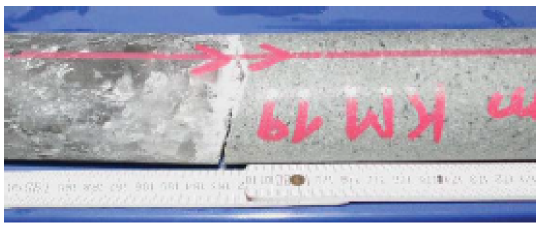
Selected Results – in situ Experiment - Permeability Contact Zone

Preliminary Results of Permeability Measurements in the Salt Rock and the Sealing Structure (Borehole Packer Tests)

North Contact Zone: 1 E -17 m² (Length of Test Interval: 18 cm)

South Contact Zone : 1 E -18 m² (Length of Test Interval: 18 cm)

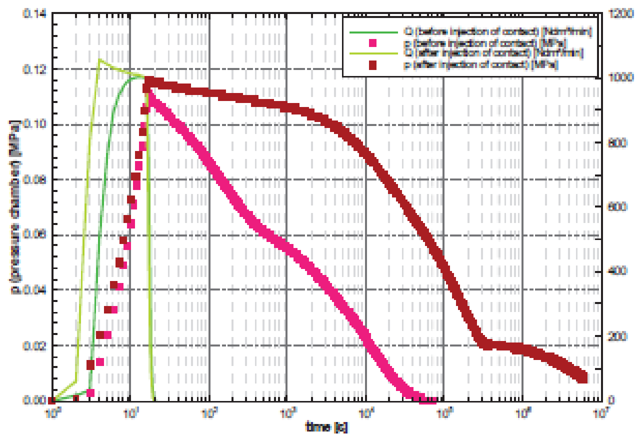
Undisturbed Construction Area: 1 E -21 m² (Length of Test Interval: 60 cm)



Core with Adhering Rock Salt Crystals (Core was Broken by the Drilling Procedure) - no visually detectable grout (injection lines in the area of the bore hole had very low intakes of grout)

Selected Results – in situ Experiment - Pneumatic Pre-Tests

Preliminary Results of Pneumatic Pre-Tests to Demonstrate the Success of the Injection
(first use of the pressure chamber)



Integral effective Gas Permeability: (total / theoretical flow against cross-section):

Prior Injection (69 days after concreting):

6E-14 m² / 2E-14 m²

After Injection (104 days after concreting):

1E-15 m² / 3E-16 m²

Comment: Values are only valid for the cross section – not for the length of the whole structure.

In-Situ Test - Summary – Proof of Technical Feasibility

Successful production of the in-situ test structure

This shows or rather proofs

Technical feasibility:

- Structural manufacturability
- Compliance of the requirements for the salt concrete
- Injectability of the contact zone

of drift seals in rock salt !!

However, some necessary technical improvements were identified (e. g. the planned final jetting of the injection pipes did not go according to plan, the over-drilling test of the cladding tube was more difficult than expected). All operating experience is collected and taken into account in future planning.

- So far all available measurement results indicate that the seals will function as expected
- All operating experience is collected and will be taken into account in future planning

Outlook

- The Main Permeability Test with Fluid is still to be implemented.
- Preparation and Evaluation of the Overall Functional Tests and Measurements not later than End of 2012.

  - First results were presented at the FMGM 2011 in Berlin
  - More results will be presented e. g. at the SaltMech7 in Paris

- Review of Tests Results with the Requirements on Drift Seals in Rock Salt
- If necessary Rerun of the Long Term Safety Assessments (with the real reachable hydraulically properties of the drift seals)

Other planed in situ-Investigations (Morsleben related):

- Appropriate in situ-test on drift seals in the anhydrite
- In situ-tests for vertical sealing systems for shafts and other vertical drifts

Drift sealing elements in the Asse II mine as a component of the emergency concept - assessment of the hydro-mechanical functionality

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Abstract

Since 1 January 2009, the Asse II mine is subjected to the provisions of nuclear law. The new operator, the Federal Office for Radiation Protection (BfS), has to ensure the safe operation and closure of the nuclear facility. At the beginning of 2010, the decision for retrieval of all radioactive waste was made as the best closure option in comparison to two others. Today, the conditions for the retrieval such as state of the barrels, radiation and chemo-toxic exposure, state of the chambers and conditions for the technical handling are investigated. For this purpose, two emplacement chambers will be drilled into exemplarily. The decision for retrieval was not declared as final one and there are several reservations. Only if the geomechanical and radiation conditions let expect a safe removal and no brine inflow escalation takes place, all rooms shall be opened.

Furthermore, on account of the permanent risk of brine inflow escalation, an emergency concept was developed with included prevention, emergency preparation and emergency measures. The construction of drift sealing elements is a main element of the emergency plan and aims at reinforcement and permeability reduction in the operation phase and fluid flow regulation in the post operation phase (after the emergency caused brine filling).

In the presentation, the most important elements for performance assessment of the drift seal's functionality are presented:

The used Sorel-concrete has weight proportions of 11-12% MgO, 62-65% crushed rock salt and 24-26% $MgCl_2$-brine. The loss of suspension's fluidity takes place after several hours, thus it can be pumped via pipes and boreholes. There is no brine loss; on the contrary, after solidification a further ability for brine incorporation due to the incomplete MgO-reaction is given. Without confinement, a swelling is observed and at restricted expansion, a swelling pressure is produced. The reaction temperature is in a range of 60-90°C. For the underground application, the material must own a sufficient strength, stiffness and low permeability. Special experiments for determination of the long-lasting mechanical resistance are explained.

Because the EDZ-generation and its permeability are of utmost importance for the tightness of a drift plug, a visco-elasto-plastic constitutive law for calculation of softening and dilatancy in the contour is introduced, calibrated and using a dilatancy-permeability relation the qualification of a special site for testing a pilot seal is proofed.

The main topic of the presentation aims at description and at hydro-mechanical coupled modeling of a drift seal experiment. The in-situ experiment lasted 7.5 years and revealed that even at a brine pressure application more than 2 MPa higher than the former (in dry state) generated radial (minimal) stresses a sufficient low permeability without any damaging and

tightness loss in the contour zone could be reached. The integral permeability was calculated on basis of inflow/outflow volume, pressure difference, geometry and the brine's viscosity in a range of lower than 10^{-15} m^2 with decreasing tendency in time.

It could be proved that even at the complicated site conditions of the Asse II mine it's possible to construct drift sealing elements with a sufficient functionality. Due to the high stressed mining system with strain-softened pillars and mainly broken stopes, in the drifts a significant excavation damaged zone and in the surrounding salt single fractures have to be expected. Hence, the drift plugs needn't have a higher hydraulic retention than the surrounding rock. Other, here not discussed, pilot seals in the Asse II mine are characterized by a still lower permeability which could be reached in frame of a material modification on basis of a higher Sorel-concrete stiffness. Thus, in the further operation phase a hydraulic protection and in case of the emergency (escalation of inflow) a regulation of the fluid flow processes in the flooded mine are possible.
Making a transfer of the findings to other sites one has to bear in mind the special geological and stress conditions of the Asse II mine. At that location, a relatively high level of permeability for meeting the functionality is sufficient. The importance of the pilot test is to see much more in the successful application of the high fluid pressures ($p_{Fluid} > \sigma_{min}$) without any damaging or tightness loss and in the understanding of the underlying hydro-mechanical interactions using model calculations. In this sense, also regarding the long testing time, the pilot test was a unique (as far as the authors know) project and is of vital importance for understanding of hydro-mechanical coupled processes in rock mechanics.

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2) Heydorn, M., Teichmann, L. & Meyer, T. 2008. Geotechnische Messungen an einer Pilotströmungsbarriere. Vortrag im Ra-hen der Tagung „Messen in der Geotechnik", TU Braun-schweig, 2008.

3) Minkley, W., J. Mühlbauer. 2007. Constitutive models to de-scribe the mechanical behavior of salt rocks and the imbed-ded weakness planes. Proc. of the 6th Conf. on the Mech. Behavior of Salt, Hannover 2007, p. 119-127, Taylor & Francis (Balkema).

4) Popp, T. 2002. Transporteigenschaften von Steinsalz - Model-lierung der Permeabilitäts-Porositäts-Beziehung. Meyniana 54, Seite 113-129, Kiel.

Peter Kamlot

Drift sealing elements in the Asse II mine[1]

Peter Kamlot

Institute for Geomechanics GmbH, Leipzig

2nd US-GERMAN WORKSHOP ON SALT REPOSITORY RESEARCH, DESIGN AND OPERATION

November 9 -10, 2011

[1] Summary of an article prepared for SaltMech 7, authors IfG, BfS, Asse-GmbH (incl. DBETEC)

IfG 1

- **Current situation in Asse II mine and emergency concept of BfS**
- **Parameters of the used Sorel-concrete**
- **Execution and hydro-mechanical coupled modeling of a drift seal experiment**

IfG 2

- Breaking processes in the pillars and stopes of the southern flank and in the adjacent overburden proceed. Because of the most chambers are backfilled, a reinforcement pressure is built up which is supported by additional concrete filling of all open gaps. In result, the displacement rates drop down[2].
- The amount of the collected overburden brine is unchanged since 2002. The brine inflow cannot be predicted, an escalation cannot be excluded.
- Presently, the conditions for the retrieval such as state of the barrels, radiation and chemo-toxic exposure, geomechanical state of the chambers and conditions for the technical handling are investigated. For this purpose, two emplacement chambers will be drilled into exemplarily.
- The decision for retrieval was not declared as final one and there are several reservations. Only if the geomechanical and radiation conditions let expect a safe removal and no inflow escalation takes place, all rooms shall be opened.

[2] For more information: Presentation at the US-German Workshop in Jackson (USA), May 2010

IfG Current situation in the Asse II mine 3

- On account of the breaking processes and on the permanent risk of inflow increase BfS developed an emergency concept. This **emergency plan** is divided into prevention, emergency preparation and emergency measures:
- The **prevention measures** aim to stabilizing the mine openings and to protection of the emplacement chambers. The planned waste retrieval mustn't be impaired, but supported in a sense of reinforcement and permeability reduction. For example, mine workings situated at the side and below emplacement chambers are pumped full of special concrete for stabilization purposes.
- Because the possibility of inflow escalation cannot be excluded, emergency preparation (drainage systems, new storage facilities) must be done for reducing the effects of such an event.
- Only in the emergency case (escalation of inflow) the retreat from the mine contains construction of shaft seals and flooding of all openings and pore spaces with $MgCl_2$-brine.

IfG Elements of the emergency concept 4

The construction of drift sealing plugs belongs to the prevention measures and aims at

- reinforcement and permeability reduction in the operation phase and
- fluid flow regulation in the post operation phase (after emergency caused brine filling).

In the following, the function of a pilot seal in a 7.5 years lasting experiment at the complicated site conditions of Asse II mine is demonstrated.

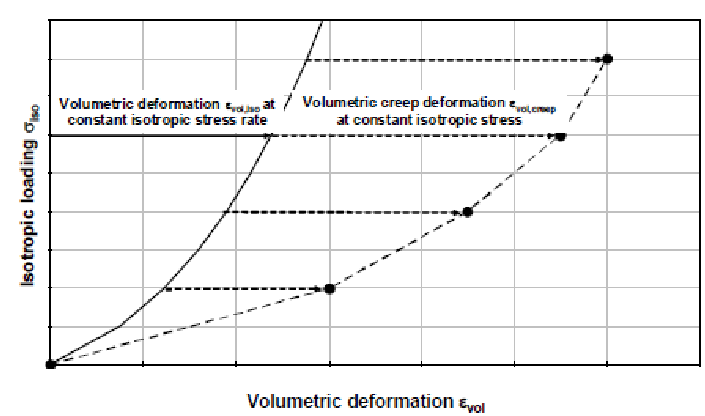
- Current situation in Asse II mine and emergency concept of BfS
- **Parameters of the used Sorel-concrete**
- Execution and hydro-mechanical coupled modeling of a drift seal experiment

- Weight proportions 11-12% MgO, 62-65% Crushed rock salt, 24-26% $MgCl_2$-brine
- Loss of fluidity after several hours, can be pumped via pipes and boreholes
- No brine loss. After solidification, further ability for brine incorporation due to incomplete MgO-reaction
- Without confinement swelling and with restricted expansion swelling pressure
- Reaction temperature 60-90°C

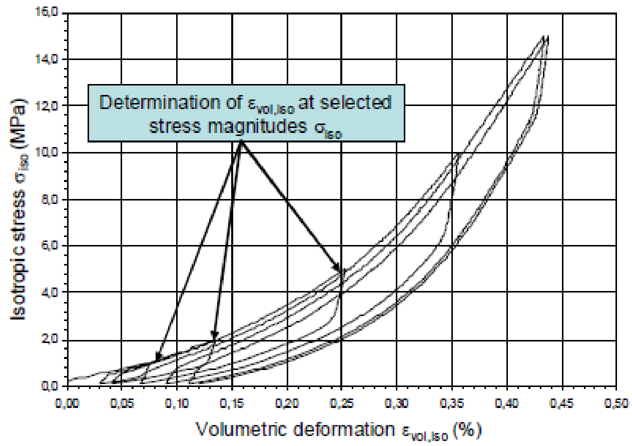
- Wet density 1.85±0.05 g/cm³
- Total porosity 0.20±0.04
- Brine saturation 0.7±0.1
- Permeability in-situ ≈ 10^{-18} m² ± 1 order of magnitude

- Cohesion 24±9 MPa
- Friction angle 15±10 degrees
- Tension strength 3±1 MPa

Because the long-lasting stiffness is of vital importance, special isotropic tests are performed at constant stress rate and constant stress. Using superposition of both deformations, the in-situ relevant stiffness is found in allocation to applied isotropic stress.



Superposition of the 2 deformation components $\varepsilon_{vol,iso}$ and $\varepsilon_{vol,creep}$ for calculation of the long-lasting compaction at selected isotropic stresses



Example for isotropic loading at 0.1 MPa/s

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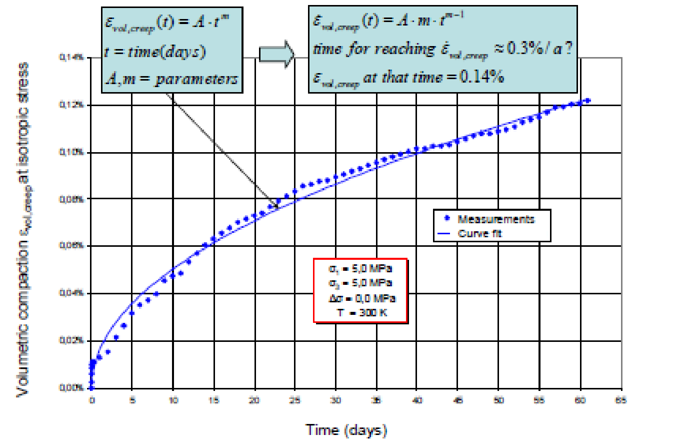


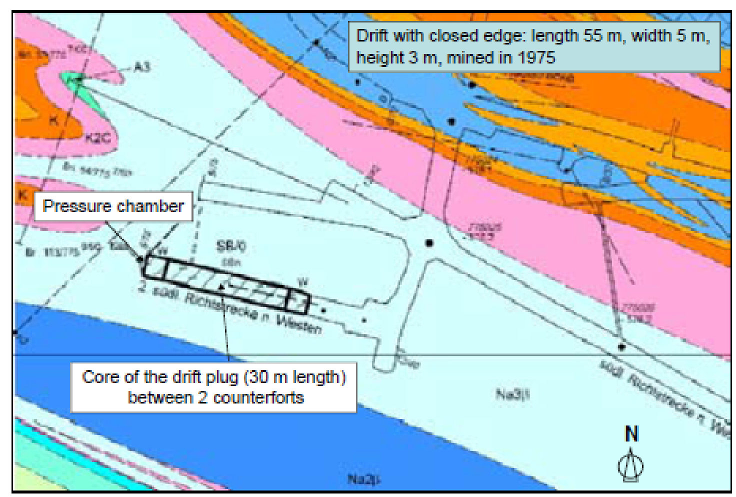
Superposition of both deformation parts and dividing σ_{iso} by the total deformation leads to the in-situ relevant stiffness: 5 MPa / (0.25%+0.14%) = 1.3 GPa

Example for isotropic creep testing at σ_{iso} = 5 MPa, curve fit for finding a numerical relation for extrapolation

10

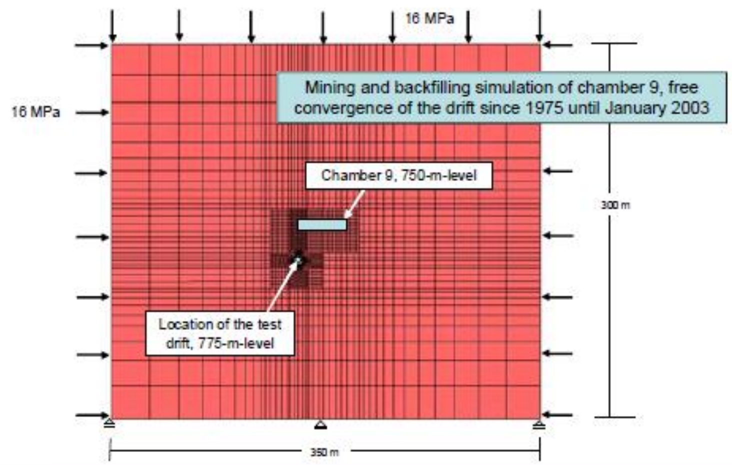
- Current situation in Asse II mine and emergency concept of BfS
- Parameters of the used Sorel-concrete
- **Execution and hydro-mechanical coupled modeling of a drift seal experiment**

11



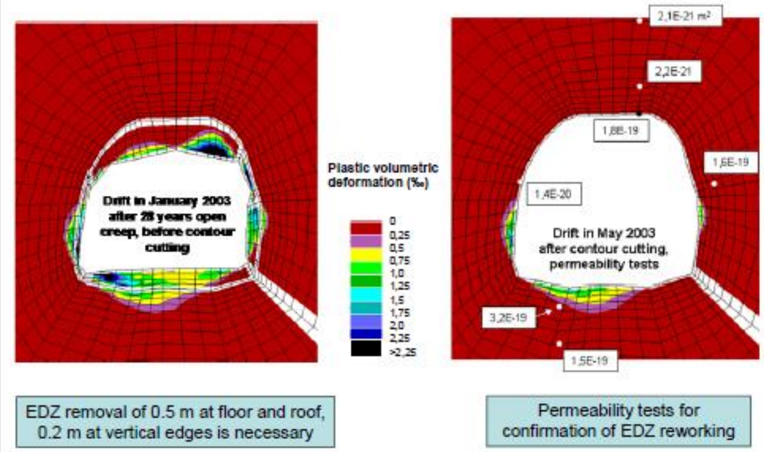
Location of pilot seal experiment at 775-m-level, Leine rock salt

12



2D-model for visco-elasto-plastic calculation of EDZ and for proposal of contour cutting depth

13

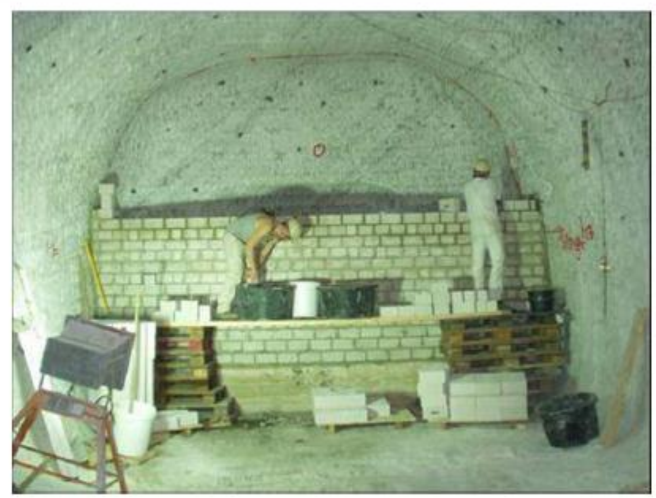


Plastic volumetric deformation in ‰ in the drift contour after 28 years free creep before contour cutting (left) and after contour cutting (right)

14

Instrumentation for measurement purposes, i.e. flat jacks, temperature transducers

15



Build-up of pressure chamber at the edge of the drift

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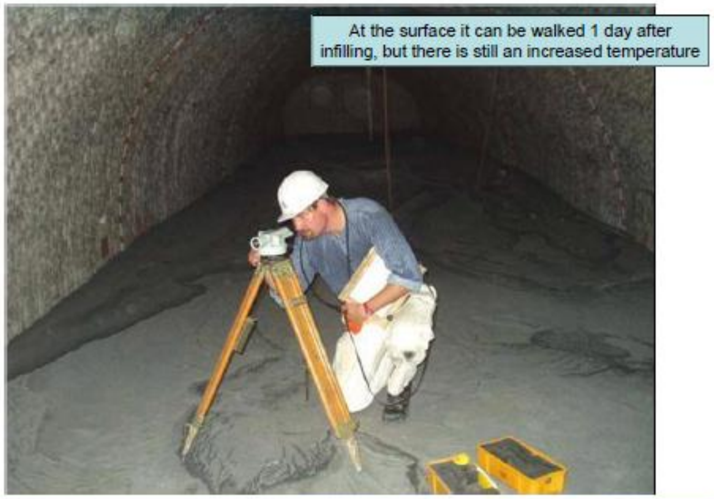
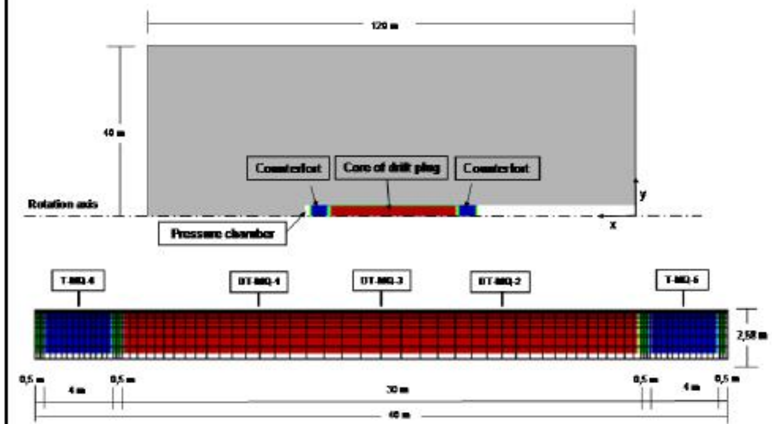


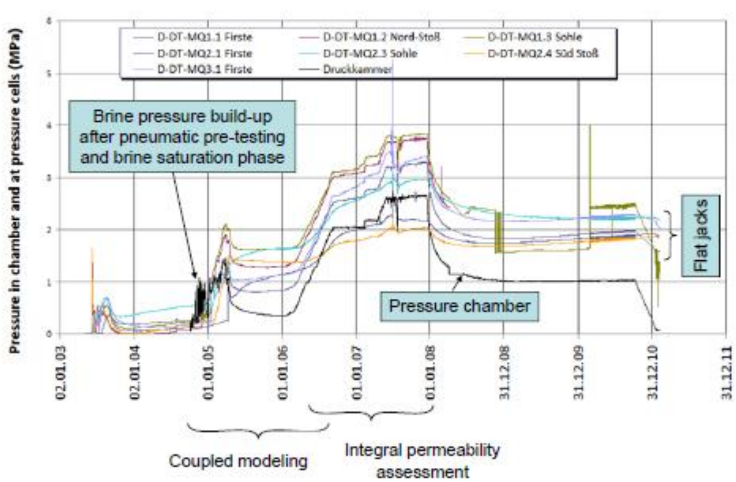
Leveling at the Sorel-concrete surface for observation of the angle of inclination

17



Axisymmetric 3D-model of the pilot drift seal, location of measurement cross cuts (temperature, radial stress)

18



Overview about the entire test course at the pilot seal from June 2003 to January 2011

19

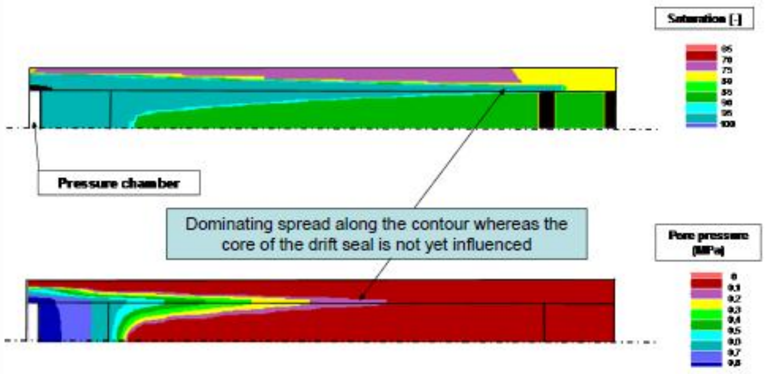
Remarks to measurements and modeling course:

- The pressure at the cells was mostly higher than in the chamber. The cells were located near to the contour and measured the total stresses in radial direction.
- No fluid pressure measurements.
- For understanding the interaction of effective stresses and pore pressure, hydro-mechanical coupled modeling in case studies was done:
  Best agreement with measurements was found using permeability $1 \cdot 10^{-14}$ m² in the immediate salt contour (0.33 m) and $1 \cdot 10^{-18}$ m² in the contour depth up to 1 m.
  Reason for that: Brine flow via channels in fine dispersed anhydrite minerals in Na3 was observed.

Rock salt: visco-elasto-plastic material law
Concrete: Elasto-plastic behavior
Simulation of free convergence until plug construction, creep induced drift convergence coupled with fluid pressure application (Darcy flow)

Hydro-mechanical coupled modeling

20

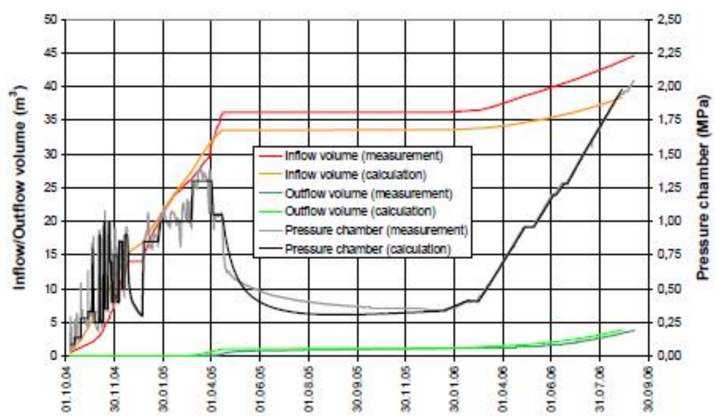


Calculated saturation front and pore pressure distribution at the beginning of 2005 (110 days after pressure generation)

21

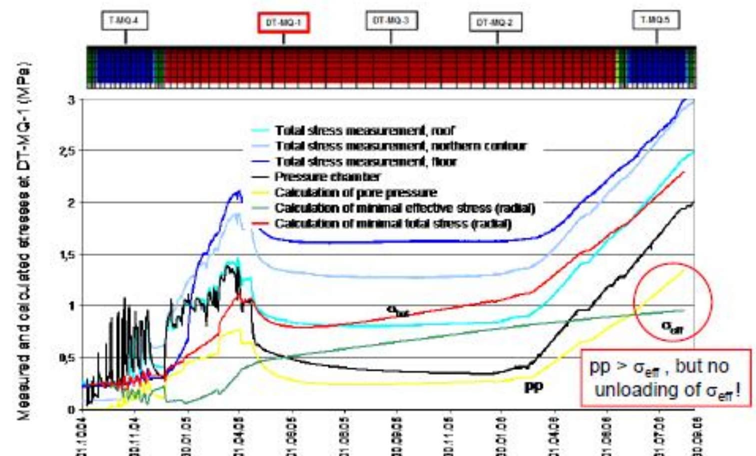
Shuttering formwork at the open side of the pilot seal in summer 2005

22



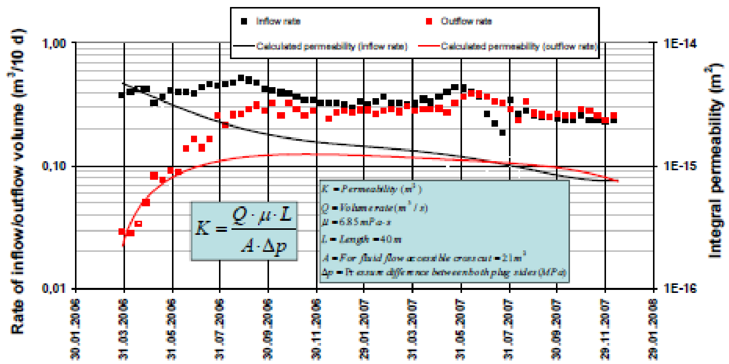
Measured and calculated inflow volume into the plug and outflow volume at the open side (middle curves represent the applied fluid pressure)

23



At cross cut DT-MQ-1 measured total stresses - Calculated pore pressure, effective stress and total stress

24



Approach of the rates of inflow and outflow due to total saturation, decrease of the integral permeability in time

25

- The effective (mechanical) stress acting in the matrix of rock salt and concrete is controlled mainly by the drift convergence and, hence, rises slowly. The pore pressure, spreading via the interconnected pores and fissures in both materials, isn't able to unload the effective stress in the matrix because the plug cannot expand. Unloading of the matrix would lead to tension stresses and integrity loss.
- Even at the complicated site conditions of the Asse II mine, it's possible to construct drift sealing elements with a sufficient functionality (mechanical support, hydraulic resistance). The plugs needn't have a higher hydraulic retention than the surrounding damaged rock.
- The presented pilot plug test proved for a fluid pressure more than 2 MPa higher than the minimal principal stress (in dry state) a permeability of lower than 10^{-15} m^2 with decreasing tendency in time.
- Further pilot seals in the Asse II mine are characterized by a significant lower permeability. That could be reached by higher Sorel-concrete stiffness due to material modification and at test sites in Staßfurt rock salt.

Conclusions

26

Salt Disposal Investigations to Study Thermally Hot Radioactive Waste In A Deep Geologic Repository in Bedded Rock Salt

R. Nelson, DOE, Carlsbad Field Office, Carlsbad NM

This presentation describes a proposed research program investigating the behavior of salt when subjected to thermal loads like those that would be present in a high-level waste repository. This research would build upon results of previous salt repository program efforts in the US and Germany and the successful licensing and operation of a repository in salt for disposal of defense TRU waste. The coupled thermal-mechanical behavior of intact and crushed salt, which both influences and is influenced by the liberation and movement of water present in the salt and hydrous minerals, will ultimately control thermal and hydro-geochemical conditions in a salt repository and at the waste package.

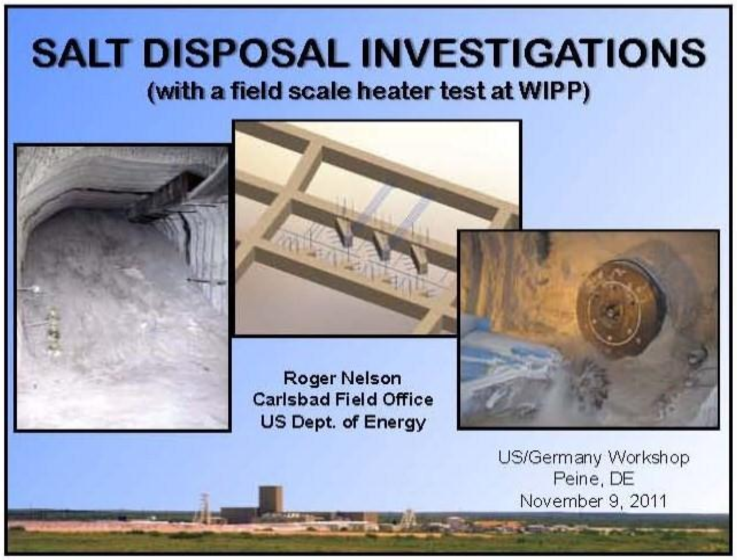
An integrated research program has been proposed to address key scientific issues, including a combination of laboratory-scale investigations, a thermal field test in an underground salt formation with a configuration that replicates a small portion of a conceptual repository design, and numerical simulations conducted to develop validated models that could be used for future repository design and safety case development. Laboratory tests are proposed to measure salt and brine properties across and beyond the range of possible repository conditions. The field test will investigate many phenomena that have been variously cited as Achilles' heels for disposal of thermally hot waste in salt, including buoyancy effects and migration of pre-existing trapped brine up the thermal gradient (including vapor phase migration).

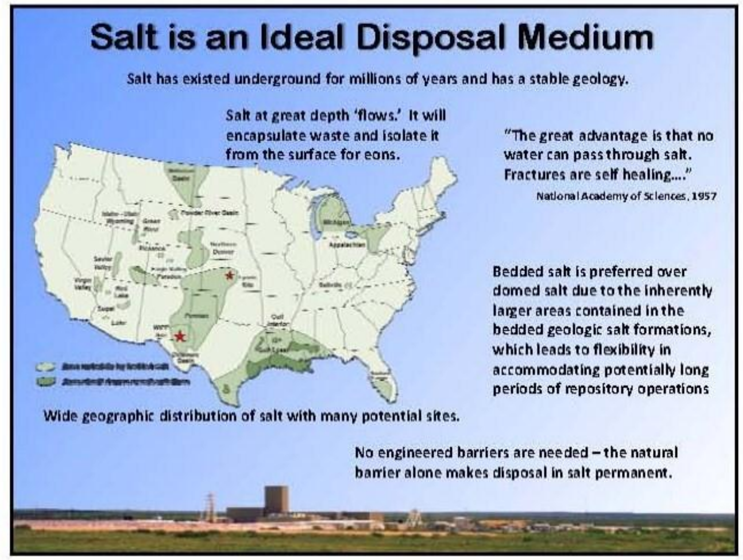
These studies are proposed to be coordinated and managed by the Carlsbad Field Office of DOE, which is also responsible for the operation of the Waste Isolation Pilot Plant (WIPP) within the Office of Environmental Management. The field test portion of the proposed research would be conducted in experimental areas of the WIPP underground, far from disposal operations. Such tests can be accomplished using the existing infrastructure of the WIPP repository at a far lower cost than if such research were conducted at a commercial salt mine at another location, or at a new underground facility established for such testing.

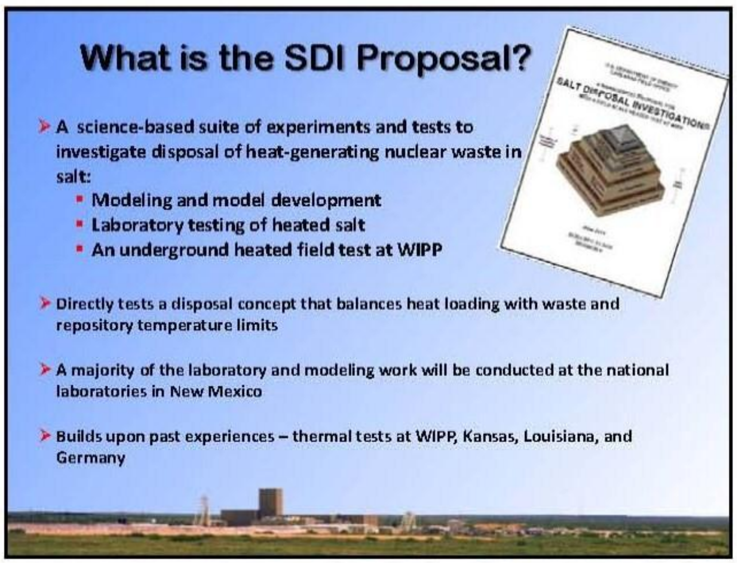
This presentation describes the proposed research program and discusses the various components and their relative duration and timing. It describes the phased field test proposed to be performed over almost a decade, including instrumentation development, several years of measurements during heating and then subsequent cooling periods, and the eventual forensic mining back of the test bed to determine the multi-year behavior of the simulated waste/rock environment. Funding possibilities are described, and prospects for near term start-up are discussed.

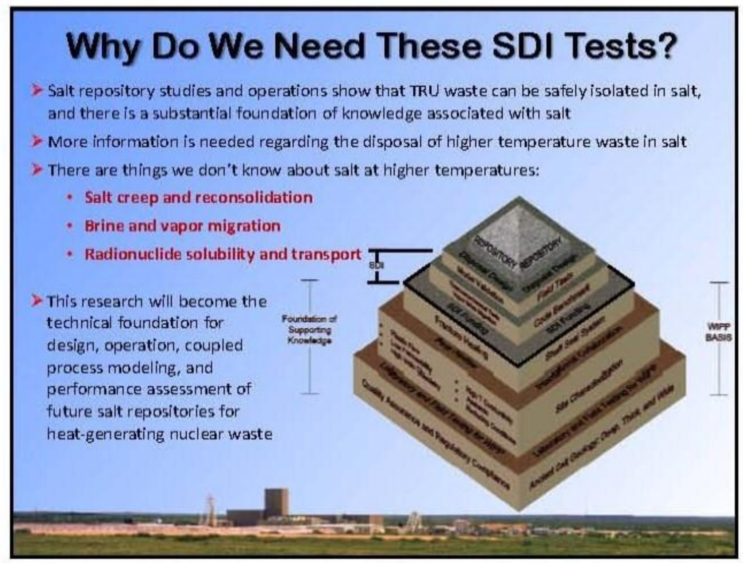
While the specific test plans remain yet to be developed, many of the research objectives are described, including both brine and water vapor transport via thermal gradients, buoyancy effects, and salt reconsolidation without the presence of water.

Roger Nelson

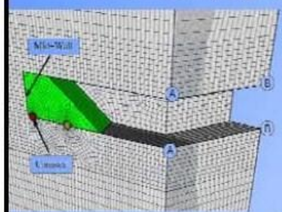


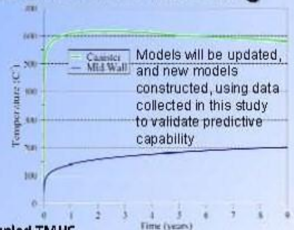




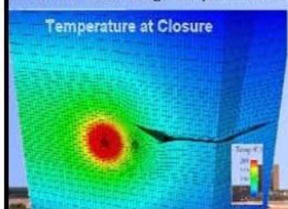


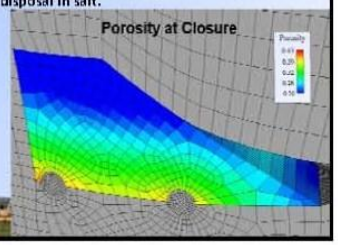
SDI Includes Development of Coupled Thermal, Mechanical, Hydrologic and Chemical Modeling





SDI model development will provide a validated, fully coupled TMHC model for future design and performance assessment of disposal in salt.





Why the SDI Field Test?

- Field test will provide a direct proof-of-principal demonstration of the alcove waste-disposal concept for heat generating waste
- Past field heater tests, many at WIPP, have provided significant benefit to knowledge of salt behavior but without the rigorous integration of thermal, mechanical, hydrologic, and geochemical processes necessary to model, and ultimately license, a deep geological repository for HLW in salt
- This test will push the envelope in terms of heat load and the average bulk salt temperature (it will run hotter and longer than previous field experiments including those at Yucca Mountain conducted explicitly for spent fuel HLW)
- Water movement is a key parameter that has not been studied in past field thermal tests
- Advanced computer modeling and data gathering techniques of today are vastly superior to those used 25 years ago
- Regulatory and technical rigor (QA) is necessary to form defensible conclusions

*Photo from Asse Tests - Germany's Waste Disposal & Research Program

SDI Also Involves Laboratory Testing

- **Laboratory studies at national labs in New Mexico (LANL + Sandia)**
- **Laboratory Thermal and Mechanical Studies**
  - Fundamentals of high-temperature intact salt response and hot, dry reconsolidation will be studied in the laboratory
  - Information derived will inform field test planning and underpin the coupled process models of the large-scale response
- **Laboratory Chemical, Hydrologic, and Material Studies**
  - Laboratory studies on salt and brine will establish the key factors that control brine migration, radionuclide solubility, and mobility at elevated temperatures
  - In addition, material interaction data will be obtained that can be used to evaluate waste forms

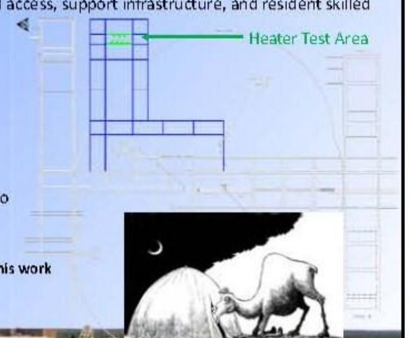
Why Conduct the Field Test at WIPP?

Order of magnitude cost, and significant schedule savings, will be realized by conducting the field test at WIPP.

This test can begin, and be completed, years sooner and tens of millions of dollars cheaper than at a location without underground access, support infrastructure, and resident skilled labor and scientific resources.

Advantages of using WIPP:

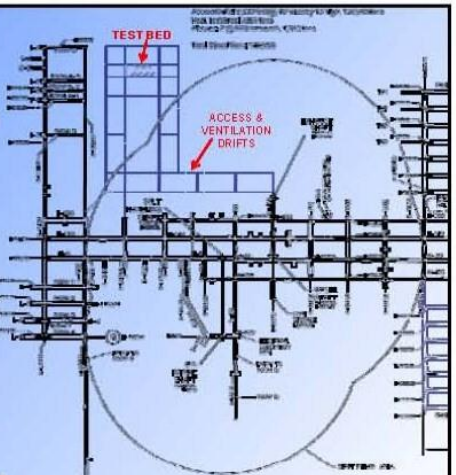
- existing trained workforce
- mining infrastructure
- construction equipment
- MSHA Qualification
- QA Program
- Data more readily transferable to other potential salt sites



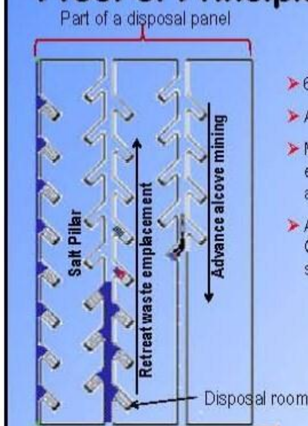
- **Staff is trained and available**
- **WIPP mining schedule accommodates this work**
- **Fast test start**
- **Less overall cost**

SDI footprint at WIPP is equivalent to an entire disposal panel

- Outside shaft pillar area
- Minimize impact on WIPP disposal operations
- Ventilate/control heat and rapid cooling at end of test
- Begin mining FY12 (21 mo)
- ~2 years of heating + 2 years cooling and then forensic testing
- Heaters on 2015
- Test concludes 2020
- ~$45M over 8 years



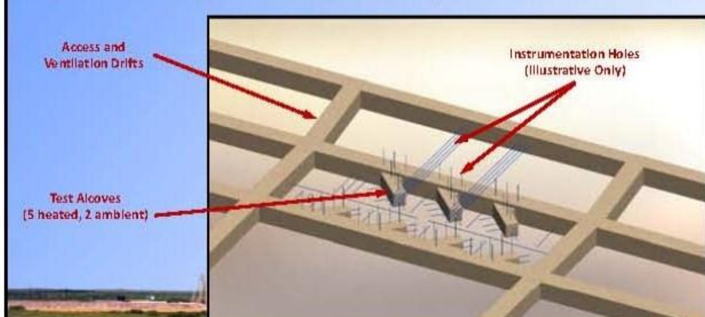
Proof of Principle Emplacement Concept



- 6 m deep alcoves
- Angled entries
- Mining and waste emplacement in adjoining rooms
- All waste (HLW, TRU, GTCC and LLW) all in a single disposal concept

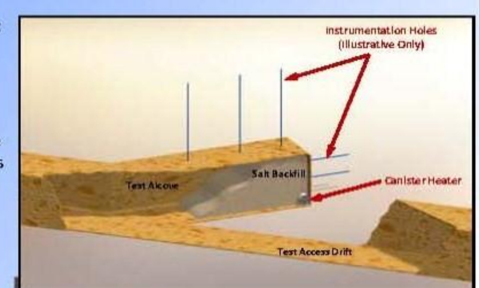
What Will the Field Test Look Like?

- The test design is modeled after a proof-of-principle layout and operational strategy for a repository in salt
- The design consists of an array of alcoves with access and ventilation drifts
- Boreholes will be drilled to contain monitoring instrumentation



What Will the Field Test Look Like?

- Electrical heaters placed in the back of the alcoves are used to simulate waste packages
- This thermal loading will produce temperatures in excess of 160°C in the nearby undisturbed salt (temperatures well above other existing salt data and beyond temperatures achieved in the Drift Scale Heater Test at Yucca Mountain)
- The alcoves will be instrumented to measure:
  - water movement
  - temperature
  - deformation
  - alcove closure
  - crushed salt pressure
  - ventilation conditions
- Two-three years heating
- Two years cooling
- Post-test forensics will confirm measured data



Test Planning and Implementation

Areas of Interest

US/German Workshop (May 2010) identified several areas of interest that could be assessed through *in situ* testing:

- Response of the DRZ to thermal and mechanical effects
- Consolidation of backfill materials (dry reconsolidation?)
- Availability and movement of brine
- Vapor phase transport mechanisms
- Potential radionuclide transport mechanisms
- Buoyancy of waste packages

Test Planning and Implementation - Challenges

Access to test area will be limited or non-feasible during heating and cooling phases of the test (until post test forensics). Remote monitoring techniques will be investigated and documented during test planning. Asse TSDE experience will be invaluable!

- Thermal: Thermocouples, Thermal Flux Meters
- Hydrology: Borehole Packer Systems, Geophysical Techniques (Electrical Resistivity Measurements, Joint Seismic and EM Imaging)
- Deformation and Closure: Closure Gages, Anchor Bolt and Wire Extensometers, Creepmeters, Pressure Cells, Inclinometers, Borehole Strain Gages, Geophysical Techniques (In Situ Seismic Wave Transmission Measurements, Seismic Event Monitoring), Wireless Remote Camera Systems
- Power: Power Meters
- Environmental and Ventilation Gages: Thermocouples, Air Speed

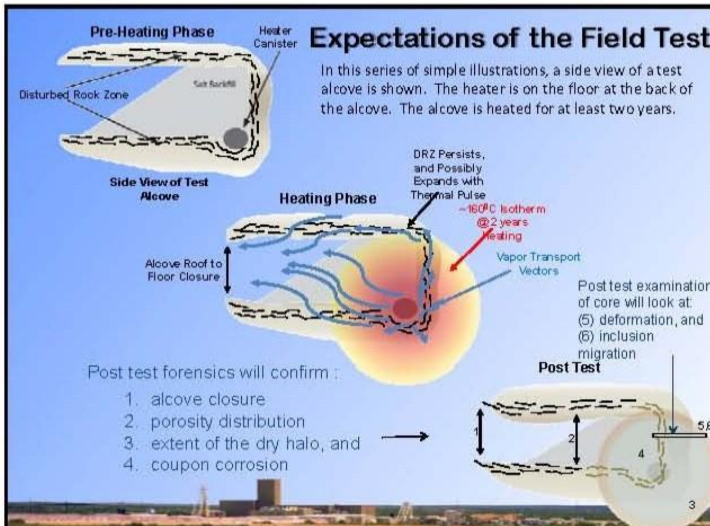
Test Planning and Implementation - Challenges

Monitoring and Instrumentation

- Instrumentation gages must operate in the harsh underground test environment with brine, high heat, and large deformations
- Instruments must be durable enough to provide data for the duration of the test (several years).
- Robust signal wiring, including wireless signal transmission, will be investigated and deployed as suitable.
- Geophysical techniques will be used and remote visual monitoring through high temperature camera systems will also be deployed.

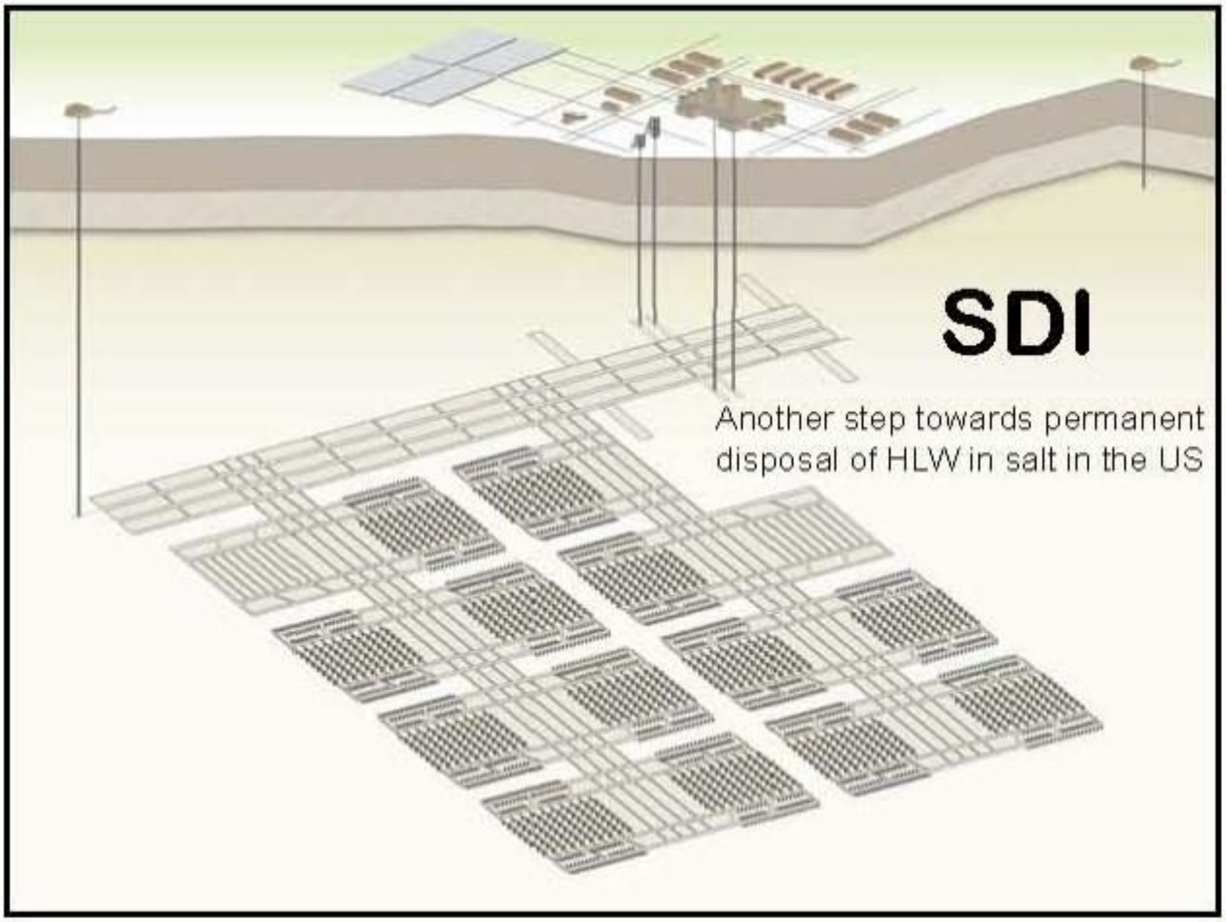
Expectations of the Field Test

In this series of simple illustrations, a side view of a test alcove is shown. The heater is on the floor at the back of the alcove. The alcove is heated for at least two years.



Post test forensics will confirm :

1. alcove closure
2. porosity distribution
3. extent of the dry halo, and
4. coupon corrosion


SDI
Another step towards permanent disposal of HLW in salt in the US

SEALING SYSTEMS FOR REPOSITORIES IN SALT II

W. Bollingerfehr
DBE TECHNOLOGY GmbH, Eschenstraße 55, D-31224 Peine, Germany

The German reference repository concept specifies that spent fuel elements are to be emplaced in self-shielding casks (type POLLUX) in horizontal drifts and vitrified waste is to be emplaced in deep vertical boreholes in a mine in salt formations. The latter needs to be reconsidered so that it meets the requirement of retrievability during repository operating time /1/. However, the safety concept considers the host rock formation as the main barrier that provides the long-term isolation of radioactive waste from men and the environment. Technical barriers and geotechnical barriers will be designed to meet the requirements of the safety concept. The waste containers as technical barriers isolate the radioactive waste and, thus, ensure that handling processes are safe during repository operation. Geotechnical barriers will be designed to close and seal the man-made openings (drifts and shafts) of the repository. In this regard, shaft seals are of uppermost importance as these barriers seal the only potential pathway for fluid intrusion into the repository.

Information is available on shaft seals constructed in the decommissioning phase of potash mines in Germany. A concept for a shaft seal for the US repository for transuranic waste at the WIPP site has been designed for a bedded salt formation. In Germany, components of a shaft sealing system have been developed, constructed, and tested for a repository for hazardous waste. However, a published concept for the eventual sealing of the shafts of a German repository for heat-generating radioactive waste does not yet exist. For this reason, BMWi (German Federal Ministry of Economics and Technology) launched a three-phase research project called "ELSA" (Schachtverschlüsse für Endlager für hochradioaktive Abfälle).

The RD&D project ELSA is divided into 3 phases:

Phase 1, which is jointly carried out by TU Bergakademie Freiberg and DBE TECHNOLOGY GmbH, consists mainly of the preparatory work for the development of concepts for shaft seals in HLW repositories in the host rocks salt and clay. The main activities in this phase are:

- Research on the state of the art regarding shaft seals with long-term stability
- Development of a safety assessment concept for shaft seals
- Identification and compilation of the boundary conditions for shaft seals in the host rocks salt and clay (geo-mechanical and geochemical conditions, permeability and porosity evolution in EDZ, properties of construction and sealing material)
- Derivation and compilation of the requirements for shaft seals for repositories for high-level waste

Phase 2 concerns the development of technical concepts for shaft seals that provide safe long-term sealing of HLW repositories. The shaft seal concepts will be developed for both, a repository in a salt formation and a repository in clay. According to current considerations, the concepts should be modular so that the geologic situations and hydro-mechanical boundary conditions at the respective sites can be taken into account. Alternatives are to be included and analysed. To assist in concept development, materials and individual components of shaft seals favoured by international and national partners are also to be studied. The aforementioned material studies could be part of this project or could be carried out separately but at the same time. Due to the international significance of this project, discussions with interested international partners are planned.

Phase 3 involves the construction and testing of the functional components of the shaft seals on a large scale. Large-scale, in situ demonstration tests are eventually necessary for the safety assessment of the respective shaft seal system for an HLW repository. Before these tests can be conducted, detailed designs have to be prepared – if possible, in close co-operation with the competent licensing authority. First, all project partners have to decide if it is sufficient to construct a single in-situ demonstration seal, equip it with sensors, and test its functionality or if an individual seal should be constructed for each of the two host rocks. Before construction can start, a possible site (mine) and the relevant approval and licensing procedures for the complete construction have to be identified, possibly for individual construction materials as well.

Currently, the schedule for the 3 phases is as follows:

- phase 1: 01.04.2011 till 30.04.2012
- phase 2: Concept development Duration approx. 1.5 to 2 years (mid 2012 to end 2013
  - Approval and licensing: Duration approx. 6 months (till mid 2014)
- phase 3: Construction and testing: Duration approx. 3 to 4 years (2014 to 2016)

The resulting project duration is approx. 5 to 6 years.

The work in phases 2 and 3 (concept development and demonstration tests) can be carried out within the scope of the international technology platform "Implementing Geological Disposal of Radioactive Waste". The substantiation of the safety analysis by means of a large-scale test carried out with international partners could increase the public and political acceptance regarding the disposal of high-level waste (not only in Germany).

ACKNOWLEDGEMENT

The work referred to in this paper was carried out in cooperation with colleagues from TU Bergakademie Freiberg and Technical University of Braunschweig and was supported by BMWi and the Project Management Agency of KIT (Karlsruhe Institute of Technology). Many thanks to them for their excellent collaboration.

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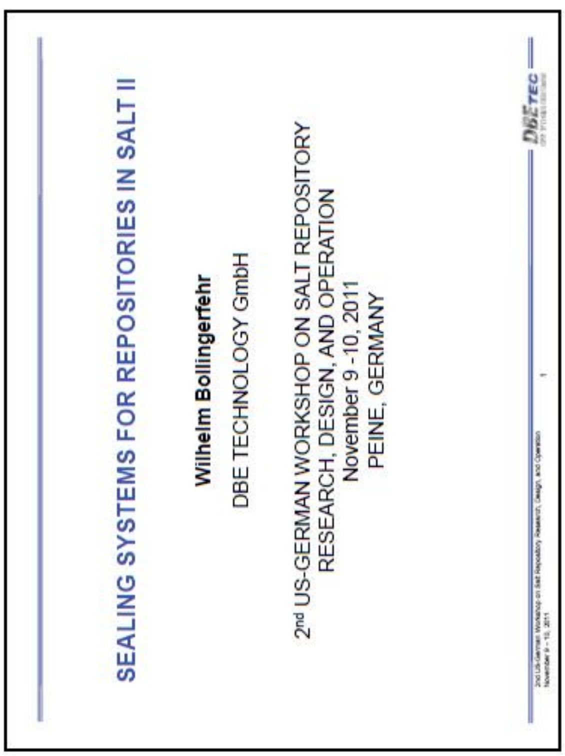
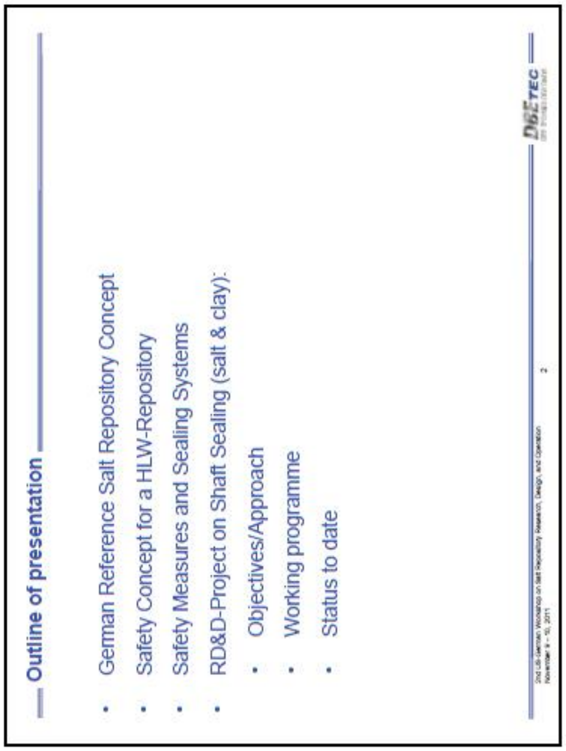
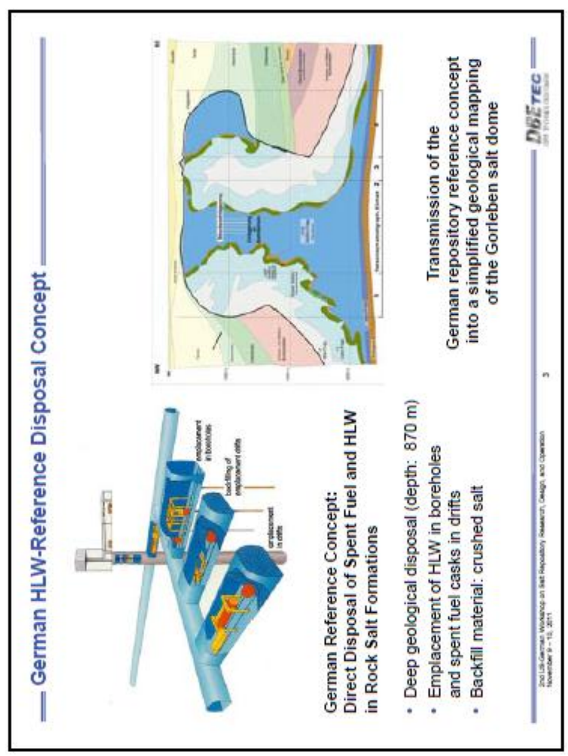
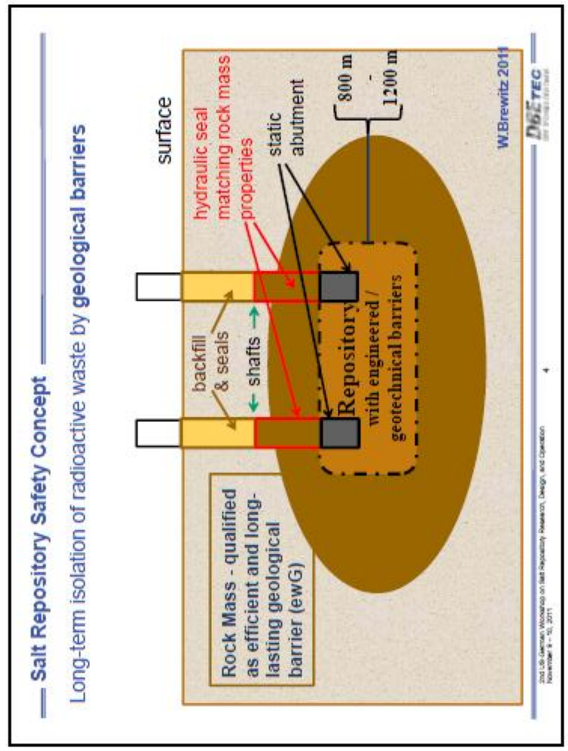
/1/ BMU 2010: Sicherheitsanforderungen an die Endlagerung wärmeentwickelnder radioaktiver Abfälle Stand 30. September 2010, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

W. Bollingerfehr









Sealing Concept (Repository in Salt)

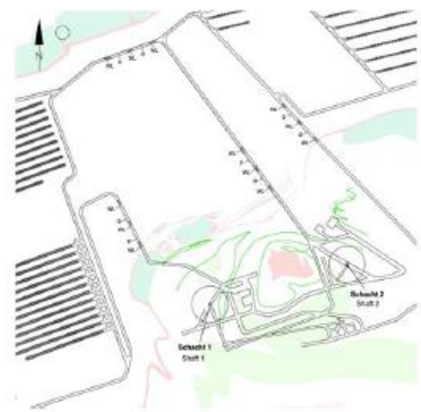
Technical measures matching the safety concept (isolation by geol. barriers)

- **Sealing of shafts:**
  - ⇒ ***Sealing of shaft*** 1 und 2
- **Sealing of main drifts:**
  - ⇒ ***Sealing of*** main drifts at emplacement level (870 m) and exploration level (840 m)
  - ⇒ ***Plugs*** to separate emplacement fields from main drifts

All drifts and infrastructure areas backfilled with crushed salt

Sealing of main drifts

e.g. position of drift seals (870 m level)



Drift sealing concept and appropriate material selection according to experience made in Asse and Morsleben repository closure projects

D = Dichtung (seal element)
ML = Widerlager (static abutment)

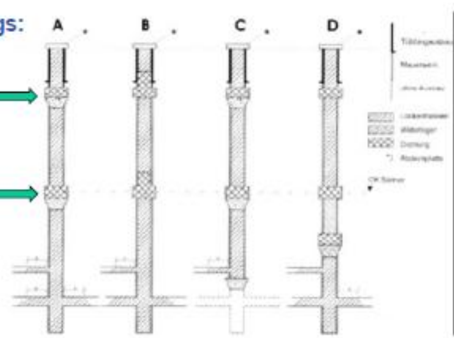
200 m

Shaft Sealings (1/4)

different types of sealings:

upper sealing elements: clay or bentonite

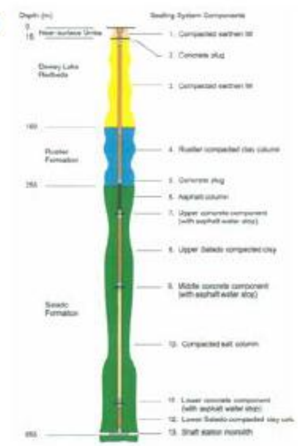
lower sealing elements: materials used depending on local geol. situation



Source: Bodenstein et al.

Shaft Sealings (2/4)

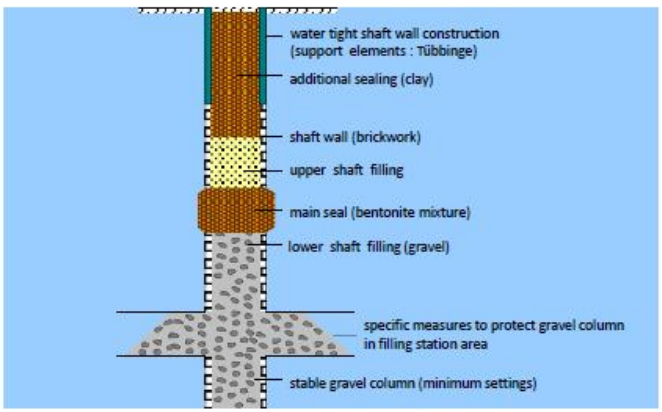
Shaft Sealing Concept WIPP



Source: SANDIA

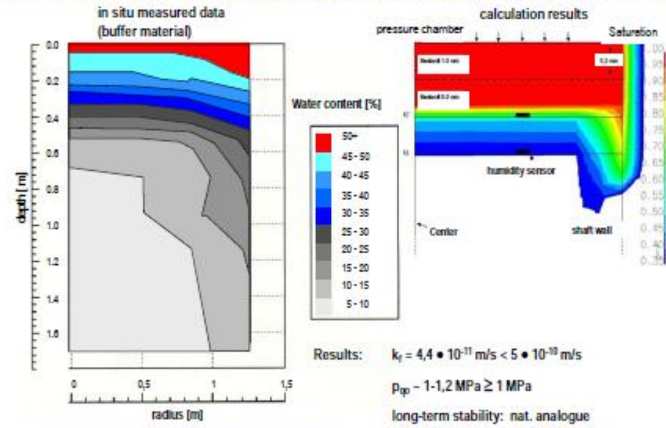
Shaft Sealings (3/4)

Shaft Sealing Concept: Shaft Salzdetfurth *Source: P. Sitz 2004*



Shaft Sealings (4/4)

Shaft Sealing Experiment Salzdetfurth: test of lower sealing element (7 MPa pressure)



Results: $k_f = 4{,}4 \bullet 10^{-11}$ m/s $< 5 \bullet 10^{-10}$ m/s

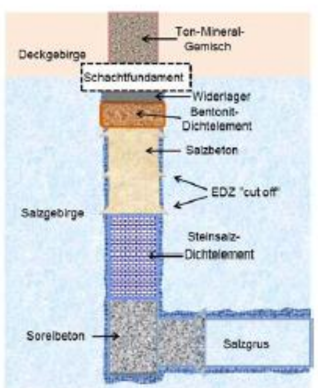
p_{gp} ~ 1-1,2 MPa ≥ 1 MPa

long-term stability: nat. analogue saliferous clay

saturation of bentonite sealing element

New approach

e.g. shaft sealing concept of GRS and Technical University of Clausthal



Main components of shaft filling and sealing:

- clay-mineral-mixture (overburden)
- static abutment below shaft foundation
- sealing element (bentonite)
- salt concrete
- EDZ cut off
- sealing element (rock salt)
- sorel concrete

New approach

RD&D-project ELSA: jointly carried out by DBE TECHNOLOGY GmbH and Technical University of Freiberg

Main Objective of the RD&D-project (acronym ELSA) is:

„development, construction and test of a shaft sealing system for a HLW-repository“

1. subproject	boundary conditions, requirements and safety proof of shaft sealings in rock salt and clay formations (1.4.2011 – 30.4.2012)
2. subproject:	Development of an appropriate shaft sealing concept and test of new supporting and sealing elements and materials
3. subproject:	large scale construction and demonstration as well as safety proof with adjustment of developed sealing concept, Evaluation of test results and recommendations for HLW-repository closure concept

RD&D-project ELSA

1. subproject working programme:

WP 1: state of the art on long-term stable shaft sealing systems

WP 2: development of a safety proof concept for shaft seals

WP 3: Identification and compilation of boundary conditions for the host rocks rock salt and clay

WP 4: deriving and compiling appropriate design requirements

WP 5: involvement of international partners

WP 6: reporting

RD&D-project ELSA

2. and 3. subprojects working programme:

- not specified in detail yet
- results of subproject 1 have to be considered
- **m**ay be carried out within the scope of the IGD-TP: International **T**echnology **P**latform: "Implementing **G**eological **D**isposal of Radioactive Waste".

Currently, the schedule for this 2 subprojects is as follows:

➢Subproject 2: Concept development (approx. 1.5 to 2 years) (mid 2012 – end 2013)
➢Approval and licensing od insitu activities: (approx 6 months) (mid 2014)
➢Subproject 3: Construction and testing: (approx. 2-3 years) (2014 – 2016)

Summary (1/2)

In Germany a safety concept:

✓for a for HLW-repository in rock salt formations exists
➢has to be devoped for a HLW-repository in clay

Safety measures to match the safety concept (salt):

- sealing of shafts and main drifts
- backfilling of all mine openings with crushed salt

Knowledge and practical experience in designing and constructing seals for repositories in rock salt exists:

✓ backfilling (material and technology)
✓ drift seals (Asse and Morsleben)

Summary (2/2)

RD&D is needed in developing and demonstration of shaft seal systems:

- **for a for HLW-repository in rock salt formations**

  ➢in particular regarding benefits when applying alternative sealing elements and materials (like bitumen and self healing backfill (SVV))

- **for a for HLW-repository in clay formations**

  ➢regarding safety proof concept
  ➢selecting appropriate material for sealing and supporting elements
  ➢constructability under real mine conditions (removal of supporing elements vs QA-ensured sealing elements

Salt Repository Seal Design and Materials

U.S. German Workshop on Salt Repository Research, Design and Operations II

November 9-10 2011 Peine Germany

Frank Hansen Sandia National Laboratories USA

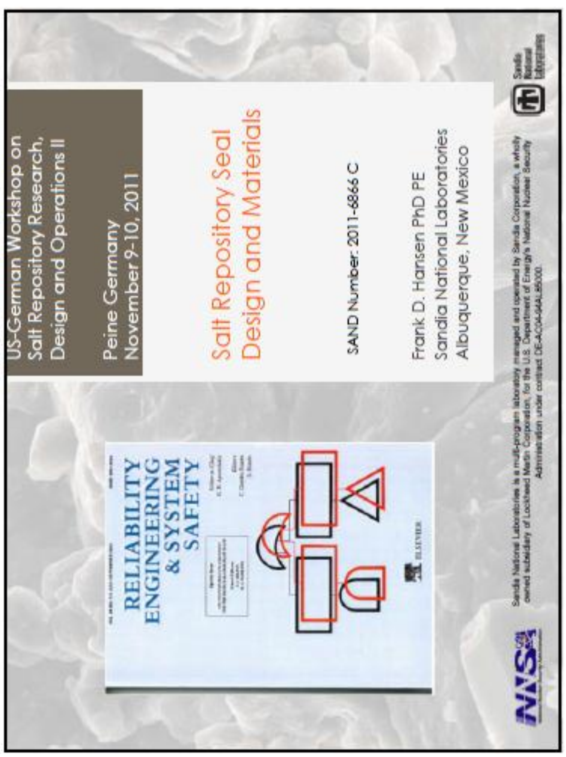
Seal systems are considered essential for nuclear waste repositories. To license a repository, there must be objective evidence that the disposed material will not contaminate the biosphere. This assurance is usually couched in terms of favorable geology operating in tandem with seal systems and other engineered barriers. Shaft seals and panel closure systems were developed in the process of gaining a compliance certification for the Waste Isolation Pilot Plant, a nuclear waste repository situated in a salt formation in the United States. This presentation emphasizes the science and engineering involved with the shaft seal system at WIPP.

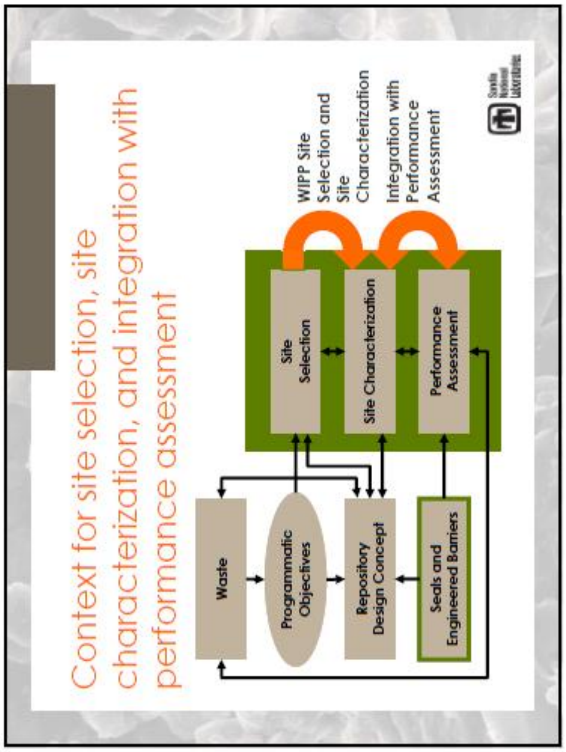
Shaft seal system functions entail material characteristics, construction, performance, and verification. Functional requirements could include low fluid permeability, stable chemistry, robust mechanical properties, and constructability. The WIPP design approach applied redundancy to functional elements and used multiple, common, low-permeability materials to ensure reliable performance. Laboratory and field measurements of component properties and performance provided the basis for the design and related evaluations. Hydrologic, mechanical, thermal, and physical features of the system were evaluated in a series of calculations. The use or adaptation of existing technology for seal construction combined with the use of commonly available materials assure that the shaft seal design can be constructed.

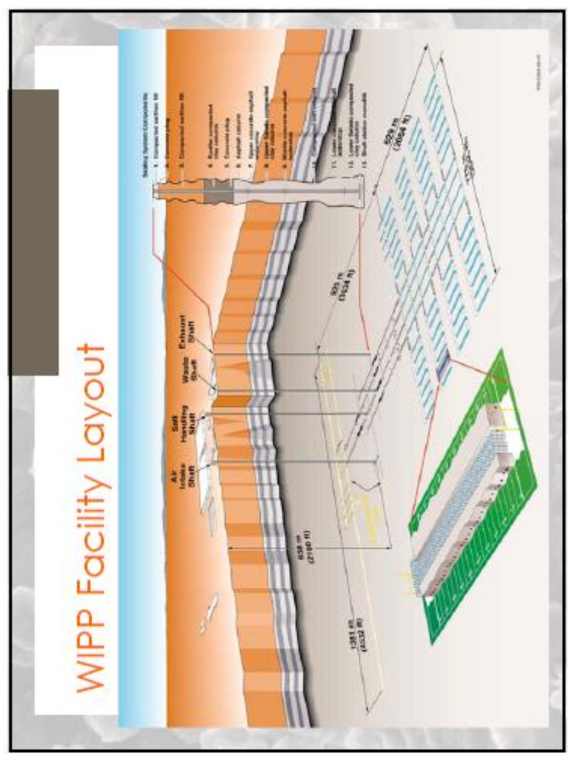
A well designed salt repository requires minimal engineered barriers. However, if licensing or public assurance requires seals to be placed in drifts or shafts, the capability to seal a salt repository permanently exists.

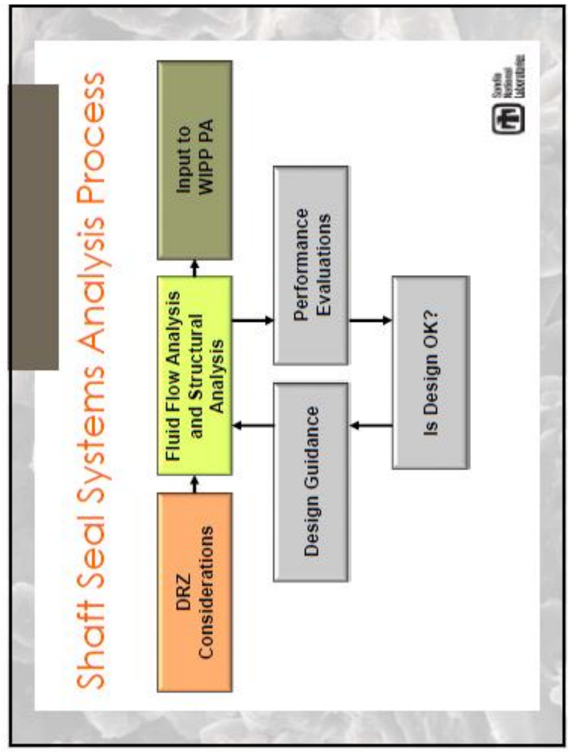
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. **SAND2011-6866C**

Frank Hansen









Material Specification

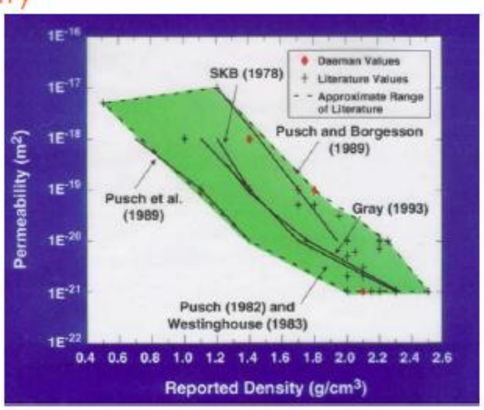
- Functions
- Material Characteristics
- Construction
- Performance Requirements
- Verification methods

Concrete Mixture Proportions

MATERIAL	lb/yd³
Portland cement	278
Class F fly ash	207
Expansive cement	134
Fine aggregate	1292
Coarse aggregate	1592
Sodium chloride	88
Water	225

$Kg/m^3 = (lb/yd^3) * (0.59)$ Water: Cement ratio is weight of water divided by all cementitious materials

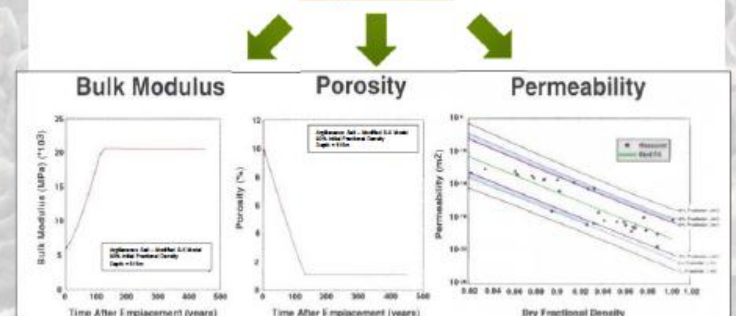
Sodium Bentonite Permeability Versus Density



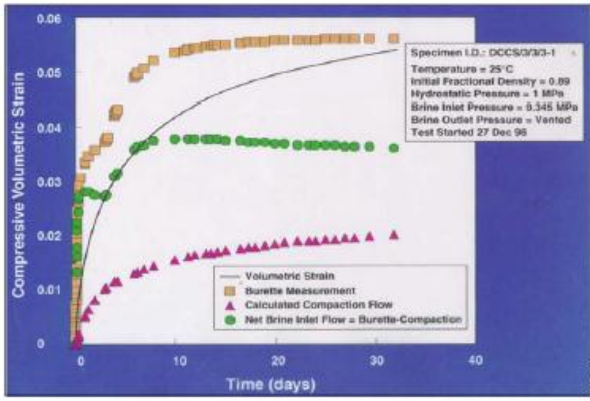
Reconsolidated Salt Properties

Lab Testing

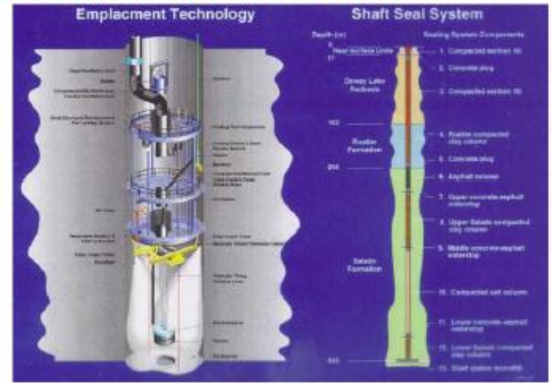
Crushed Salt



Brine Permeability Tests on Specimen DCCS/3/3/3-1



Shaft Seals System Studies



Model 1 – Brine Flow Down

Objectives

- To predict cumulative brine flow through the seal system down to the salt column and the repository
- To demonstrate the effectiveness of the concrete-asphalt

Assumptions

- Single-phase saturated flow
- 50-year, open-shaft period prior to closure
- Far-field BC is hydrostatic consistent with highest undisturbed Rustler head

Model 2 – Salt Column Performance

Objectives

- Predict the intrinsic permeability of the salt column component of the seal system
- Demonstrate effectiveness of the salt column as a low permeability seal within 200 years after closure
- Estimate gas migration from the repository horizon

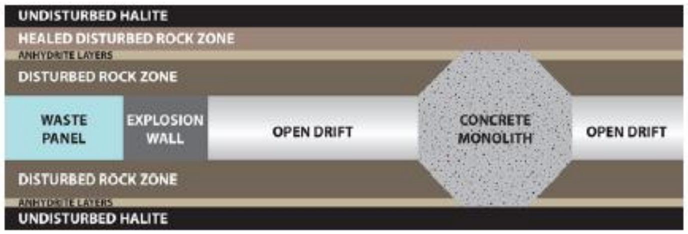
Assumptions

- Two-phase flow (brine and hydrogen)
- 50-year, open-shaft period prior to closure
- Hydrostatic outer boundary condition relative to MB-139

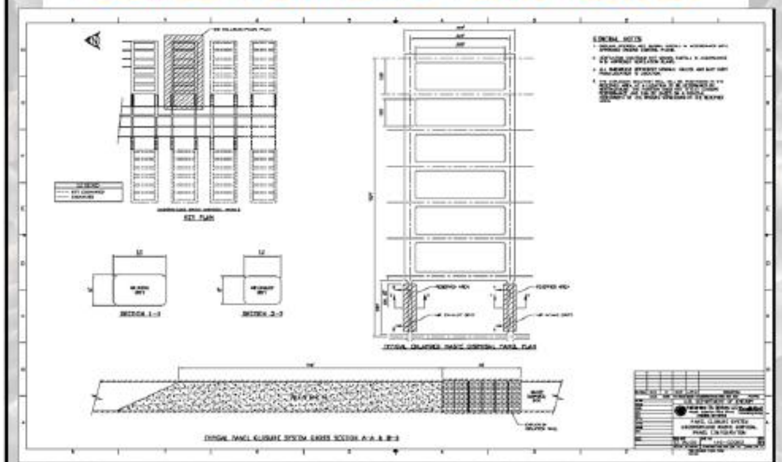
Simulation Code

TOUGH28W is a multi-dimensional, multi-phase coupled fluid and heat simulator for porous and fractured media. This Sandia version of the code was developed from the LBL code TOUGH2

Option D Panel Closure System



Possible Alternative Panel Closure



Isolation & Containment Strategic Choices for Seals & Backfill (concluded)

Design
- Concept of operations dictates size, shape & arrangement
- Barrier capability achieved by independent elements (redundancy)
- Multiple elements
- Differing materials
- Design review
- Quality assurance

Feasibility
- **Materials**
  - Available off-the-shelf no new technology required
  - Demonstrate-proof of principle testing
  - Scalable (lab/field)
  - Suitable properties (density, permeability)
  - Conductivity, durability
  - Analogy, practice, experience
- **Construction**
  - Industry Standard
  - Demonstration
- **Performance**
  - Hydrologic properties
  - Mechanical properties
  - Special accommodations (swelling, desiccation)

Bases
- Results of LTT&M/Science program verify these bases for the safety case
- Modeling
- Continued evaluation via performance confirmation

Shaft Seal System Conclusions

- The WIPP shaft seal system effectively limits fluid flow within the seal system.
- The salt column becomes an effective barrier to gas and brine migration by 100 years after closure.
- Long-term flow rates within the seal system are limited.
- Reference to available reports
- SAND97-1287 Shaft Seal System Parameters Document
- SAND96-1326/1 Shaft Seal Design Report

Project Virtus
Virtual Underground Research Laboratory in Salt

Tilmann Rothfuchs[1], Joachim Behlau[2], Michael Jobmann[3], Stefan Masik[4]
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[3]DBE TECHNOLOGY GmbH, Peine, Germany
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Abstract

According to international consensus all countries using nuclear power consider the emplacement of high-level radioactive waste (HLW) in deep geologic formations as the best solution for the long-term final disposal /Zitat NEA/. Potential host rocks primarily considered in Germany are rock salt and clay formations.

To acquire necessary experiences regarding the construction of an Underground repository and the long-term behavior of the host rock under the impact of heat and radiation, Underground Research Laboratories (URL) are operated in some countries. After closure of the Asse URL in 1995, an own URL was not longer available in Germany.

Anyhow, to furnish research and waste management organizations with an adequate instrument for the analysis of the repository processes and for the development of repository concepts and designs the idea of a virtual URL/repository was born in 2006. After an intensive phase of discussion, the project VIRTUS was launched in late 2010.

The main objective of the project VIRTUS is:

Development and provision of a software platform for the visualization of safety relevant processes predicted and investigated by numerical simulations

The project VIRTUS is based on three columns which are:

1 Development of the VIRTUS Software Platform including

a. Export of geologic and mine building data from openGEO (geological 3D-model of BGR) to the VIRTUS platform
b. View into the URL/repository system from an arbitrarily chosen perspective with 3D-display of the geology and the mine infrastructure (shafts, drifts, rooms, test sites)
c. Virtual flight through the geology and the mine building
d. 3D-display of URL experiments
e. Editing the geological and mine building model and export to relevant Process Level Codes (PLC)
    - Generation of code specific interfaces for the coupling of the VIRTUS platform with relevant Process Level Codes (PLC) such as Code_Bright, Jife, Flac, Rockflow
f. 3D-visualization of the results of numerical simulations
    - for a better process understanding as well as

- for the design of repository systems

  in context with repository near field, mine building, and geology up to the surface

g. Provision of links to computed data displayed in 2D cuts through the geologic structures (in transparency or cut-off of geological structures)

h. Provision of specific data through links in the 3D model to documents, measuring data, model parameters,

i. Presentation of the results of numerical simulations to the public in animated cartoons

2 Compilation, documentation and maintenance of a consolidated quality assured database

for the provision of:

j. Model parameters and parameter functions for PLC simulations

k. Existing documents and relevant literature from 40 years of research for the salt option

l. Selected (measuring) data and results of experiments performed in the past in URLs (e. g. Asse and others)

3 Provision of Possibilities for model and code benchmarking through prototypical THM-modeling

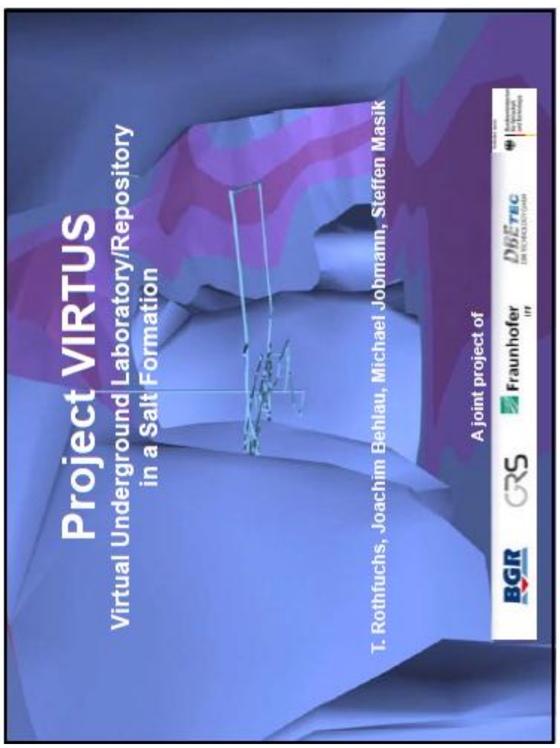
m. of selected URL-lead experiments considering drift and borehole disposal concepts

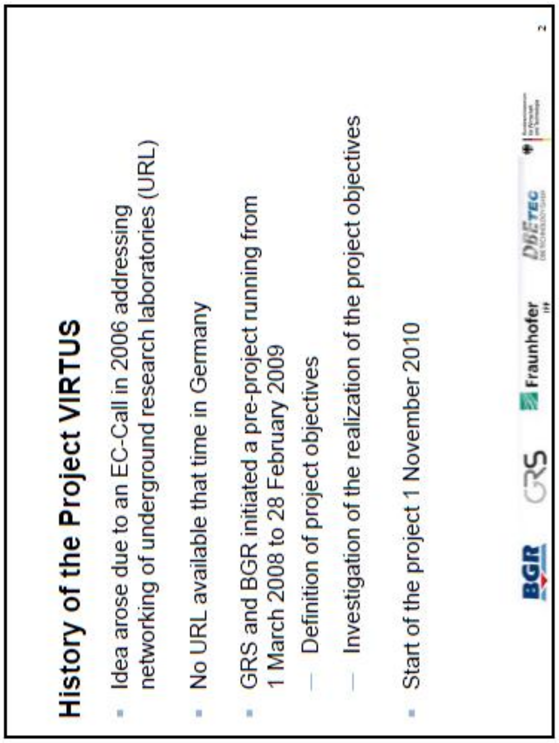
n. and other HLW-repository configurations

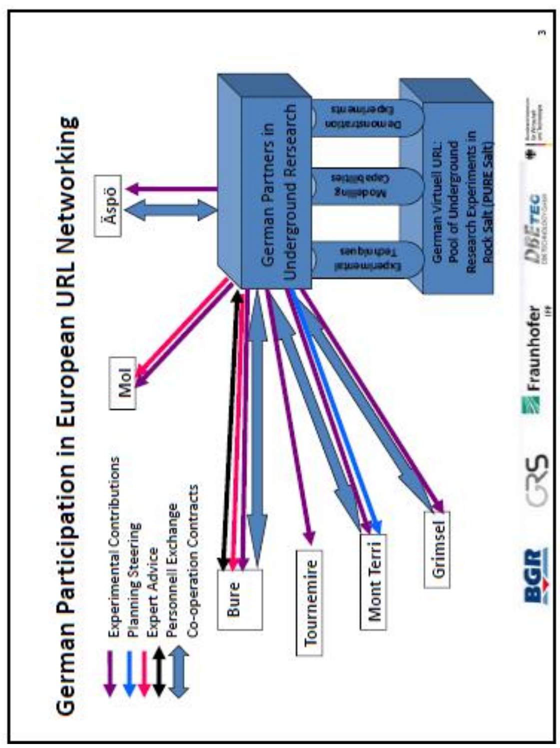
The VIRTUS Software platform is to provide relevant institutions with a powerful instrument for the analysis and visualization of the very complex processes taking place in an URL or a repository system as well as for the quick and efficient planning and check of repository designs within complicated geologic structures.

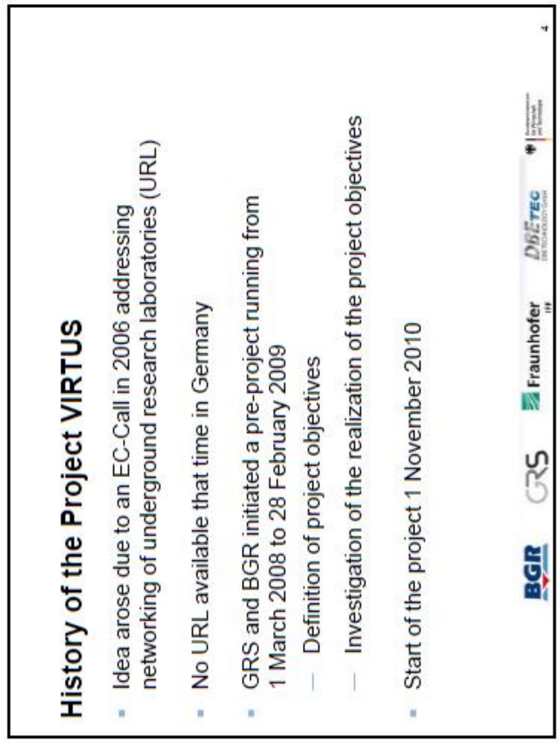
The 3D visualization of the results of numerical simulations within the 3D geologic structures of a repository is to help the involved researchers as well as the interested public to better understand and appraise the complex run of processes in a repository.

Tilmann Rothfuchs[1], Joachim Behlau[2], Michael Jobmann[3], Stefan Masik[4]









Objective of the Project VIRTUS

Development and provision of a software platform for the

Visualization of safety relevant processes predicted and investigated by numerical simulations

done for the support of

- investigations in a virtual underground laboratory

or for

- designing a repository system in geologic salt formations

5

The Three Columns of the project VIRTUS

1 **The VIRTUS Software Platform**

2 **Compilation, documentation and maintenance of a consolidated quality assured database**

3 **Provision of possibilities for model and code benchmarking through prototypical THM-modeling**

6

The Three Columns of the project VIRTUS

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7

- 3D-visualization of the results of numerical simulations
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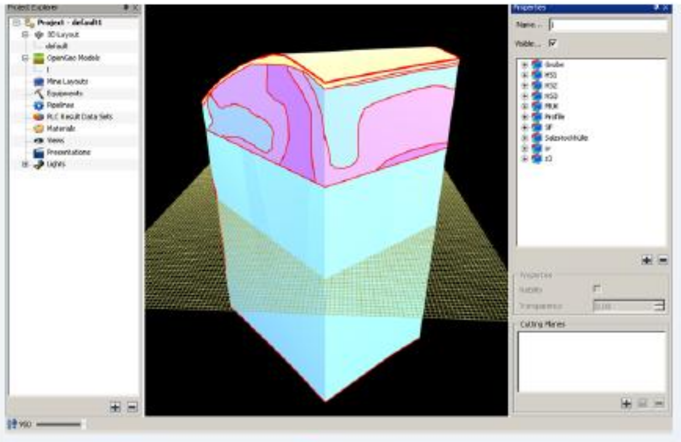
- Presentation of the results of numerical simulations to the public in animated cartoons

8

Selection of a block model for a PLC simulation



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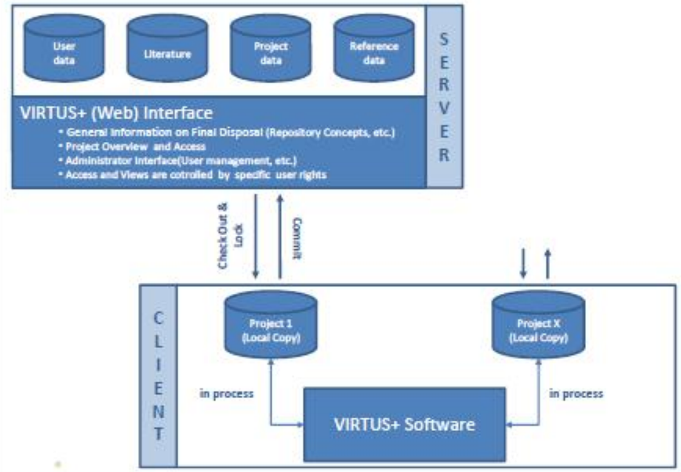
9

Project VIRTUS: Architecture



10

Project VIRTUS: Impressions with regard to the envisaged features of the VIRTUS platform

Example 1: 3D Views and Cuts

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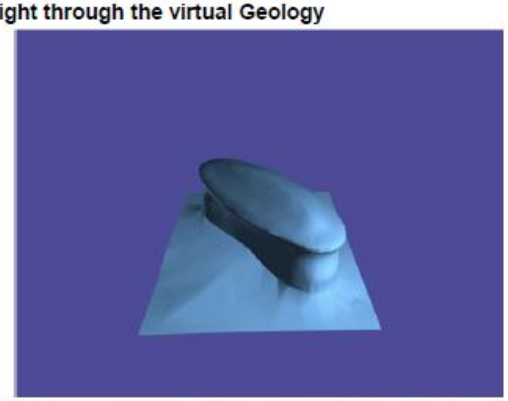
11

Project VIRTUS: Impressions with regard to the envisaged features of the VIRTUS platform

Example 2: Flight through the virtual Geology



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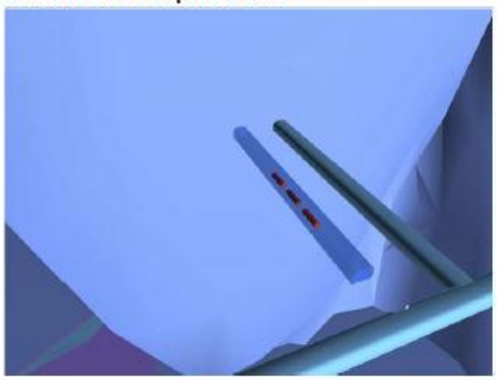
12

Project VIRTUS: Impressions with regard to the envisaged features of the VIRTUS platform

Example 3: Visualization of computed data



13

Future developments

- Coupled THM computations of large repository systems are significantly more time consuming in comparison to uncoupled computations

  In order to enable numerical simulations of complex repository systems within reasonable time periods the considered PLCs are to be improved with regard to an application on internet connected fast computer systems

- Respective developments are to be considered parallel to the project VIRTUS in the long term

- Coupling of VIRTUS platform with PA codes

14

Session 3

Gary Callahan: Crushed Salt Reconsolidation Model

US-German Workshop on Salt Repository Research
Peine, Germany
November 9–10, 2011

Crushed Salt Reconsolidation Model

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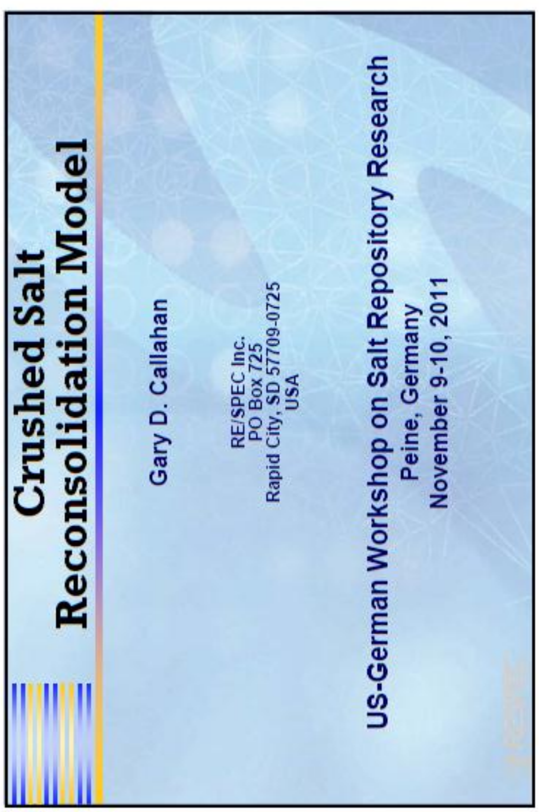
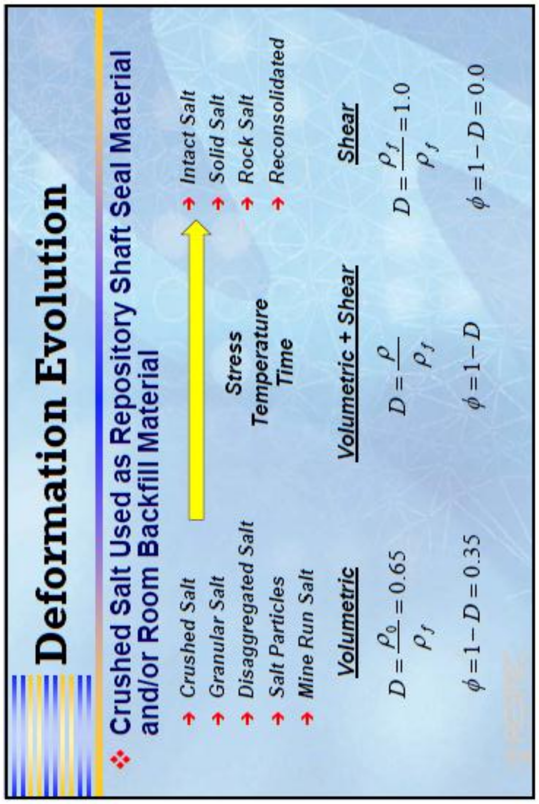
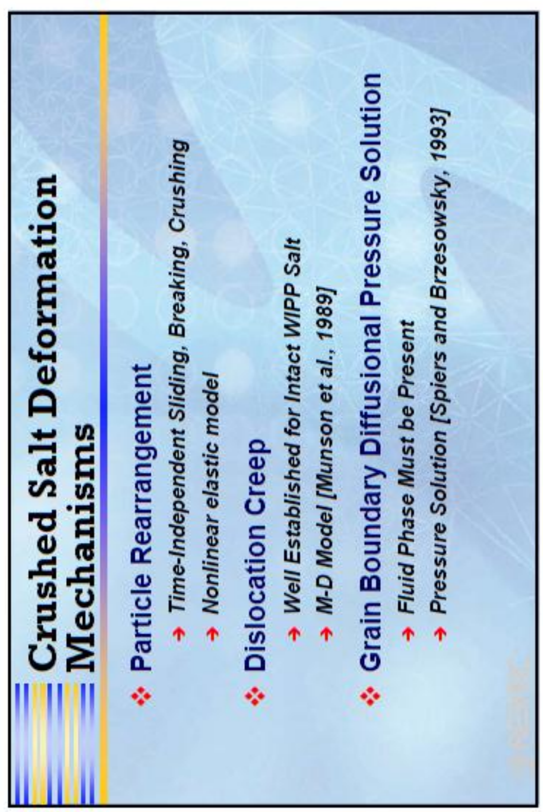
ABSTRACT

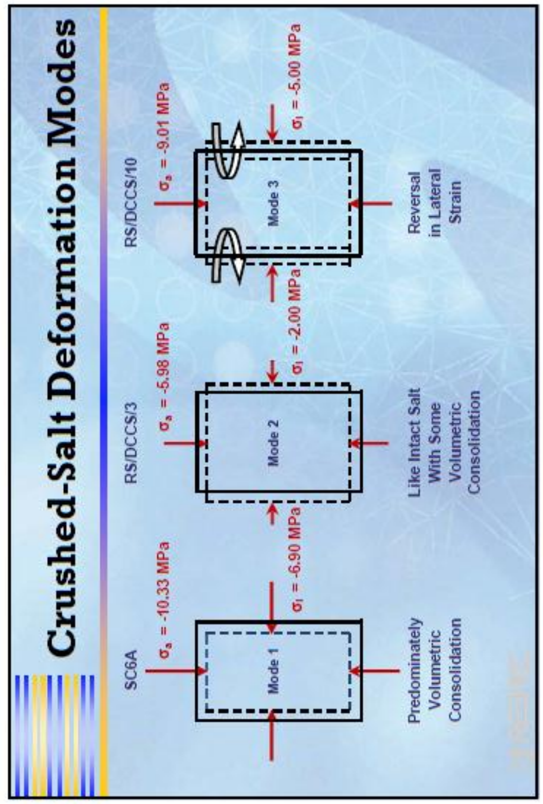
Crushed (disaggregated) salt may be used as a component in repository shaft sealing and as repository room backfill. In these situations (with sufficient stress, temperature, and time), the crushed salt evolves from a loose, highly porous material to a dense, low porosity material or essentially intact salt. To investigate the deformational behavior of crushed salt, 40 hydrostatic consolidation tests and 18 shear consolidation tests were conducted. To enable modeling the mechanical behavior of crushed salt in a repository setting, a constitutive model was developed to capture the major deformation components of the crushed salt. The constitutive model used to describe the reconsolidation of crushed salt includes two mechanisms – dislocation creep and grain boundary diffusional pressure solution. The constitutive model is generalized to represent three-dimensional states of stress. Upon complete consolidation, the crushed-salt model reproduces the multimechanism deformation (M-D) model typically used for the Waste Isolation Pilot Plant (WIPP) host geological formation salt. Parameter values for the model were determined through nonlinear least-squares model fitting to the experimental database. Using the fitted parameter values, the constitutive model was validated against constant strain-rate tests, a load path outside of the laboratory experimental database. Based on the fitting statistics, the ability of the model to predict the test data, and the ability of the model to predict load paths and test data outside of the fitted database, the model appears to capture the creep consolidation behavior of crushed salt reasonably well. Analysis results of a shaft seal problem are presented to demonstrate model-predicted consolidation of the shaft seal crushed-salt component. Current work is exploring the capability of the model to represent dry granular salt consolidation at elevated temperature.

Gary Callahan

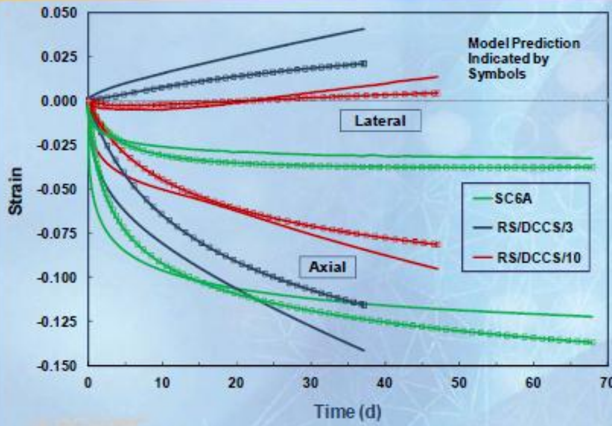








3 Tests/3 Deformation Modes



Test	Densities (kg/m³)		
	Initial	Test Start	Final
SC6A	1,375	1,701	2,053
RS/DCCS/3	1,954	1,964	2,087
RS/DCCS/10	1,958	1,981	2,146

Creep Consolidation Model

- **Kinetic Equation**

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

$\dot{\varepsilon}_{eq}^{d}\left(\sigma_{eq}^{f}\right)$ = Dislocation Creep [Munson et al., 1989]

$\dot{\varepsilon}_{eq}^{w}\left(\sigma_{eq}^{f}\right)$ = Pressure Solution [Spiers and Brzesowsky, 1993]

σ_{eq}^{f} and σ_{eq} = Effective Stress Measures

  - *Effective stress measures void dependence derivable from isolated spherical void in power-law creeping material presented by Wilkinson and Ashby [1975]*
  - *Detailed Model Information in Report SAND98-2680*

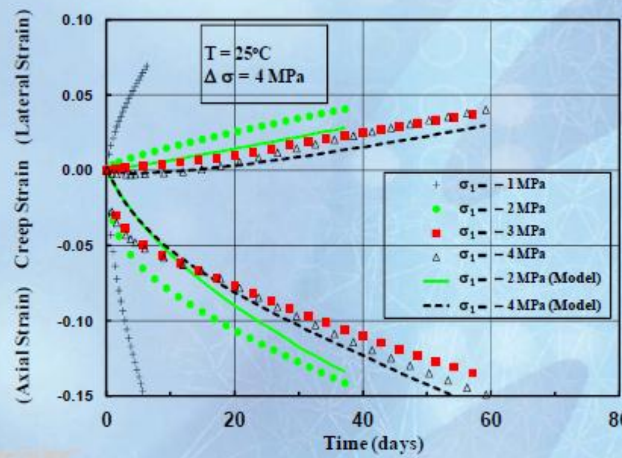
Parameter Value Determination

- **Experimental Database**
  - *40 Hydrostatic Consolidation Tests*
  - *18 Shear Consolidation Tests*
- **Nonlinear Least Squares Fitting**
  - *Dislocation Creep Parameters Fixed (Intact Salt)*
  - *Flow Potential Parameters Determined by Fitting the Lateral-to-Axial Strain Rate Ratio (Shear Tests)*
  - *Remaining Parameters Determined by Fitting Shear or Shear and Hydrostatic Combined Test Database*

18 Shear Consolidation Tests

- **Demonstrates Balance Between Mean and Deviatoric Stress Terms in the Flow Potential**
- **Key Consideration: At Some Value of Density the Lateral Strain Should Change Direction**
  - *10 Tests Show Axial and Lateral Strains Moving Inward, 6 Tests Show Lateral Outward, and 2 Tests Show Inward/Outward Transition*
  - *Higher Stress Difference Tests Show Lateral Strain Rates Approach Zero as Density Increases*
- **Axial Stress > Confining Pressure**
  - *Stress Difference: 0.44 to 5.0 MPa*
  - *Mean Stress: -2.33 to -8.05 MPa*
  - *Initial Densities: 1,375 to 1,958 kg/m³*

Constant $\Delta\sigma$ Tests with Increasing σ_m

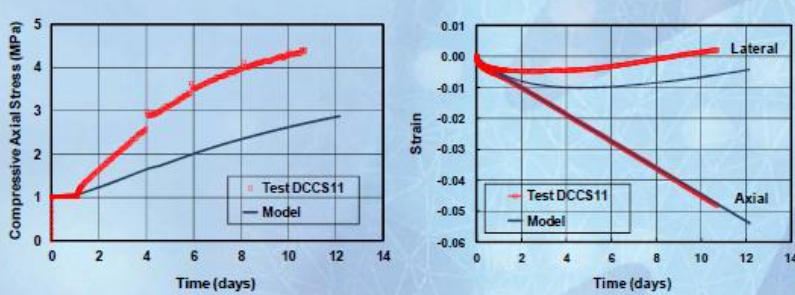


Constant Strain-Rate Tests

- Axial Strain Rates
  - *$-0.5 \cdot 10^{-7}$, $-1.0 \cdot 10^{-7}$, and $-2.0 \cdot 10^{-7}$/sec*
- Test Load Path
  - *Rapid Application of Nominal 1 MPa Hydrostatic State of Stress (< 1 minute)*
  - *Hold Hydrostatic Stress and Monitor Axial Strain Rate*
  - *When Axial Strain Rate < Target, Apply Axial Strain Rate While Holding Confining Pressure Constant*
- Provides Alternate Load Path for Model Verification

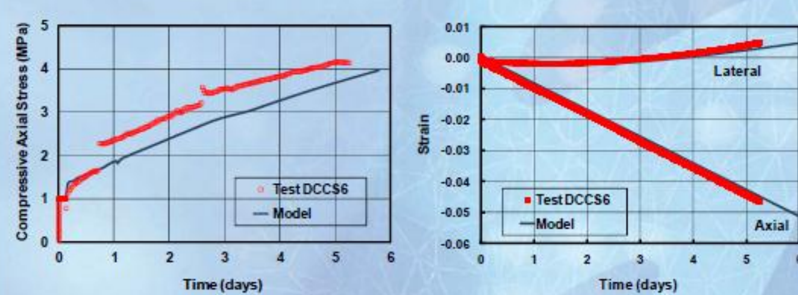
Constant Strain-Rate Test

Strain Rate 5 x 10^{-8}/sec



Constant Strain-Rate Test

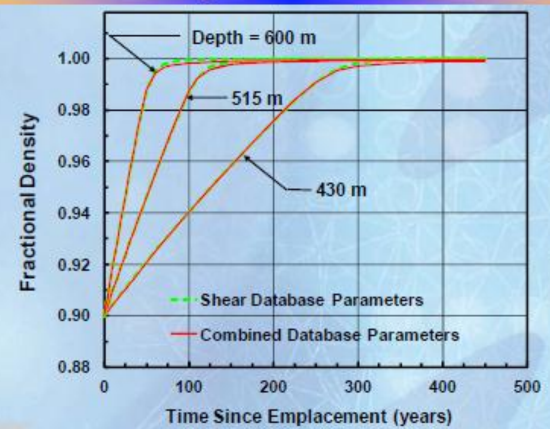
Strain Rate 1 x 10^{-7}/sec



Shaft Seal Analyses

- Shaft Sealed 50 Years After Excavation
- Finite Element Analysis in Axisymmetry
- Plane Strain Axial Direction
- 500-Year Analysis
- Shear and Combined Test Database Parameters Used in Simulations
- Crushed-Salt Component Examined
  - *Three Depths: 430 m, 515 m, and 600 m*

Crushed-Salt Shaft Emplacement



Current Effort

- Examine Model Adequacy to Represent Consolidation Processes of Dry Granular Salt at Elevated Temperatures
  - *Current model database mostly at room temperature*
  - *No shear consolidation tests at elevated temperature but 8 hydrostatic tests (2 mean stress levels) up to 100°C but very short durations <5 days.*
  - *Expand the laboratory test database with elevated temperature tests*
  - *Assess the adequacy of the existing reconsolidation model to predict elevated temperature tests*
  - *Implement model improvements to enhance elevated temperature predictions as required*

Conclusions

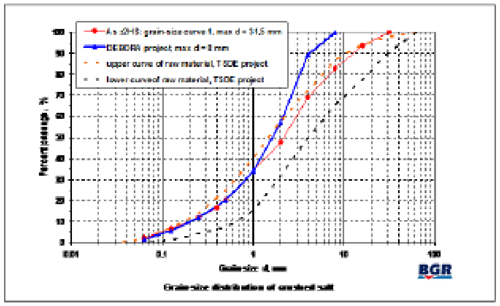
- Creep Consolidation Model Formulated for WIPP Crushed Salt that Includes Two Important Deformation Mechanisms and Captures the Volumetric and Deviatoric Deformational Behavior
- Model Appears to do an Excellent Job of Representing Crushed Salt Behavior for Consolidation Tests and Load Paths Outside of the Fitted Database
- Current Work Explores Model Ability to Represent Dry Granular Salt Consolidation at Elevated Temperatures

Dieter Stührenberg:
Compaction and Permeability Behaviour of Crushed Salt and Crushed Salt with added Bentonite (No Abstract)

Backfill reconsolidation, Testing and Modeling

Main influence variables on the compaction behavior of crushed salt:

Temperature, compaction rate, grain-size distribution, moisture content and additives (e.g. Ca-bentonite)



Investigations on crushed salt:

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

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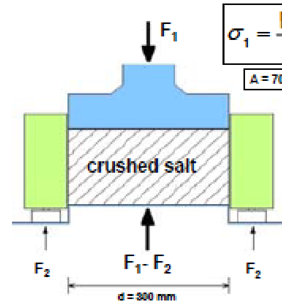
Backfill reconsolidation, Testing and Modeling

BGR Oedometer tests

An oedometer is the standard test equipment to characterise the compaction behaviour of fissured rock.



$$\sigma_1 = \frac{F_1 - F_2}{A}$$ = Backfill resistance

A = 706.9 cm²

Compaction rate: $\dot{\varepsilon}_V = \dot{\varepsilon}_1 = \frac{-dV}{dt \cdot V_0}$

Constant compaction rates analogous to a constant room convergence rate:

- $6.9\cdot10^{-7}$ s^{-1} ⇔ 0.36 mm/h
- $6.9\cdot10^{-8}$ s^{-1} ⇔ 0.036 mm/h
- $6.9\cdot10^{-9}$ s^{-1} ⇔ 0.0036 mm/h
- $6.9\cdot10^{-10}$ s^{-1} ⇔ 0.00036 mm/h

(sample: h_0 = 145 mm)

In situ drift convergence rate: about 10^{-10} s^{-1} and smaller

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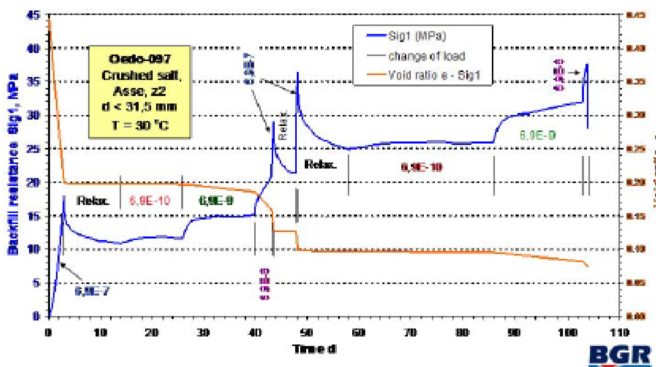
Backfill reconsolidation, Testing and Modeling



Backfill resistance σ_1 and void ratio e of Crushed salt vs. time

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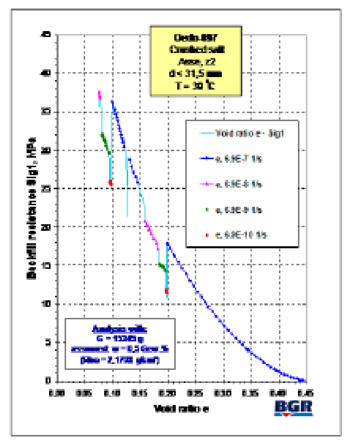
Backfill reconsolidation, Testing and Modeling



Oedometer test 097:
Compaction behaviour of crushed salt, T = 30 °C
Backfill resistance vs. void ratio

Measured data:

The backfill resistance increases with decreasing void ratio (porosity)

but it decreases with decreasing compaction rates

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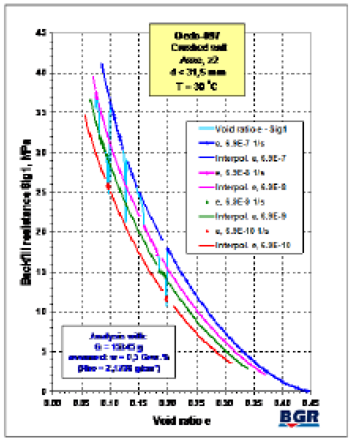


Oedometer test 097:

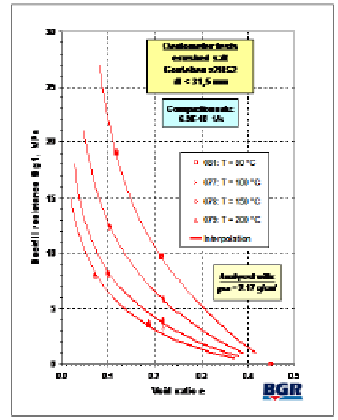
Compaction behaviour of crushed salt, T = 30 °C

Backfill resistance vs. void ratio

Measured and interpolated data:

With the complete test results the data from equal compaction rates can be interpolated well, even at very small compaction rates like under in situ conditions.

At the most BGR oedometer tests the at compaction rates are separated by one order of magnitude.



Oedometer test:

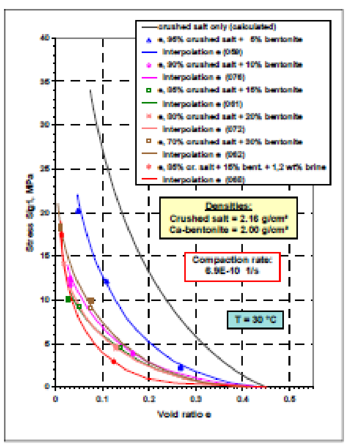
Influence of temperature on the compaction behaviour of crushed salt

Backfill resistance vs. void ratio

Measured and interpolated data:

Compaction rate: $6.9 \cdot 10^{-10}$ s^{-1} (0.00036 mm/h)

The backfill resistance decreases with increasing temperature



BGR oedometer tests:

Compaction behaviour of crushed salt with added bentonite- /brine, T = 30°C

General observation:

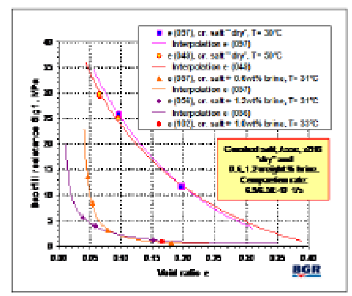
At room temperature, the backfill resistance of crushed salt can be reduced considerably with an addition of 10 to 15 weight percent Ca-bentonite.

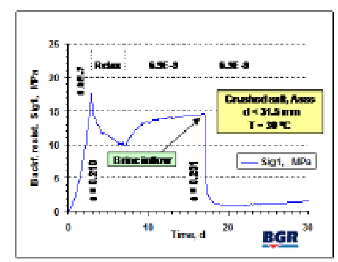
The backfill resistance can be decreased furthermore with a small amount of brine in the sample.

$$\rho_S^{SB} = \frac{G^{Salt} + G^{Bent}}{V_S^{Salt} + V_S^{Bent}}$$

Oedometer tests:

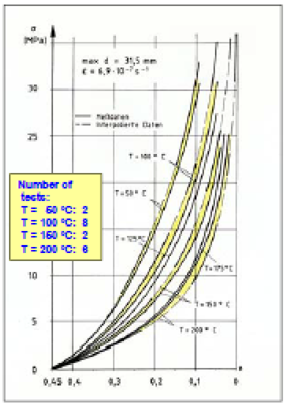
Compaction Behaviour of Crushed salt with added brine or brine inflow





Small amounts of moisture reduce the backfill resistance considerably, particular at low compaction rates.

A sudden influx of a brine to an incompletely compacted sample results in a sudden drop in its backfill resistance.



Reproducibility of Oedometer tests

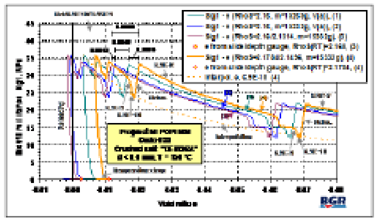
Reproducibility of Oedometer test results:

The results of strain controlled odometer tests are well reproducible (BGR, 1995).

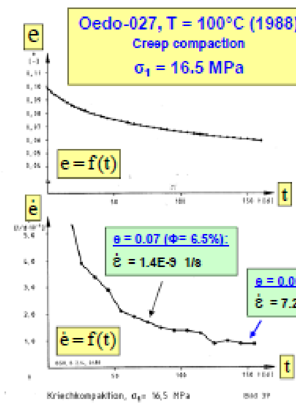
Uncertainty analysis:

The applied rock salt density ρ_s is the most sensitive parameter in determining the void ratio of crushed salt (Project REPOPERM, 2009)

The uncertainty is approximately Δe = 0.01 (1%)



Uncertainty analysis of Oedo-099 in REPOPERM

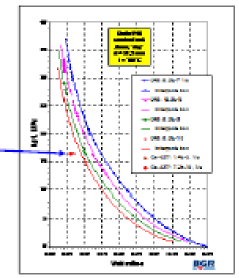


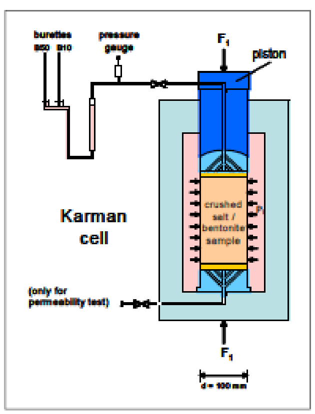
Creep compaction

The compaction of crushed salt also continues, when the pressure of the host rock cannot be increase considerably.

Compaction rate of about 7E-10 1/s:

The backfill resistance (16.5 MPa) is only 75% of that in a strain controlled test.





Test equipment TRE-2001 (M6)

Triaxial compression tests

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

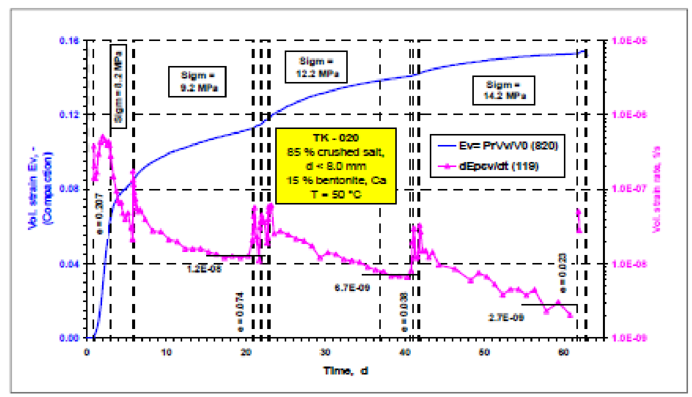
Stress components:

$$\sigma_1 = \frac{F_1}{A} \qquad \sigma_3 = p_i$$

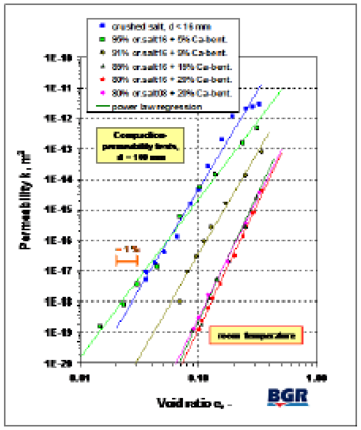
Mean stress: $\sigma_m = \frac{1}{3}(\sigma_1 + 2\sigma_3)$

Volumetric strain, vol. strain rate:

$$\varepsilon_V = \frac{\Delta V}{V_0} \qquad \dot{\varepsilon}_V = \frac{d\varepsilon_V}{dt}$$



Triaxial compaction test TK-020, volumetric strain, vol. strain rate vs. time, in dependance of mean stress; Δ σ ≈ 0.6 MPa ≈ const.



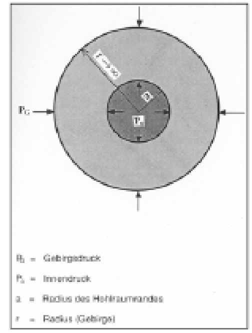
<u>Permeability</u> of crushed salt and mixtures of crushed salt and Ca-bentonite with brine

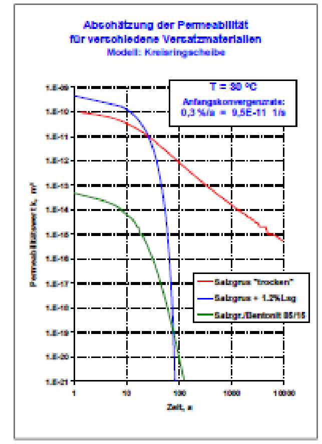
Stepwise compaction by axial load in a combined compaction-permeability apparatus (d = 10 cm). Different fluid pressures. Permeability calculation after Darcy's law, fitted using a power law regression.

<u>Reduction of permeability:</u>
10 % Ca-bentonite: 2 orders of magnitude
15 or 20 % Ca-bentonite: 4 ord. of magnit.

Backfill reconsolidation, Testing and Modeling

<u>Plane circular ring model (1996)</u>
Simple estimation of the permeability evolution in a backfilled drift at low temperatures (30 °C)





2nd US-German Workshop, Peine, Nov. 9, 2011

BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

Backfill – Constitutive Modelling (Presentation 1)
and
Material Parameters for Crushed Salt Backfill (Presentation 2)

U.S. German Workshop on Salt Repository Research, Design and Operations II

November 9-10 2011 Peine Germany

Christian Lerch DBE-TECHNOLOGY Germany
Klaus Wiezorek Gesellschaft für Reaktorsicherheit Germany

The design of a repository in rock salt for HLW typically includes the backfilling of open cavities with crushed salt. Important aspects include the minimisation of open cavities, heat transport away from the casks into the host rock, and long-term barrier integrity. The last two points are of particular importance with respect to long-term safety. Long-term safety has to be accounted for in experimental investigations and in the development of constitutive models of crushed salt. The implementation of a long-term barrier includes not only the crushed salt, but also the contour zone and the damaged zone close to the contour.

Some proofs on repository safety are performed based on numerical calculation methods. Different abstraction levels are used. Performance assessment codes (PAC) represent programs with the highest abstraction level. Generally, they are highly optimised programs for simulation of strongly simplified systems. Process level codes (PLC) allow the description of more complicated systems closer to reality, but at much higher numerical cost. Simplified results of PLC calculations can be abstracted into PA calculations. A necessary requirement in a PLC calculation is that all relevant processes of the crushed salt behavior can be described by the material models and that these material models are developed from reliable and defensible parameter inputs. These demands exist in every process class (process classes are the mechanical, the thermal, and the hydraulic behavior /WIE 12/). Other possible process classes which could be implemented in PLC would be the chemical and the radiological process classes. The focus of the two presentations are the material models of the PLC and the availability of experimental data as a basis for these material models, from which the parameter values of the material models can be derived.

The current state of development in PLC models provides the ability to describe THM coupled processes. Differences between PLCs arise at the sub-process model level. The primary sub-processes for the expected evolution of a radwaste repository in rock salt can be described. However, the level of precision within the separate sub-processes may vary. For example, a higher robustness exists in the thermal behavior than in the mechanical behavior /BEC 99/ /BEC 04/. Other processes and sub-processes associated with the expected or even unexpected evolution of a repository in rock salt have been disregarded up to now or have only been examined in separate calculations /WIE 12/. Examples include the healing of crushed salt and damaged rock salt within the mechanical process class or two-phase flow in hydraulic behavior; both are a topical research objects /KRO 09/. Up to now such processes are implemented in PLCs in a simplified manner at the most. Effects associated with the presence of moisture attain a significant importance with respect to THM coupling. They are not only a degree of freedom within the hydraulic process, but have significant influence on the mechanical compaction behavior and are influenced by the temperature field.

Experimental data is required for the investigated physical behavior as well as the material models /WIE 12/. In part the behavior of the crushed salt can be derived from that of undamaged rock salt. The compaction behavior as the key sub-process over all under dry conditions of a repository was previously extensively investigated and well documented, providing confidence in its validity. Open questions are at this time related to the transferability from different test methods and differences in test procedures at labs /BEC 99/. Other sub-processes, such as heat conduction, are based only on a single test series with limited pointwise check measurements /WIE 12/. These check measurements show that certain measuring methods lead to results in agreement with the test series, while other are less suitable for the investigation of crushed salt. Additional investigation of heat conduction behavior particularly at the beginning of compaction where porosity is highest is needed. Other material parameters, e.g. the elastic parameters, which are base parameters of each material model, were examined only at very few porosities /WIE 12/. It is not clear why so few data which are only from one lab exist. Such data gaps should be closed. A key parameter in the backfill behavior is permeability. Although a significant quantity of test data is available, uncertainty exists in some range of porosity and with respect to stress state. The reason (amongst others) can be found in the transferability of test conditions at the repository scale and in increasing understanding of the influence of other parameters, such as mechanical load.

In the past the test data have often been examined only against the background of minimizing open cavity volume. With respect to long-term safety the behavior of the crushed salt becomes more important in an enlarged range of parameter values, e.g., of porosity, and with other sub-processes like two-phase flow. Nevertheless, in addition to the above mentioned limitations the uncertainties in sub-processes which are often not in the focus of experimentation should be addressed. The significance of resolving these remaining parameter uncertainties affects the validation of model performance more than the forecast future behavior of a repository. With respect to the above mentioned differences in the state of knowledge from experimental behavior and the need to adequately describe process evolution in the repository, information gaps still exist which should be addressed according to their rating:

- data needed to reduce uncertainties in selected approaches
- data needed to secure material models or material parameter values, respectively
- data needed to develop material models

The current state in the development of the PLCs and in the data, which are the basis of the numerical models, allows the computational descriptionof the development of a radwaste repository in its undisturbed evolution over a wide range of time. There are limitations in the time scale with respect to the achievement of low backfill porosities. The consideration of hydraulic behavior is such a limitation with regard to moisture influence as well as on two-phase flow. Additional limitations are associated with the basis of some assumptions. The availability of reliable measuring data is substantially more difficult than the development of a mathematical model to describe the physical behavior. The verification of the material parameter values and the material models on the basis of suitable benchmark tests shows a continuing need. Finally, the preservation of information is an essential task.

/BEC 99/ 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 Commission, Nuclear Science and Technology, EUR 19124 EN

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Christian Lerch

Backfill

Christian Lerch
DBE TECHNOLOGY GmbH

2nd US-German Workshop on Salt Repository Research, Design, and Operation

November 9 – 10, 2011
Peine, Germany

Needs for Backfill

- Geotechnical barriers are placed in parallel to the intact salt rock barrier
  - To avoid water / brine intrusion into disposal chambers (WIPP, Gorleben working model, Morsleben repository)
  - To channel or to prevent brine flow (Asse research mine)
  - Early stage efficiency
- Backfill is placed in abandoned mining excavations
  - To stabilize the geological barrier
  - To minimize void volume
  - To saturate water or brine
  - To transfer or conduct heat in the case of HAW / SF (Gorleben working model)
- Complementary: Chemical barriers/buffers are placed close to the waste
  - To reduce radionuclide mobility

Process Level Codes

Organisation	Codes	Method	Process classes
BGR	Jife	FEM	THM
GRS	Code_Bright	FEM	THM
IfG	ITASCA-SW (FLAC,FLAC3D,UDEC)	FDM DEM	THM
KIT	ADINA	FEM	THM
TEC	ITASCA-SW (FLAC3D,3DEC,PFC3D)	FDM DEM	THM
TUC	MISES3 FLAC3D	FEM FDM	THM THM
…			

Codes

- Differences in
  - Methods
  - Schemes for time integration
  - Solver
- Similarities
  - General purpose analysis
  - Mechanical part: Additive decomposition of strain rate tensor, thus, no multiplicative decomposition of deformation gradient tensor
- PAC are different from PLC

Thermal Modelling - 1

- Transport processes
  - Conduction
  - Advection
  - Radiation
    - ☞ Not all processes act in a code at the same time
    - ☞ Heat Conduction is the common process
- Heat capacity
  - Neglecting influence from air

$$\rho c_p = (1-\eta)\,\rho_{RS}\,c_{p,RS}$$

- Heat conductivity
  - Mixed mode model
  - Geometric related model
  - Empirical model

Thermal Modelling - 2

- Heat conductivity
  - Mixed mode model (a: Thermal resistance)

$$\lambda(T,\eta)=\frac{1}{\left(\frac{1-a}{(1-\eta)\lambda_{RS}(T)+\eta\lambda_A(T)}+\frac{a(1-\eta)}{\lambda_{RS}(T)}+\frac{a\eta}{\lambda_A(T)}\right)}\approx\frac{(1-\eta)\lambda_{RS}(T)\lambda_A(T)}{(1-\eta)\eta a\lambda_{RS}(T)+\lambda_A(T)}$$

  - Geometric related model (c: Material parameter)

$$\lambda(T,\eta,\eta_0)=\frac{\lambda_{RS}(T)(1-\eta)}{\left(c\left(1-(1-\eta)^b\right)+(1-\eta)^b\right)};\quad b=\frac{\ln(2/3)}{\ln(1-\eta_0)}$$

- Empirical model (c, m: Material parameter)

VSG ☞ $\lambda(T,\eta,\eta_0)=\lambda_{RS}(T)\left(1-\frac{\eta}{\eta_0}\right)^m+\frac{\eta}{\eta_0}\lambda_C(T)$

$$\lambda(T,\eta)=\lambda_{RS}(T)(1-c\,\eta)$$

Thermal Modelling - 3

- Dependence on initial porosity in empirical model is a material parameter
- Thermal conductivity λ_c states as a fit function
- An approach based only on rock salt conductivity is not able to represent the increase in heat conductivity with temperature for very loose material
- Mixed model and geometric model tend to a higher heat conductivity for high porosities
- Chosen function: Empirical model 1
  - ☞ Next Presentation

Hydraulic Modelling - 1

- Transport processes
  - 1-Phase-flow
    - Fluid transport
    - Particle transport
    - Diffusive transport
  - 2-Phase-flow

☞ Not all processes act in PLC named above at the same time
☞ Some PA codes deal with the more special processes
or
coupling on code level between general purpose PLC and more special codes (e.g. Tough)
☞ Typically: Fluid transport is the common process

Hydraulic Modelling - 2

- Darcy flow
  - Poro-Perm-Function

$$k(\eta) = k_0\,\eta^n \qquad k(\eta) = k_0 \frac{e^{\left(\frac{\sigma_{max}}{\sigma_{c,\eta}}\right)}}{\left(\frac{\eta_c}{\eta} e^{\left(\frac{\sigma_{max}}{\sigma_{c,\eta}}\right)}\right)^{n_1} + \left(\frac{\eta_c}{\eta} e^{\left(\frac{\sigma_{max}}{\sigma_{c,\eta}}\right)}\right)^{n_2}}$$

    - Next Presentation

  - Approximation with "cubic law"

$$k(\eta) = k_{Matrix} + \frac{(b_0 + s\,\varepsilon)^3}{12s}$$

    - Ability for anisotropic permeability

  - Anisotropic damage model (Jife)

$$k(\eta) = c\,V^{\frac{2}{3}}\,\varepsilon^3_{ii,pl}$$

    - Ability for anisotropic permeability

! Currently influences from moisture are treated as a parameter in PLC not as a property

? Reliability in prediction due to the small amount of water needed to effect mechanical behaviour

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Mechanic Modelling - 1

- Processes
  - Time independent and time dependent processes
  - Reversible and irreversible processes

  - Grain movement and rotation
  - Grain fracturing
  - Grain deformation
  - Friction reduction influenced by moisture
  - Fluid assisted diffusion transport
  - Solution recovery

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Mechanic Modelling - 2

- Dry conditions (based on Project RepoPerm)
  - Processes in rock salt act in the same manner as in backfill
  - Backfill should show an approximate correspondence in creep behaviour with that from rock salt close to the end of compaction
  - Compaction rate must go to zero for small porosities
  - Deviatoric and volumetric creep should act under similar stress conditions because stresses produce quite similar deformations in the contact area on grain level
  - Solidification of the crystals should be considered
  - Geometry dependence of backfill should be very similar in comparison between different constitutive models (i.e. strain rate vs. strain at constant state of stresses and of temperature)
  - At small porosities there is a change in the geometry dependence of compaction
- Wet conditions
  - Already small quantities of water have a significant influence on compaction
  - Different modes under different states, i.e. gliding under low stresses and diffusive transport at high stress concentrations

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Mechanic Modelling - 3

- Predominant hydrostatic, dry conditions

  Zhang

$$\dot{\varepsilon}_{c,vol} = A e^{\left(-\frac{Q}{RT}\right)} \left(\ln\frac{\eta_0}{\eta}\right)^{-\beta} \left(\frac{\sigma_0}{\bar{\sigma}}\right)^{\alpha}$$

  Korthaus

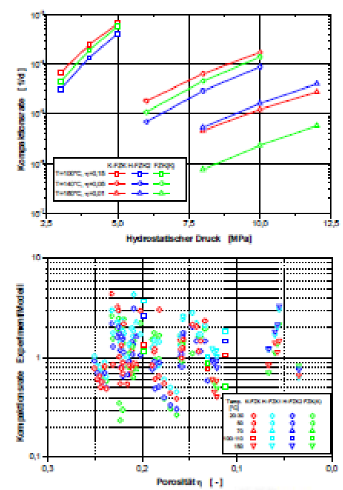
$$\dot{\varepsilon}_{c,vol} = A e^{\left(-\frac{Q}{RT}\right)} \frac{\eta^{c_2}}{c_3 e^{c_4 \varepsilon_{vol}} - 1} \left(\frac{\sigma_0}{\bar{\sigma}}\right)^{\alpha}$$

  WIPP

$$\dot{\varepsilon}_{c,vol} = B_0^{*} \frac{e^{B_1^{*}(1+\varepsilon_{vol})}}{(1+\varepsilon_{vol})} \left(1 - e^{-B_2\sigma_0}\right)$$

  mod. WIPP

$$\dot{\varepsilon}_{c,vol} = A e^{-\frac{Q}{RT}} \frac{e^{B_1^{*}(1+\varepsilon_{vol})}}{(1+\varepsilon_{vol})} \left(1 - e^{-\left(B_2|\sigma_0| + B_3\sigma_0^2\right)}\right)$$



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Mechanic Modelling - 3

- Combined hydrostatic / deviatoric models

Models bases
- generally on an idea of geometric grain configuration
- approach of visco-plasticity
- partly on dissipation postulat

Code_Bright

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{dc} + \dot{\varepsilon}_{gd} + \dot{\varepsilon}_{ps}$$

Jife, Hein (F^{3D})

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{dc} + \dot{\varepsilon}_{gd}$$

further codes (MARC, ADINA,..)

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{dc}$$

$\dot{\varepsilon}$: total strain rate
$\dot{\varepsilon}_{el}$: elastic strain part
$\dot{\varepsilon}_{dc}$: dislocation creep
$\dot{\varepsilon}_{gr}$: grain rearrangment
$\dot{\varepsilon}_{ps}$: pressure solution (fluid assisted diffusion transport)

not yet implemented:
$\dot{\varepsilon}_{sr}$: solution recovery
$\dot{\varepsilon}_{d}$: damage
$\dot{\varepsilon}_{h}$: healing

DBETEC

Project BAMBUS II (2002) - Modelling

BAMBUS (Backfilling and sealing of underground repositories for radioactive waste in salt)
- Partner: BGR, DBETEC, G.3S, GRS (UPC), IfG, KIT, NRG, US DOE
- Sponsored by EC, BMWI (D)
- 4 Work packages: In-situ investigation, labor test, modelling, desk studies
- Results from work package Modelling:
  - 3D thermal modelling is necessary
  - Thermal calculation is in good accordance (but not in the same accuracy for the cold and the hot area within the same calculation)
  - Drift closure is over-predicted
    - Field measurements possibly did not capture some early-time deformation
    - Some differences in stress-strain approximation in backfill behaviour
  - ☞ Under-predicted thermal activated creep in host rock (BGRa in case of BGRb)
  - ☞ Thermal conductivity in backfill

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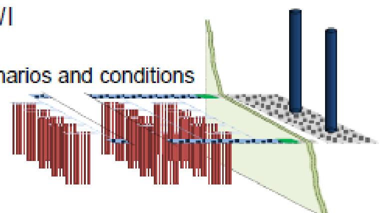
Project RepoPerm

RepoPerm (Restporosität – Permeabilität)
- Partner: BGR, DBETEC, GRS (Braunschweig)
- Sponsored by BMWI
- Work packages:
  - WP1: Relevant scenarios and conditions



  - WP2: Lab tests - Different creep compaction tests, grouting test, accretion test, triaxial test
  - WP3: Material laws and model calculations
    - Comparison between different constitutive models
    - Post-calculation from BGR Oedo-99, code modification
    - Blind prediction from GRS creep compaction test (WP2)
    - Re-calibration and improved approximation

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Next Steps: Part in Project RepoPerm

- Integration of internal back stress
  - Transferability between experimental data from deformation (BGR) and from stress (KIT, partly BGR) driven state
- FADT
  - Integration into codes
  - Verification and validation
- Behaviour near the end of the compaction process under dry and wet conditions

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Further requirements

- Back to the roots: Some of key quantities are not sufficiently defensible, e.g. heat conductivity, elastic properties: Young's modulus, Poisson ratio, bulk modulus
- More data about compaction behaviour from triaxial tests under variable conditions is needed
- Behaviour at the end of the compaction process: Transferability between rock salt behaviour and crushed salt
- Influence from a small amount of moisture
- Relevance of moisture under conditions in German repositories
- Benchmark
  - TSDE-Recalculation
  - In-situ-test with higher compaction grades than TSDE (about 25%)
  - In-situ-test under moisture influenced conditions

C. Lerch / 09.09.2011

DBE TEC

Klaus Wiezorek

Material Parameters for Crushed Salt Backfill

2nd US-German Workshop on Salt Repository Research, Design, and Operation

Peine, November 9-10, 2011

Klaus Wieczorek*, Oliver Czaikowski*, Christian Lerch**

*GRS Braunschweig **DBE Technology

The Role of Crushed Salt Backfill in a Salt Repository

The change in the philosophy of safety assessment to the concept of the „Containment Providing Rock Zone" influenced the importance of different components in a salt repository. In particular, the role of the crushed salt backfill became more prominent. The backfill serves to

- Conduct the heat produced by HLW to the host rock
- Reduce the open voids in the repository
- Provide, with increasing compaction, support to the rock
- Seal, after compaction, the disposal areas in the long term and assume the role of the drift seals

The thermal-hydraulic-mechanical (THM) behavior of crushed salt has to be well understood in order to reliably predict the backfill behavior. This requires

- Suitable constitutive models (especially for the mechanical behavior)
- Realistic material parameters

Required Material Parameters for Crushed Salt (1)

- **Thermal parameters**
  Thermal conductivity, specific heat, thermal diffusivity as a function of temperature, porosity, solution content
- **Hydraulic parameters**
  Permeability as a function of porosity (single phase permeability to brine and gas), Two-phase flow parameters (capillary pressure curve, relative permeabilities)
- **Mechanical parameters**
  Elastic parameters as a function of porosity, parameters for the various constitutive models describing compaction and time-dependent behavior for dry and moist crushed salt
- **Coupling parameters**
  TM coupling: thermal expansion coefficient, HM coupling: Biot coefficient

Required Material Parameters for Crushed Salt (2)

Some of the required material parameters can be derived from known parameters of the competent rock salt.

- E.g., **Specific heat** and **thermal expansion coefficient** can be calculated as product of respective values for rock salt and solid fraction of the crushed salt

Other parameters are more critical: Their complex dependence on porosity (and partly on temperature) requires direct measurement on the porous material:

- **Thermal conductivity**
- **Permeability**
- **Two-phase flow parameters**
- **All mechanical parameters**

These are addressed here.

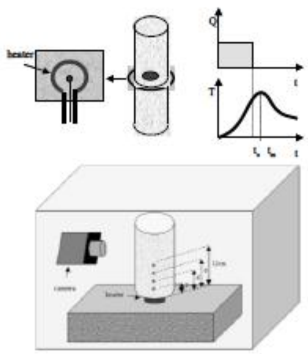
The dependence on the grain spectrum is not considered explicitly. For the reference backfill, the grain spectrum is defined.

Thermal Conductivity (1)

Thermal conductivity of crushed salt was measured in the frame of the EC projects BAMBUS and BAMBUS II, there are also additional sources (see reference list). Different techiques were used:

- Transient measurements
  (fast, easy, but capture only a small part of the sample, coupling problems will lead to underestimating thermal conductivity)
- Stationary measurements
  (capture complete sample, but are complex, heat loss will lead to overestimating thermal conductivity)
- Infrared techniques
  (reliable, but complex evaluation, very few results available)

Not all measurements are documented satisfactorily.



Thermal Conductivity (2)

Observations

- Strong dependence on porosity and temperature
- Thermal conductivity increases with decreasing porosity
- Thermal conductivity decreases with temperature at low and intermediate porosity, but increases with temperature at high porosity (heat radiation)
- Significant deviations in data, depending on technique

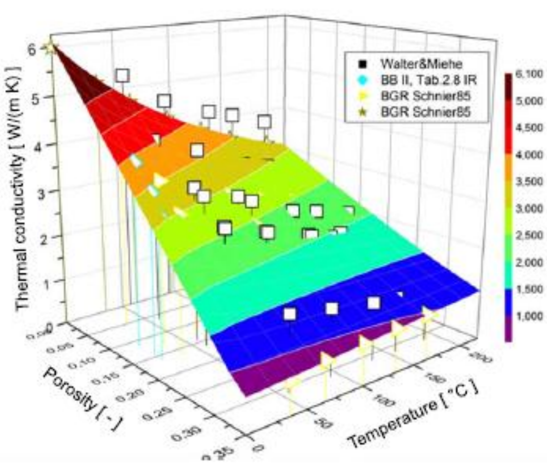
Conductivity function (Korthaus in BAMBUS II, Birch & Clark for porosity = 0)

$$\lambda_{CS} = \left(1 - \frac{\eta}{\eta_0}\right)^m \cdot \lambda_S + \frac{\eta}{\eta_0} \cdot \lambda_G \qquad \eta_0 = 0.38 \qquad m = 1.14$$

$$\lambda_S = \frac{\lambda_0}{1 + c_\lambda \cdot \vartheta} \qquad \lambda_0 = 6.1 W/(m \cdot K) \qquad c_\lambda = 0.0045 °C^{-1}$$

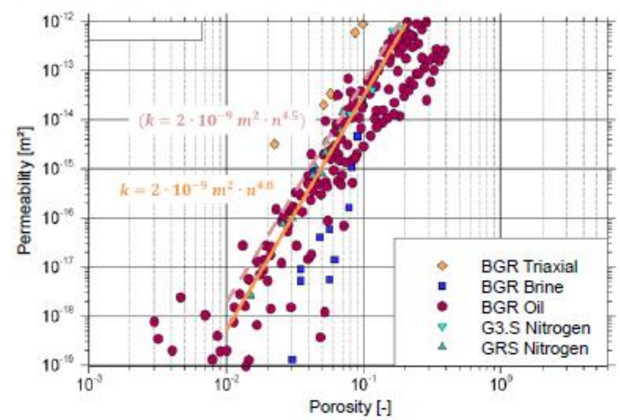
$$\lambda_G = a_0 + a_1 \cdot \vartheta \qquad a_0 = 0.42 W/(m \cdot K) \qquad a_1 = 0.0027 W/(m \cdot K^2)$$

Thermal Conductivity (3)



Permeability (1)

Project REPOPERM: Compilation of existing data



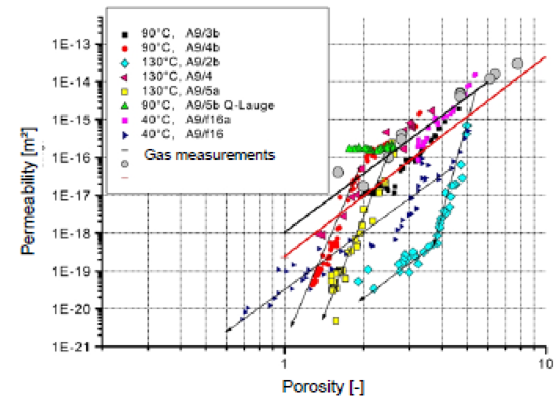
Permeability (2)

Observation

- Measurements with brine show considerably lower permeabilities than gas or oil measurements, especially at low porosity.
- This is explained by pressure solution at grain contact planes (due to local stress peaks) and precipitation in the pores, leading to alteration of the pore space.
- Since very small amounts of brine are sufficient to start the process, and since these will be present in the repository, measurements with brine seem to be the representative ones.

Permeability (3)

Measurements with brine by Elliger and Konen under varying load



Permeability (4)

Observation

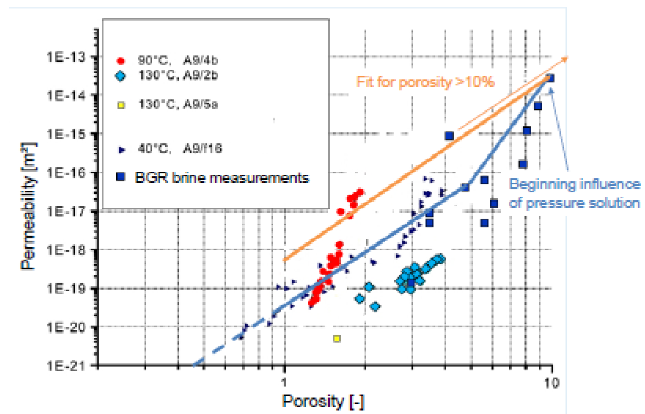
- Part of the data show extremely high values
- Most measurement curves show characteristic bends which coincide with load changes

Explanation

- The dry samples were prepared by compaction under high short-term load to porosity values below 6 % and only then saturated with brine. The permeability tests were afterwards performed at load steps of 2 MPa, 4 MPa, and 10 MPa (injection pressure <1 MPa).
- This sample preparation is not representative for in situ.
  - Pressure solution and precipitation could only occur during the measurement itself, but not during preparation
  - A low porosity at low mechanic load is not realistic (no unloading is expected)

Permeability (5)

Measurements of Elliger at load >4 MPa, BGR measurements, suggested curve



Two-Phase Flow Parameters

The only measurements were performed by Cinar et al., but

- No measurements with real crushed salt; commercial salt with a single grain size was used
- The samples were prepared by high-load short-term compaction (see problem of Elliger's measurements)
- Only a very narrow porosity band (4.0 % – 5.5 %) was investigated, and extrapolation to other porosities is problematic

Since two-phase flow parameters are essential to describe saturation of the backfill in case of a brine influx, there is a definite need for research.

Mechanical Parameters: Elasticity

Since the elastic behavior has always been considered less important than the compaction or generally time-dependent behavior, very few data exist.

Measurements (short-term triaxial loading-unloading tests) were performed by Korthaus in the frame of BAMBUS II.

Porosity	E [MPa]	ν [-]	K [MPa]
0.224	710	0.335	720
0.01	11450	0.278	8600

Mechanical Parameters: Time-Dependent Behavior

Time-dependent behavior has been discussed in the previous presentation by C. Lerch. GRS uses an approach implemented in CODE_BRIGHT including

- Intragranular viscoplasticity (dislocation creep), as for competent rock salt
- A viscoplastic approach for intergranular deformation (grain reorganization)
- For crushed salt containing moisture: fluid-assisted diffusional transfer (FADT)

For calibration of the model (currently underway), lab test data are necessary. Data are available from BGR's oedometer tests (earlier presentation of D. Stuehrenberg)

- At ambient and elevated temperature
- With increased solution content

For calibration the data are, however, not always well suited, and there are, for now, only two tests with solution content.

Conclusions

Although crushed salt has been investigated for many years, there are still considerable knowledge deficits regarding the material parameters. The parameters can be categorized as follows:

- A: Data covering the range of interest are available from different experimentalists, but there are drawbacks with regard to the method or documentation. Individual suited experiments are needed to reduce the uncertainty and confirm the chosen approach.
  Thermal conductivity and permeability fall under this category.
- B: Few data are available, often only from one experimentalist using one measurement method. Parameter values or calibrations derived are not sufficiently confirmed.
  Elastic properties and time-dependent mechanical behavior would be cat. B.
- C: No or no suitable data are available. Parameters are vague.
  This applies to the two-phase flow parameters.

Some, but not all, deficits are tackled in ongoing projects, especially the BMWi project REPOPERM 2.

GRS

Acknowledgment

The compilation of material parameters for crushed salt, part of which is presented here, is prepared in the frame of the BMU (German Ministry for the Environment, Nature Conservation and Nuclear Safety) project “Vorläufige Sicherheitsanalyse Gorleben” (Preliminary Safety Analysis Gorleben).

GRS

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Thursday, November 10, 2011
Session 4

Jacques Grupa: Deformation and Healing Rock Salt

2nd US-German workshop on rock salt (Peine, Germany,11/2011)

Deformation and healing of Rock Salt - session 4.

J. Grupa[a], C. J. Spiers[b], N. Muhammad[b], J. H. P. De Bresser[b], C. J. Peach[b]

[a] *Nuclear Research and consultancy Group (NRG), The Netherlands*
[b] *HPT Laboratory, Utrecht University, The Netherlands*

Summary:

The presentation by NRG and UU focusses on the relevance of experimental work and fundamental process understanding for the safety assessment of disposal of radioactive waste in rock salt.

The presentation consists of three parts: an introduction by NRG, and two examples of experimental work done at the University of Utrecht.

INTRODUCTION

Since the 1980s Utrecht University (UU) and NRG (at that time a division of ECN) cooperate in the Dutch and EU research programs into geological disposal of radioactive waste. At that time, ECN developed and tested an analytical solution to the (Norton) creep equation for rotational and spherical symmetrical cavities in rock salt [1]. This model, together with a compaction model for crushed rock salt [13] developed at UU, was implemented in the PA-code REPOS_ECN.

Recently a small benchmark was performed in the PAMINA project [2], where this model was tested against a FLAC3D (DBEtec) and the PA-code LOPOS (GRS). The results where very good, but that was to be expected because the models used essentially the same creep equation, and the same numerical values for the (Norton) coefficient and the exponent.
These values are based on extensive experimental observations (up to 7 years of data), but as Fig. 1 illustrates, 7 years are still short in comparison with the time convergence processes that are expected to take place in a repository.

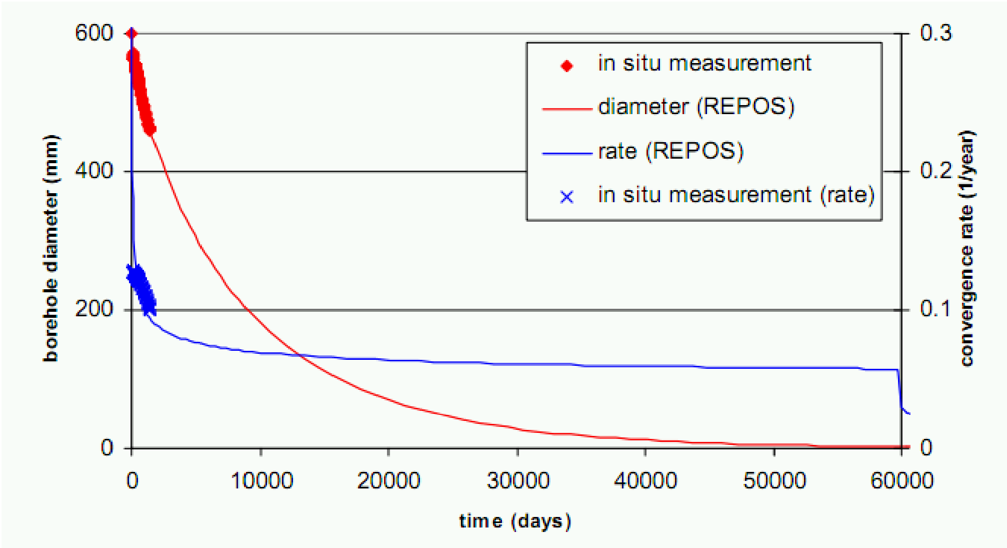

Fig. 1 Experimental observations [2] and extrapolatio needed in a PA

Given the potential impact of the waste on our environment, such extrapolations require fundamental understanding of the operative process, tested through experimental work. Moreover, the knowledge and science on rock salt is still growing and ongoing, also outside the world of waste disposal. This means that even existing and accepted safety cases still have to be confronted with the developing knowledge, to check on a regular basis the scientific basis of the safety case.

Spontaneous self healing of the EDZ

NRG subcontracted UU to establish an EDZ healing model for application in the Theresa project [3]. One part of this model was spontaneous crack healing, the other part was healing by mechanical crack healing in a confining stress field. Spontaneous healing is caused by transport of salt ions through a water layer hygroscopically attached to the salt. Due to suface tension, the salt ion concentration in water in larger cracks is higher than the salt concentration in small cracks. This leads to diffusion driven transport of ions from large cracks to smaller cracks, resulting in dissolution of solid salt in large cracks and deposition of salt in small cracks. Through this process, the number of connection between cracks in the percolating crack network in the EDZ reduces, and more and more cracks become diconnected from the percolating network, reducing the permeability and eventually causing the networ to break down, i.e. the EDZ becomes imppermeable.

This proces of salt displacement was observed in a dedicated experimental setup [4]. The spontaneous reduction of permeability was observed by measuring the electrical resistance of water saturated salt samples [5].

The Theresa project showed that in normal repository conditions, healing through mechanical deformation is faster than spontaneous healing. Still, considering safety and robustness, it is good that there is a second process that also leads to healing of the EDZ.

Effect of confining pressure on plastic flow of salt

One key question regarding the behaviour of dense rock salt is what microphysical mechanism controls plastic flow by dislocation motion at temperatures in the range 100-200°C. Some researchers suggest that dislocation creep at these conditions is controlled by climb [6-7], while others conclude control by cross slip or glide [8-11]. One possible way to address this problem is to establish the pressure dependence of dislocation flow of rocksalt, which differs depending on the mechanism controlling creep: glide, cross slip or climb. Recently, UU has conducted new tri-axial experiments to investigate the effect of pressure on the strength of salt [12]. It was found that the strength of salt increases with an increase in confining pressures (Fig. 2). Dislocation climb provides the best explanation for the observed behaviour.

Conclusion

This paper gives two examples of our continuously increasing understanding of the fundamental microphysical process influencing the behaviour of rock salt. The results tend to confirm the outcome of previous empirical work, and as such help to improve the safety cases for disposal in rock salt.

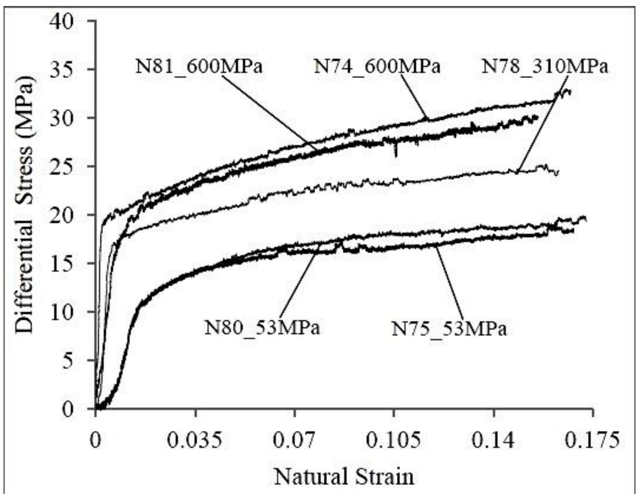

Fig. 2 Differential stress vs. natural strain for samples of rock salt deformed at different confining pressure at otherwise similar conditions (constant strain rate 10^{-6} s^{-1} and constant temperature 125°C)

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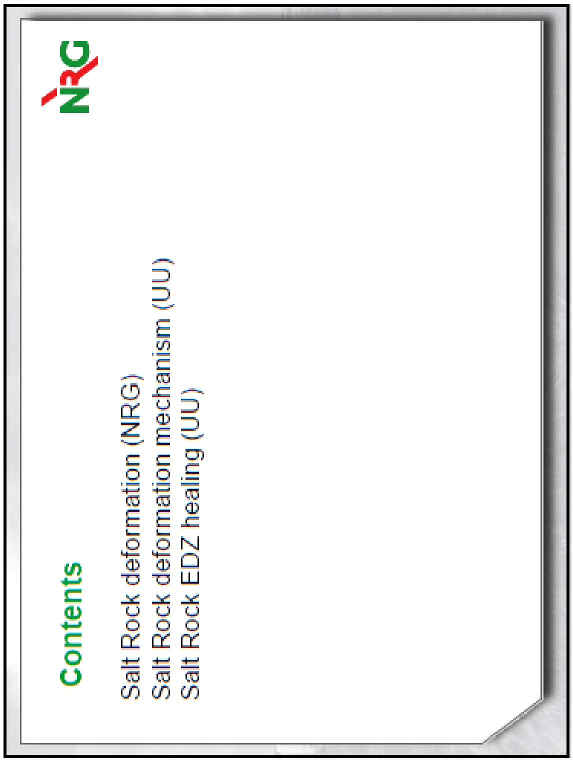
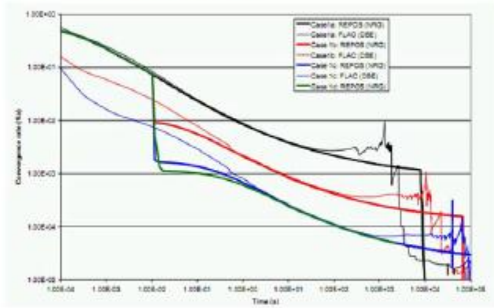
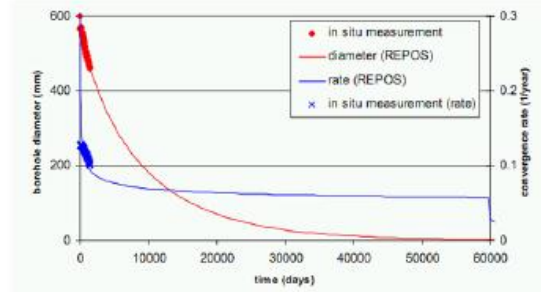


PAMINA Benchmark



Free convergence of a brine filled cavity (brine pressure 0 Mpa, 5.9 Mpa, 9.4 Mpa, variable brine pressure).
Results of DBEtec/GRS/NRG benchmark in PAMINA are very satisfactorily.

Experimental Confirmation



Experimental convergence data up to a few years.
Extrapolation to > 1000 years requires excellent process understanding and confirmation of this understanding.

Examples of efforts of UU to increase and confirm process understanding

1. Microphysical Modelling of EDZ Healing
Maartje Houben, Chris Spiers (Utrecht University)
Jacques Grupa (NRG)

2. Effect of confining pressure on plastic flow of salt at temperature 125 C: Evidence for the mechanism controlling dislocation creep
Nawaz MUHAMMAD, Christopher J. SPIERS, Colin J. PEACH, Johannes H.P. De BRESSER
HPT Laboratory, Department of Earth Sciences, Faculty of Geosciences, Utrecht University, the Netherlands

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Microphysical Modelling of EDZ Healing

Maartje Houben, Chris Spiers (Utrecht University)
Jacques Grupa (NRG)

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Microphysical Modelling of EDZ Healing

- EDZ permeability is caused by a percolating network of micro cracks
- Closure of micro cracks occurs in a 'compacting stress field' and spontaneously
- The associated change in porosity is small or even zero
- The change in permeability is large (e.g. from $>10^{-16}$ m^2 to $<10^{-21}$ m^2)

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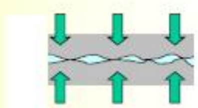
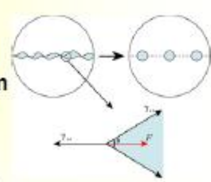
Mechanisms

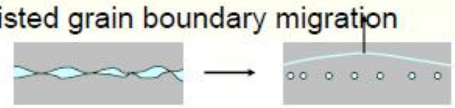
•Mechanical closure due to:
- **elastic deformation**
- **plastic flow**



•Surface energy driven crack healing
(needs adsorbed water or free brine film: >20 ppm



•Fluid assisted grain boundary migration
(ne



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Closure of Micro Cracks

- Mechanical closure model
  - Assumption: Salt in the EDZ is work hardened by plastic flow in the excavation phase
  - Principle: Cracks close when normal stresses between them exceed yield stress (max previous flow stress)
- Test/calibrate mechanical closure model vs. BGR/GRS data on mechanically induced porosity-permeability reduction in damaged salt (data exchange needed)

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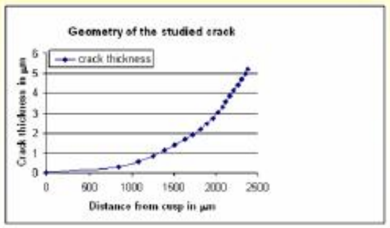
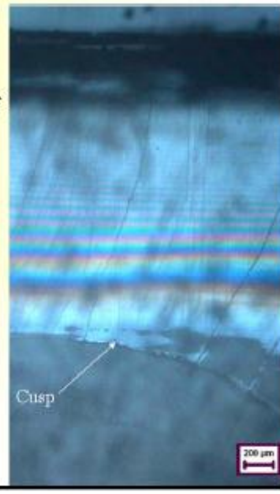
Closure of Micro Cracks

- Crack healing by mass transport
  - Direct measurement of geometry of an 'artificial' crack using Newton fringes





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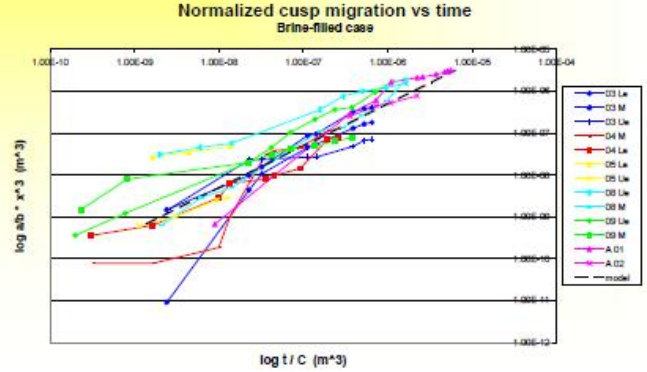
Models for single crack healing by mass transport: Validated & calibrated against experiments on brine-filled cracks.........



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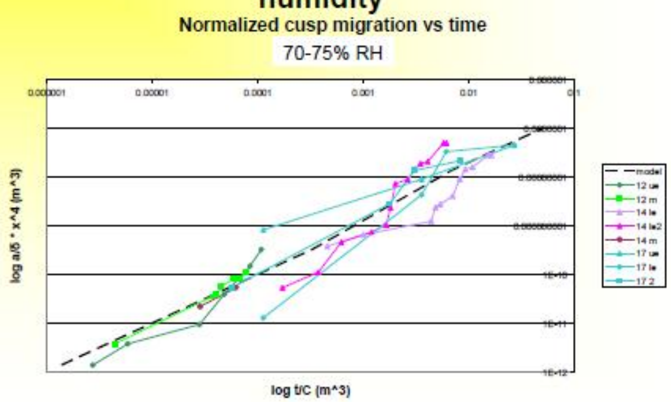
........and on cracks filled with air at 40-75% relative humidity



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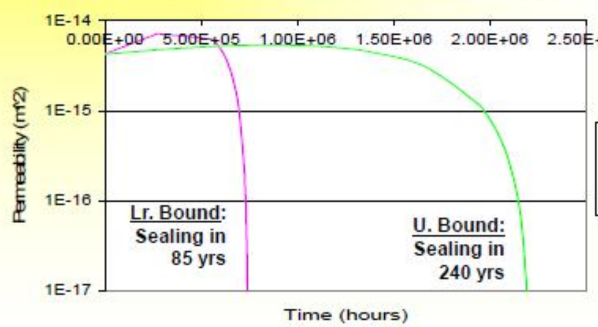
Permeability evolution due to crack healing by mass transport

Upper & lower bound curves. Crack porosity 0.33%, Grain size 1 cm, T= 40 °C .



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Conclusions

- Mechanical closure model based is characterised by large uncertainties; the mechanism is very important in the active convergence stage of openings
- Healing of brine- and water-vapour-filled cracks by diffusive mass transort can be accurately quantified in lab experiments, and agrees well with theoretical models
- This process is very fast when brine is present but can also be very slow at low humidities.

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Work on salt at UU in collaboration with NRG

- Crack healing rates from electrical impedance measurement
- Mechanism controlling dislocation creep in salt from determination of P-dependence of flow strength/rate (aim is to improve extrapolations to long term)
- Measurement of pressure solution rates in natural, coarse grained salt using new stress-relaxation technology
- Effects of microcrack damage and intrusion of brine on mechanical behaviour: competition between crack growth and healing

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Effect of confining pressure on plastic flow of salt at temperature 125°C:

Evidence for the mechanism controlling dislocation creep:

N.MUHAMMAD, C. J. SPIERS, J.H.P. De BRESSER
(HPT) Laboratory, Utrecht University, NL

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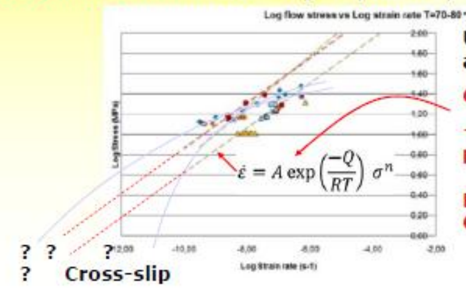
Aim – Long term dislocation creep: Progress to date

Long disputed – what controls dislocation creep in salt at 20-200°C?

- Dislocation Climb or Cross-slip?? (others??)



Usually assumed:
Climb control
+
power law
But some claim Cross-Slip

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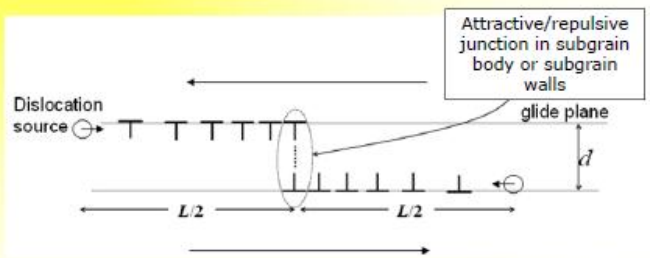
(a) Climb-Controlled Dislocation Creep



- Attractive/repulsive junctions (dipoles) form obstacles to edge dislocation glide
- Creep rate controlling step = annihilation of dipole by climb
- Activation volume for climb > 0

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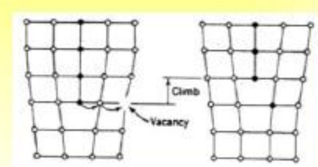
Theory of Climb Controlled dislocation creep (edge dislocations)



$$\dot{\varepsilon} = \frac{A\mu}{T}\left(\frac{\sigma}{\mu}\right)^n \exp\left[-\frac{\Delta U_{sd} + P\Delta V}{kT}\right]$$

Creep rate decreases with increasing confining pressure P !!!!!

ΔV>0

Material becomes stronger at higher confining pressure !!

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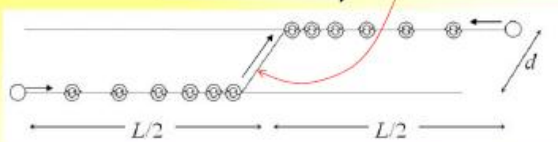
(b) Cross-slip Controlled Dislocation Creep



- Attractive/repulsive junctions or dipoles form barriers to screw dislocations
- Annihilation occurs by cross-slip of screw dislocations
- Dislocations jump into cross-slip plane: controls creep rate
- Activation volume for cross-slip < 0 (in NaCl)

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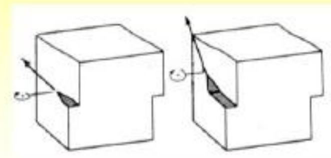
Theory of Cross-Slip Controlled dislocation creep (screw dislocations)

$$\dot{\varepsilon} = K'\left(\frac{\sigma}{\mu}\right)^2 \exp\left[-\frac{\Delta U_{cs}(\sigma, P)}{kT}\right]$$



Creep rate typically increases with increasing confining pressure P !!!!!

ΔV<0:

Material becomes weaker at higher confining pressure !!

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Experiments

- *Aim: To determine the Pressure dependence of flow strength at constant Strain Rate:*
  - Cross-Slip: weaker at higher pressure!!
  - Climb: stronger at higher pressure!!

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Mechanical testing

- High Pressure Triaxial Testing Machine (0.8GPa)

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Present Experimental Conditions!

- Dry synthetic salt, grain size 200-400µm
- Hydrostatic/Confining Pressure (Argon gas)
- 50MPa to 600MPa
- Temperature 125ºC
- Strain Rate 10^{-6} s^{-1}

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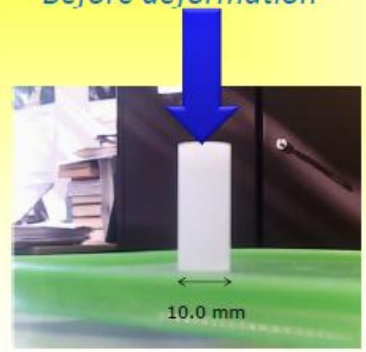
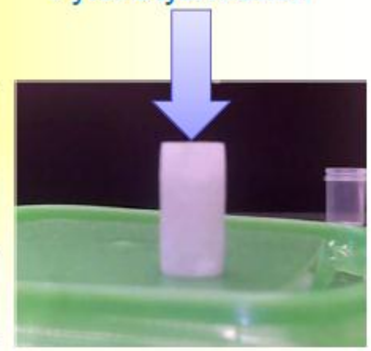
Salt Sample Before deformation



Salt Sample After deformation



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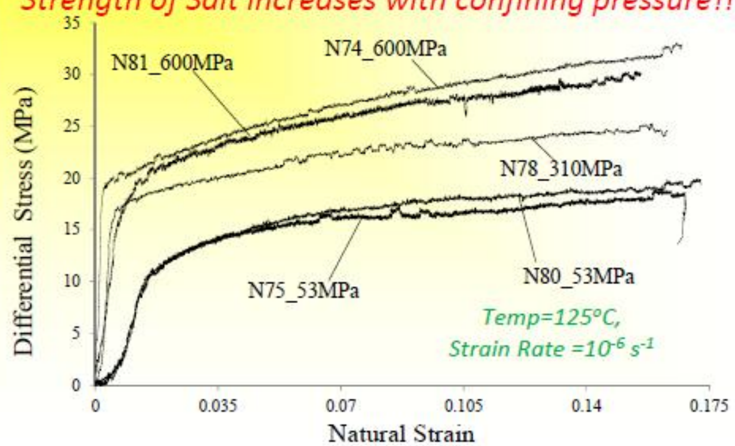
Stress vs. Natural Strain

Strength of Salt increases with confining pressure!!



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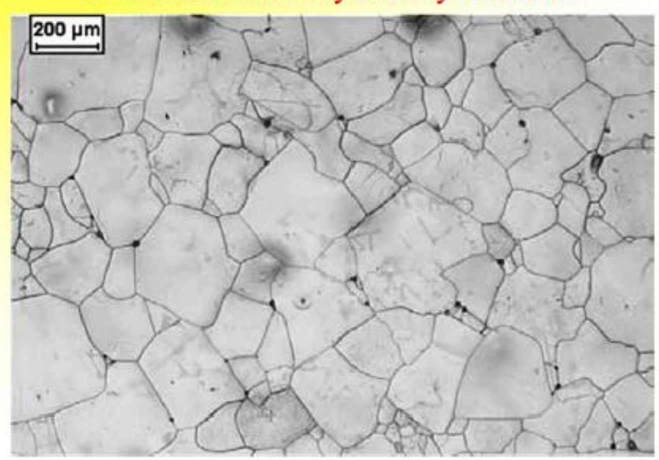
Microstructure Before Deformation



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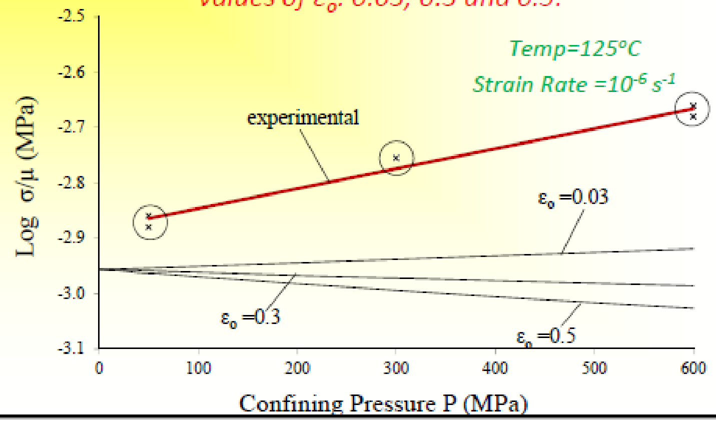
Comparison of experimental data with cross slip dissociation model controlled regime with different values of ε_o: 0.03, 0.3 and 0.5.



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Conclusions/Discussion

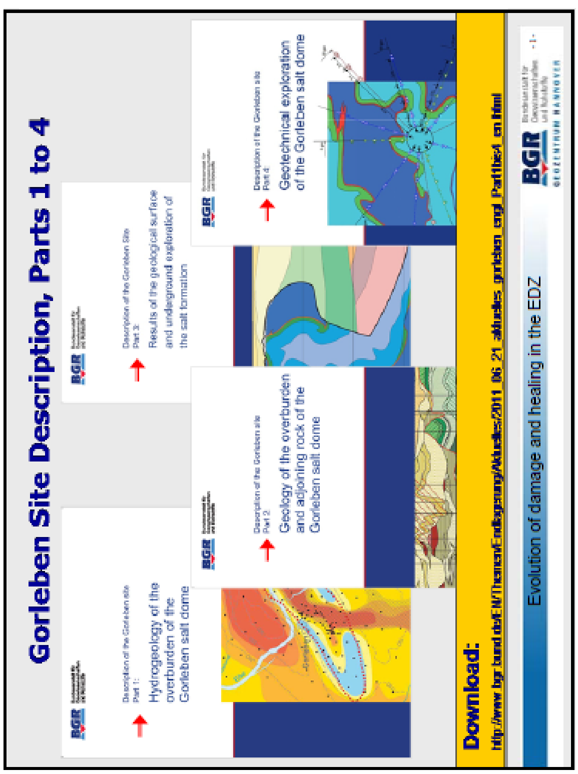
- Effect of P is real!
  (higher P-------> higher flow strength)
- Estimate of $\Delta V \approx 2.5 \times 10^{-29}$ m^3/molecule
  ~half molecular volume
- Consistent with Climb Controlled Creep Model
- Eliminates Cross-Slip control
- Gives physical basis for $n \approx 5$ in steady state creep law
- Experiments underway to explore (and extrapolate to) wider range of Temperatures and Strain rates

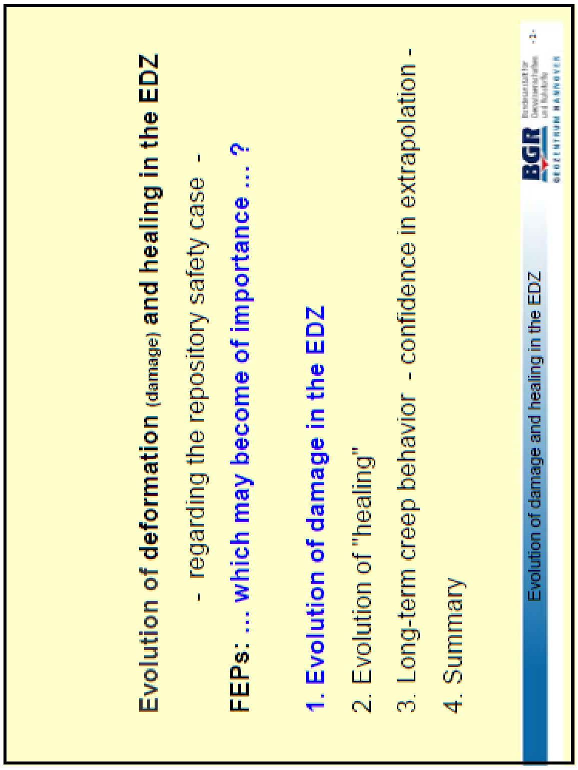
Evolution of deformation and healing in the EDZ

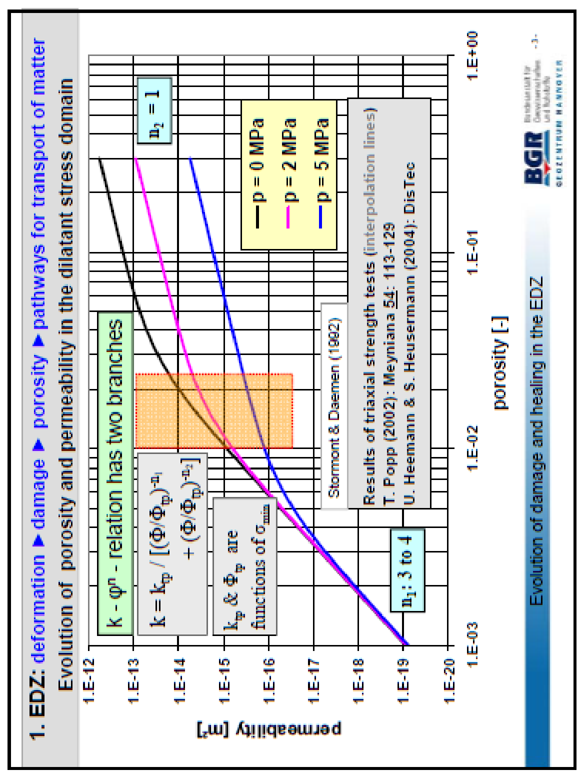
D. Stührenberg & O. Schulze - BGR, Hannover, Germany

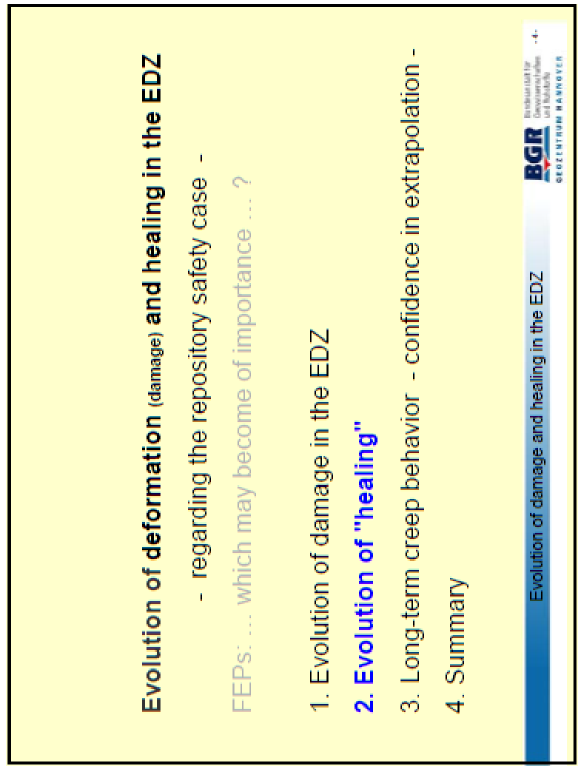
Abstract

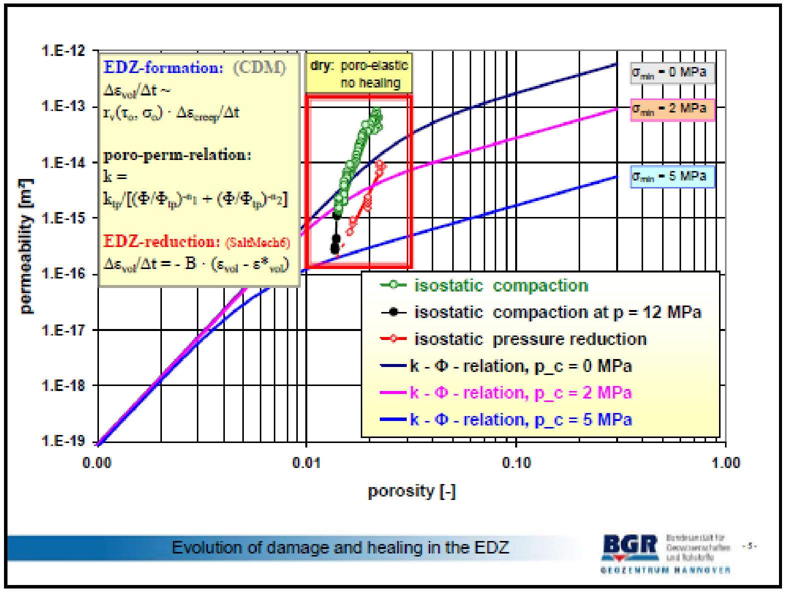
During operation of underground openings in a rock salt formation, an Excavation Damaged Zone (EDZ) will form. However, a repository for radio-active waste will be backfilled before closure to maintain the isolation capacity of the geological barriers against biosphere.
In present planning, crushed salt is the preferred backfill material. Driven by convergence, the crushed salt will compact and the state of stresses in the EDZ will return from the dilatant to the non-dilatant stress regime. Thus, as a consequence of backfilling also the rock salt in the EDZ will re-compact and re-consolidate sooner.
Recent results from laboratory work on the evolution of porosity and permeability of crushed rock salt as well as of pre-damaged rock salt are presented. Special emphasis was put on the measurement of permeability and its evolution at small quantities of porosity. The dependence of their evolution on the different pre-conditioning in dry or humid air is especially worked out. Although the porosity was reduced to the limits of resolution (i.e. $< \pm 0.5$ %) in any case, the permeability remains rather high during compaction of dry material (i.e. $k \geq$ 1.0E-16 m²), whereas the permeability decreases to a rather low value after a pre-conditioning of the crushed salt and of the pre-damaged rock salt in humid air (i.e. $k \leq$ 1.0E-21 m²).
It has to be stressed that these substantial differences in re-consolidation (solely poro-elastic compaction vs. true healing) are already caused by the small variation of the humidity in the environmental air during pre-conditioning and that these differences persist after the re-drying of the specimens.
In addition to these results, which are planed to be presented at the SaltMech 7 conference, Paris 2012, we discuss the confidence in the extrapolation of well known constitutive creep laws into the regime of very low and still decreasing effective stress and increasing minimum stress - since the healing is promoted by convergence (i.e. creep).

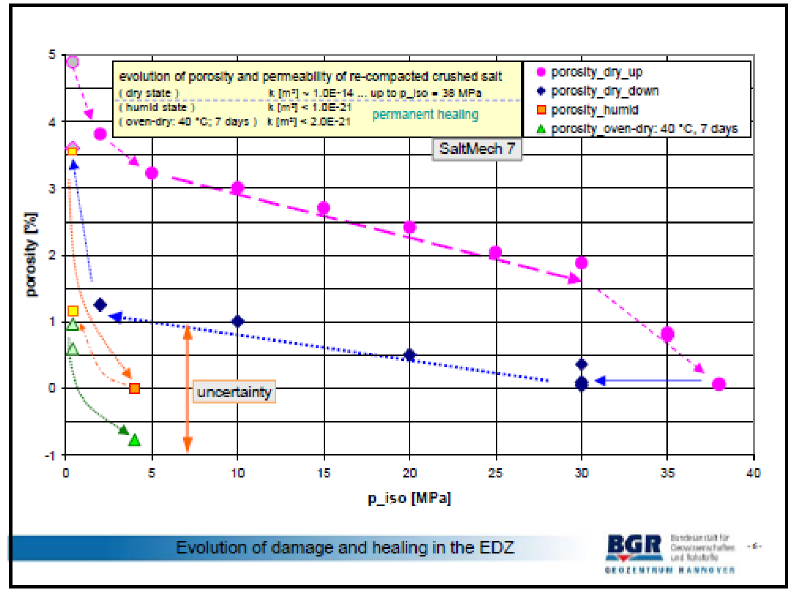

Gorleben Site Description, Parts 1 to 4
Description of the Gorleben site Part 1: Hydrogeology of the overburden of the Gorleben salt dome
Description of the Gorleben site Part 2: Geology of the overburden and adjoining rock of the Gorleben salt dome
Description of the Gorleben site Part 3: Results of the geological surface and underground exploration of the salt formation
Description of the Gorleben site Part 4: Geotechnical exploration of the Gorleben salt dome
Download:
Evolution of damage and healing in the EDZ
BGR
-1-

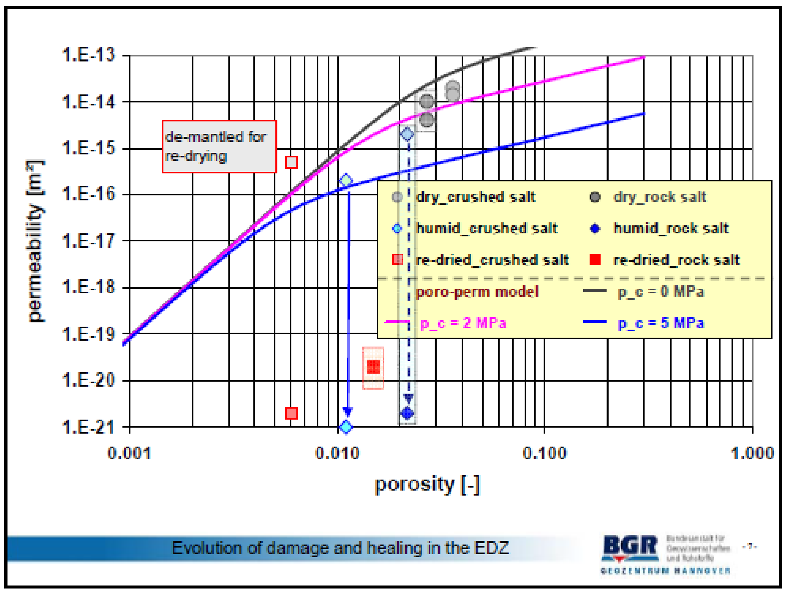

Evolution of deformation (damage) and healing in the EDZ
- regarding the repository safety case -
FEPs: ... which may become of importance ... ?
1. Evolution of damage in the EDZ
2. Evolution of "healing"
3. Long-term creep behavior - confidence in extrapolation -
4. Summary
Evolution of damage and healing in the EDZ
BGR
-2-


1. EDZ: deformation ▸ damage ▸ porosity ▸ pathways for transport of matter
Evolution of porosity and permeability in the dilatant stress domain
k - φ^n - relation has two branches
k = k_tp / [(Φ/Φ_tp)^-n1 + (Φ/Φ_tp)^-n2]
k_tp & Φ_tp are functions of σ_min
n1: 3 to 4
n2 = 1
p = 0 MPa
p = 2 MPa
p = 5 MPa
Stormont & Daemen (1992)
Results of triaxial strength tests (interpolation lines)
T. Popp (2002): Meyniana 54: 113-129
U. Heemann & S. Heusermann (2004): DisTec
permeability [m²]
porosity [-]
1.E-12
1.E-13
1.E-14
1.E-15
1.E-16
1.E-17
1.E-18
1.E-19
1.E-20
1.E-03
1.E-02
1.E-01
1.E+00
Evolution of damage and healing in the EDZ
BGR
-3-


Evolution of deformation (damage) and healing in the EDZ
- regarding the repository safety case -
FEPs: ... which may become of importance ... ?
1. Evolution of damage in the EDZ
2. Evolution of "healing"
3. Long-term creep behavior - confidence in extrapolation -
4. Summary
Evolution of damage and healing in the EDZ
BGR
-4-







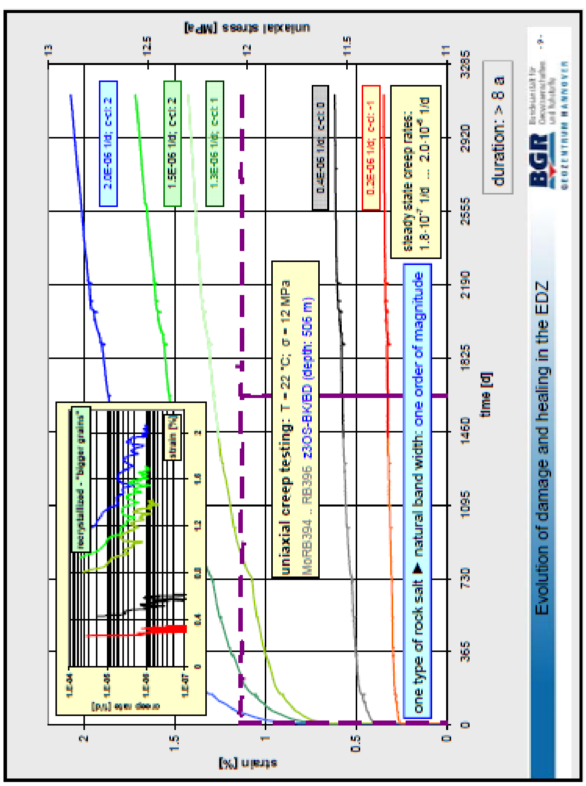
Evolution of deformation (damage) **and healing in the EDZ**

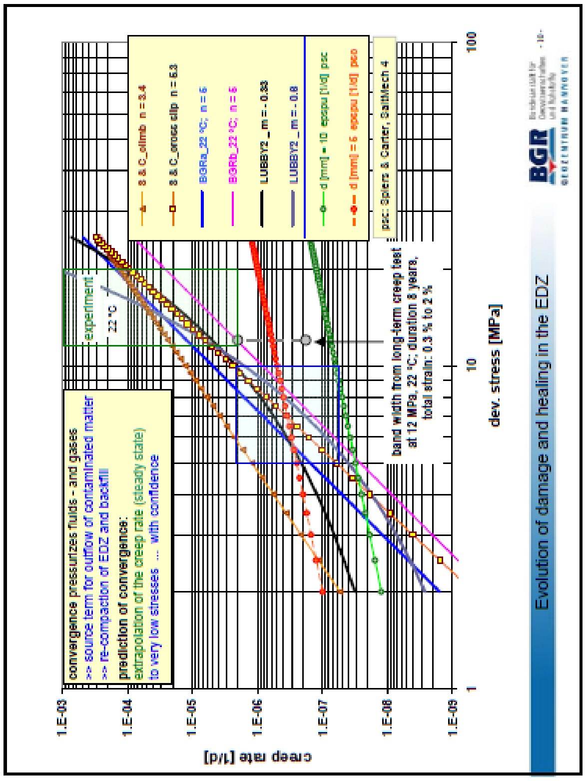
- regarding the repository safety case -

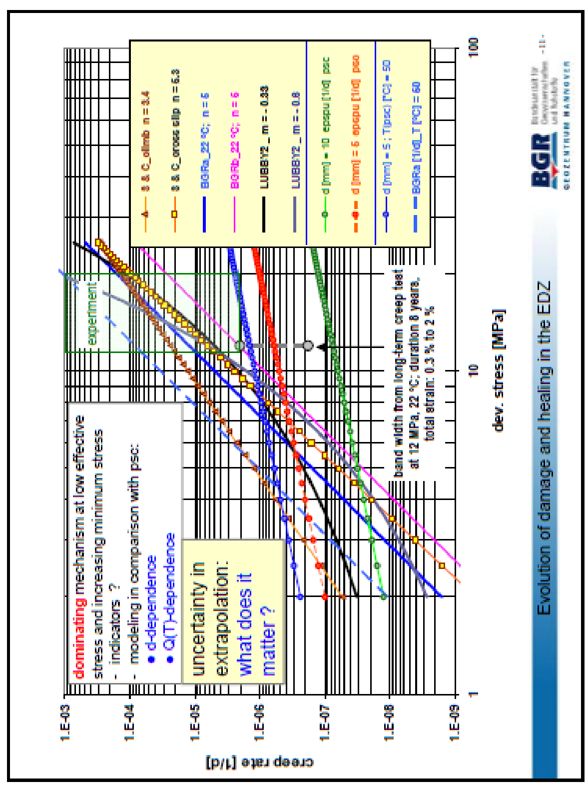
1. Evolution of damage in the EDZ
2. Evolution of "healing"
   - requires (re-)compaction of EDZ and backfill
3. **Long-term behavior - confidence in extrapolation ...**
   ... of creep laws for the prediction of convergence at low and decreasing effective stress
   ... and increasing minimum stress
4. Summary

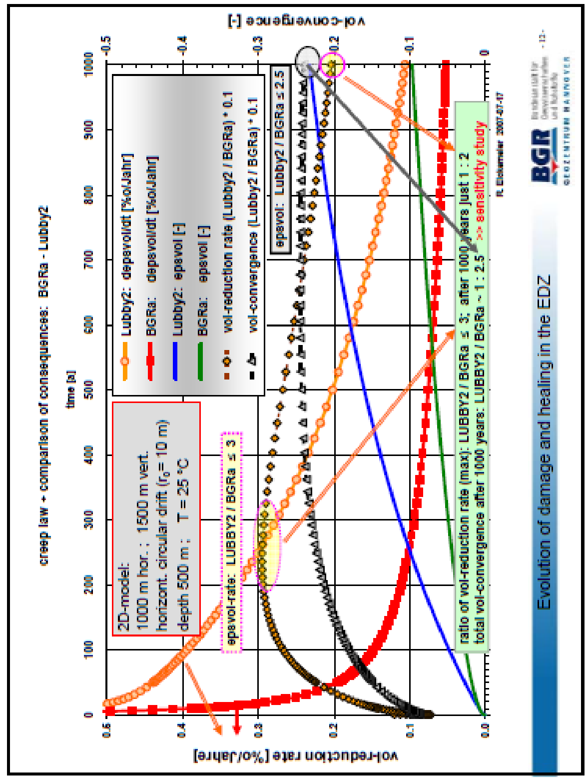
Evolution of damage and healing in the EDZ

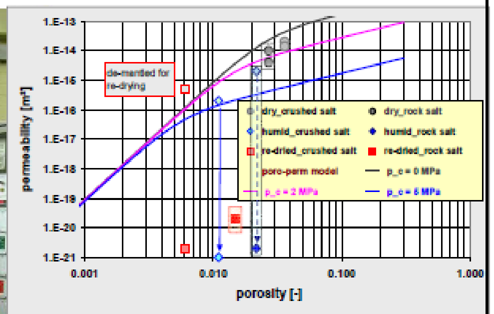
BGR -8-


uniaxial creep testing: T = 22 °C; σ = 12 MPa
MoRB394 ... RB396 z3OS-BK/BD (depth: 505 m)
one type of rock salt ▶ natural band width: one order of magnitude
duration: > 8 a
time [d]
strain [%]
uniaxial stress [MPa]
Evolution of damage and healing in the EDZ
BGR


convergence pressurizes fluids - and gases
>> source term for outflow of contaminated matter
>> re-compaction of EDZ and backfill
prediction of convergence:
extrapolation of the creep rate (steady state) to very low stresses ... with confidence
band width from long-term creep test at 12 MPa, 22 °C; duration 8 years, total strain: 0.3 % to 2 %
experiment
dev. stress [MPa]
creep rate [1/d]
Evolution of damage and healing in the EDZ
BGR


dominating mechanism at low effective stress and increasing minimum stress
- indicators ?
- modeling in comparison with psc:
• d-dependence
• Q(T)-dependence
uncertainty in extrapolation: what does it matter ?
band width from long-term creep test at 12 MPa, 22 °C; duration 8 years, total strain: 0.3 % to 2 %
experiment
dev. stress [MPa]
creep rate [1/d]
Evolution of damage and healing in the EDZ
BGR


creep law + comparison of consequences: BGRa - Lubby2
2D-model:
1000 m hor. ; 1500 m vert.
horizont. circular drift
depth 500 m ; T = 25 °C
time [a]
vol-reduction rate [%o/Jahre]
vol-convergence [-]
>> sensitivity study
Evolution of damage and healing in the EDZ
BGR

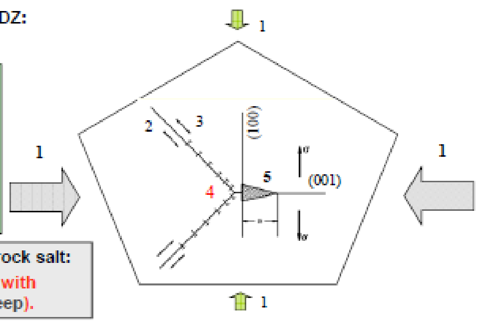


Thank you
for your attention

work in progress - very draft

1. Evolution of damage in the EDZ:
no deformation, no damage

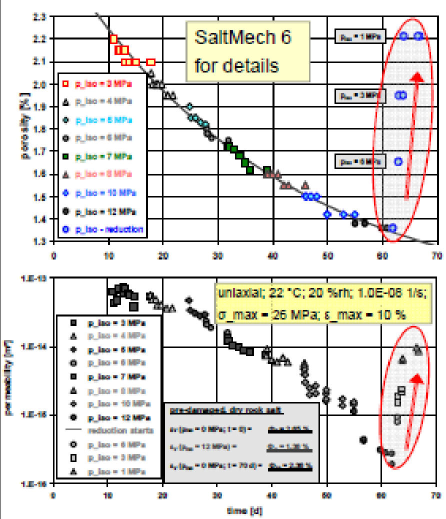
micro-mechanical processes
1: stresses activate dislocations
2: gliding plane
3: gliding direction
4: pile-up of dislocations
5: micro-crack formation



The CDM dilatancy concept for rock salt:
Evolution of damage is coupled with deformation by dislocations (creep).

non - dilatant deformation		dilatancy, damage and failure			
transient and steady state creep	compaction and healing	humidity induced creep processes	softening - damage induced deformation	failure	post-failure behaviour

$(\Delta\varepsilon/\Delta t)_{tot} = (\Delta\varepsilon/\Delta t)_{creep}$ • f(Φ) • F_h • $\delta(d_{damage\,...\,max}, \sigma_{min})$ • P_F



deformation produces damage
▶ porosity and permeability

EDZ-formation: (CDM)

$\Delta\varepsilon_{vol}/\Delta t \sim r_v(\tau_o, \sigma_o) \cdot \Delta\varepsilon_{creep}/\Delta t$

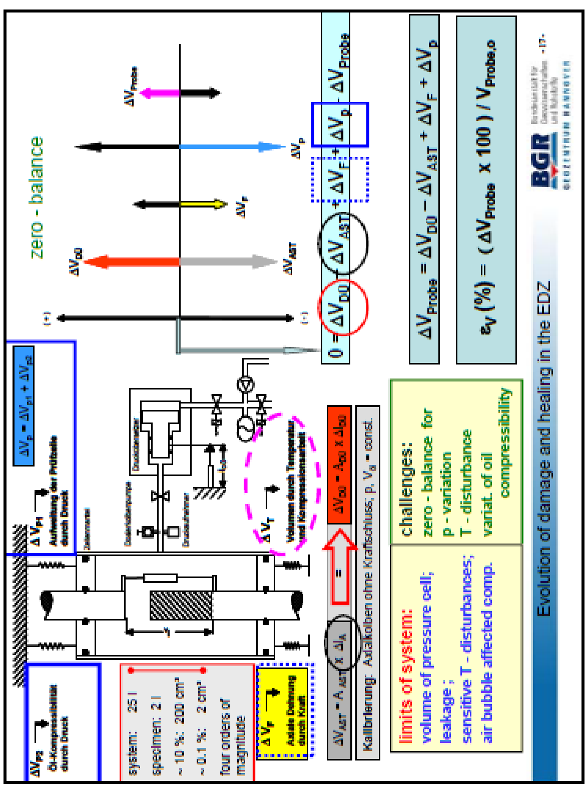
re-consolidation
by re-compaction

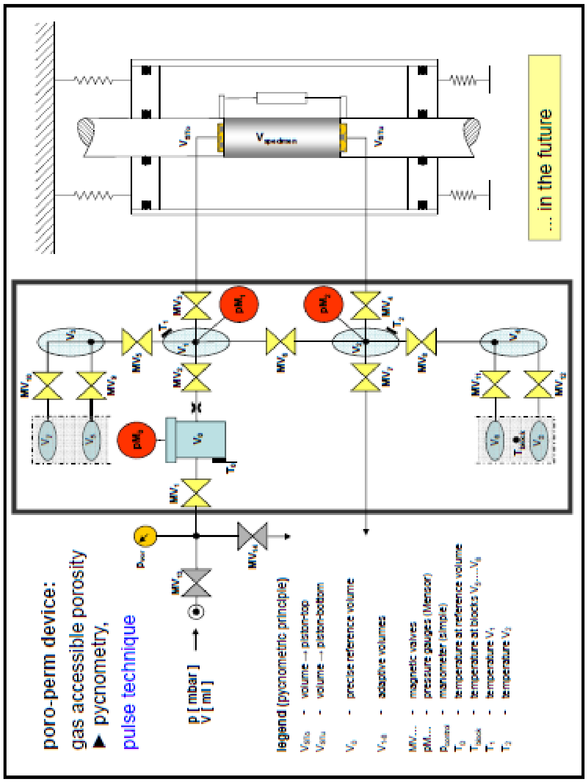
EDZ-reduction:

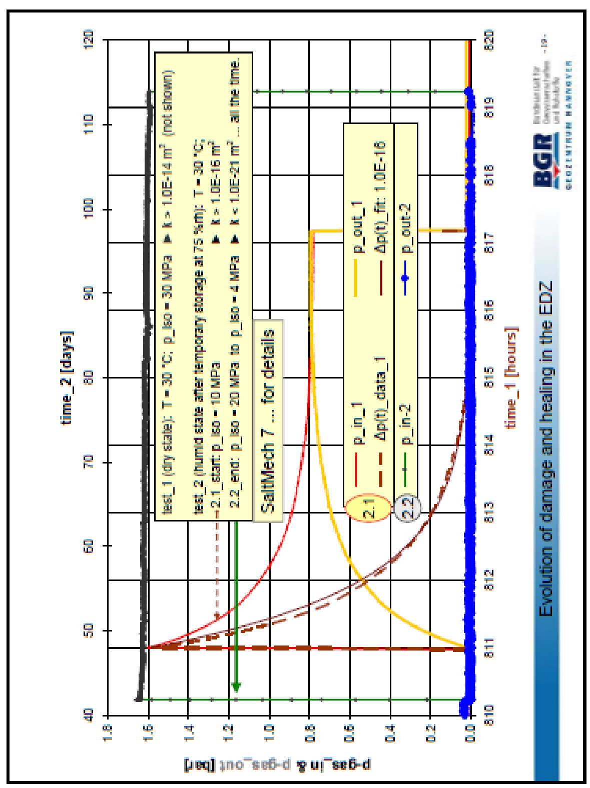
$\Delta\varepsilon_{vol}/\Delta t = - B \cdot (\varepsilon_{vol} - \varepsilon^*_{vol})$

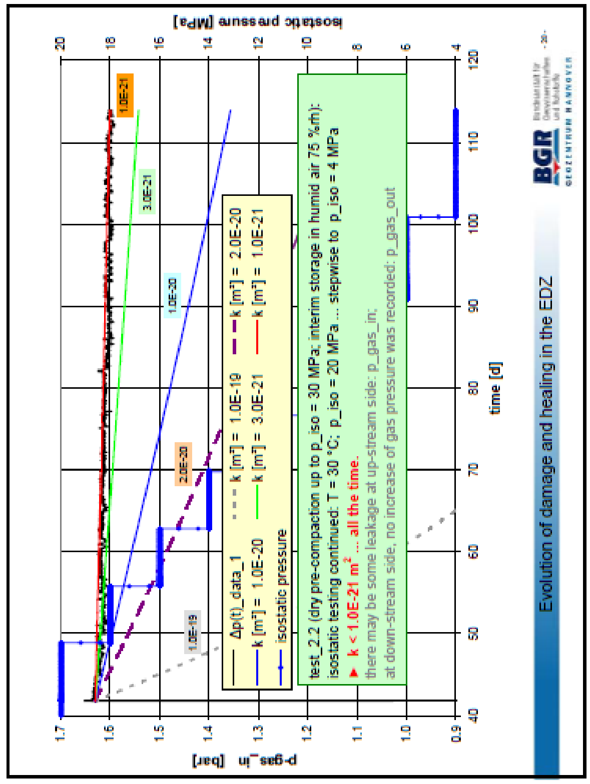
permeability-porosity-relation:

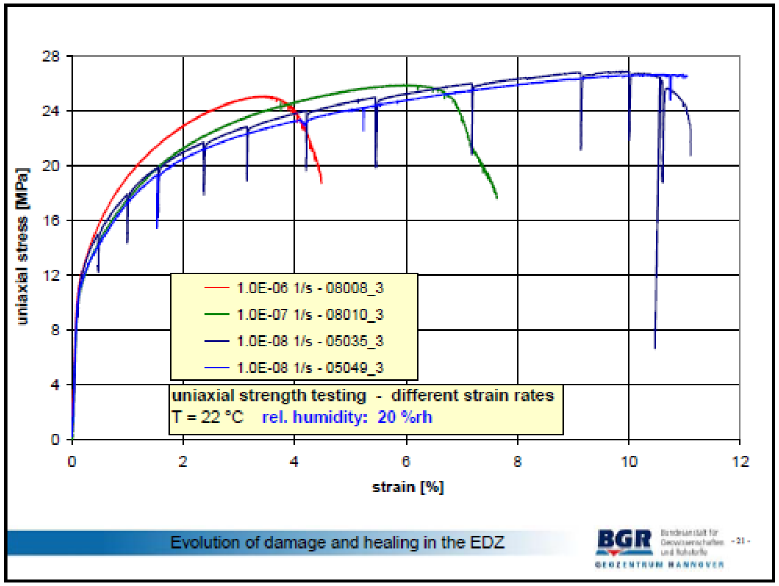
$k = k_{tp} / [(\Phi/\Phi_{tp})^{-n_1} + (\Phi/\Phi_{tp})^{-n_2}]$

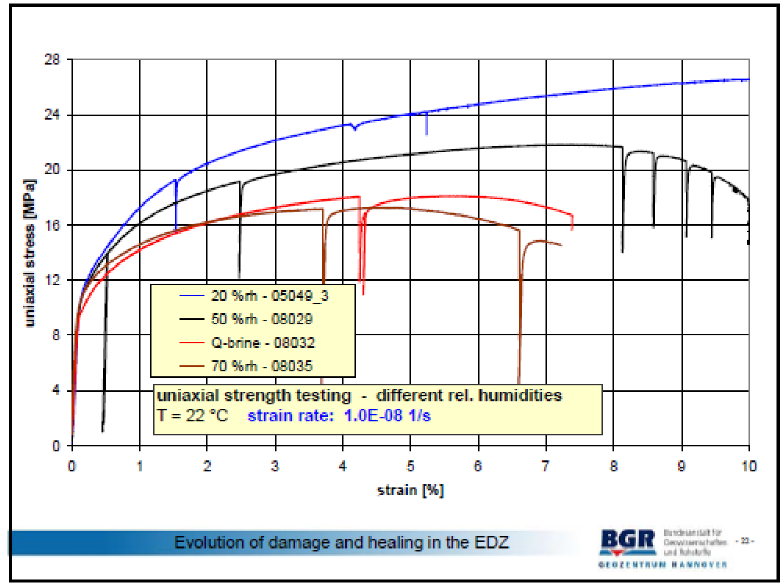

zero - balance
limits of system:
volume of pressure cell;
leakage ;
sensitive T - disturbances;
air bubble affected comp.
challenges:
zero - balance for
p - variation
T - disturbance
variat. of oil
compressibility
Evolution of damage and healing in the EDZ
-17-

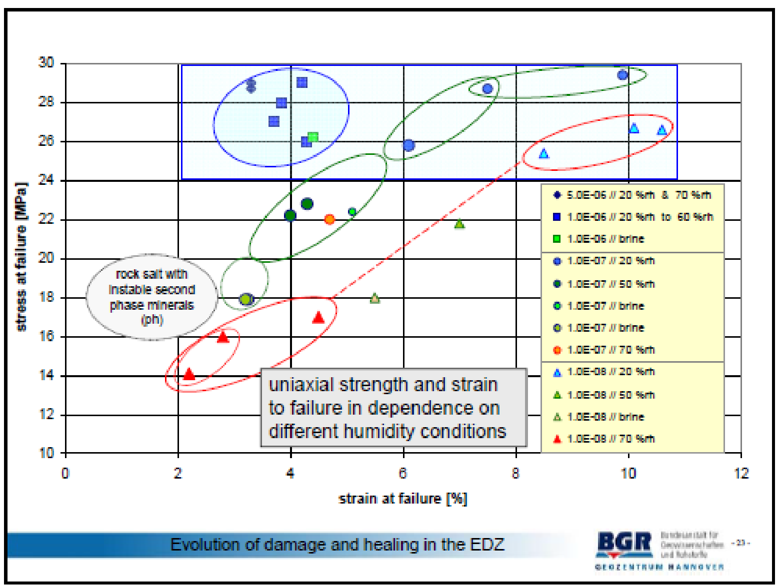

poro-perm device:
gas accessible porosity
▶ pycnometry,
pulse technique
... in the future

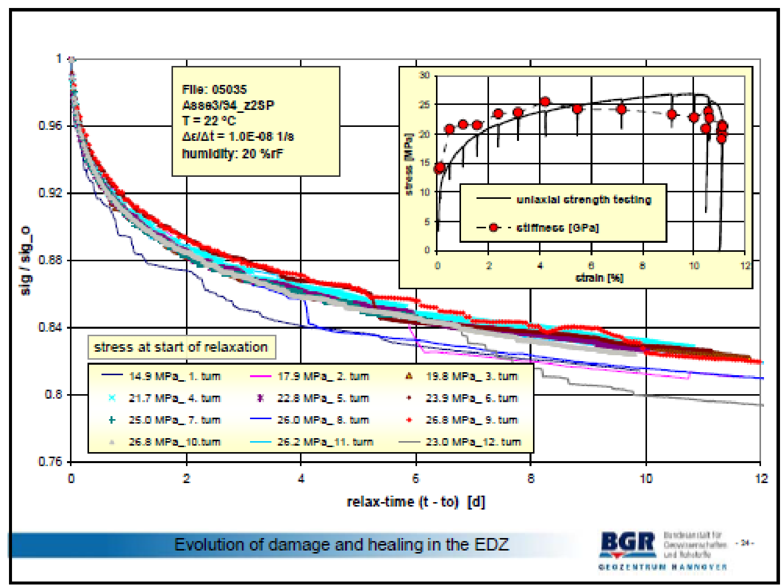

time_2 [days]
time_1 [hours]
p-gas_in & p-gas_out [bar]
SaltMech 7 ... for details
Evolution of damage and healing in the EDZ
-19-

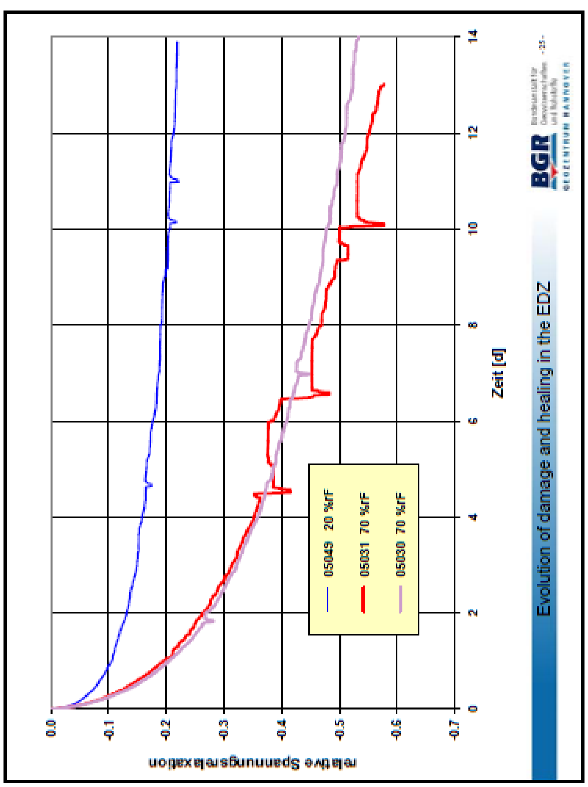

time [d]
p-gas_in [bar]
isostatic pressure [MPa]
Evolution of damage and healing in the EDZ
-20-

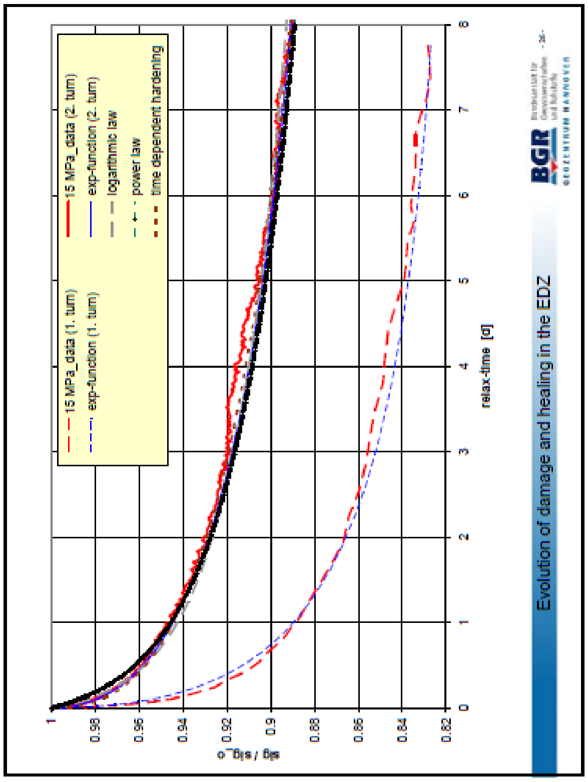

uniaxial stress [MPa]
strain [%]
1.0E-06 1/s - 08008_3
1.0E-07 1/s - 08010_3
1.0E-08 1/s - 05035_3
1.0E-08 1/s - 05049_3
uniaxial strength testing - different strain rates
T = 22 °C rel. humidity: 20 %rh
Evolution of damage and healing in the EDZ
BGR
GEOZENTRUM HANNOVER
- 21 -

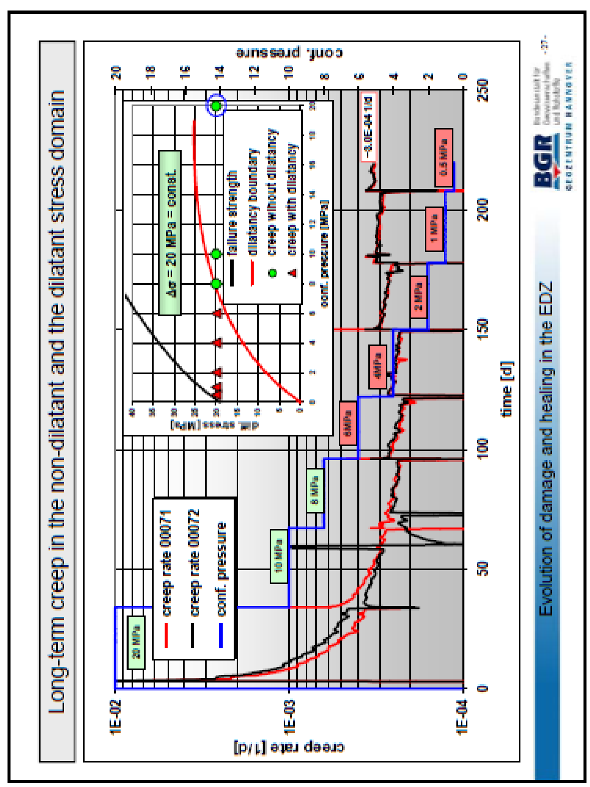

uniaxial stress [MPa]
strain [%]
20 %rh - 05049_3
50 %rh - 08029
Q-brine - 08032
70 %rh - 08035
uniaxial strength testing - different rel. humidities
T = 22 °C strain rate: 1.0E-08 1/s
Evolution of damage and healing in the EDZ
BGR
GEOZENTRUM HANNOVER
- 22 -

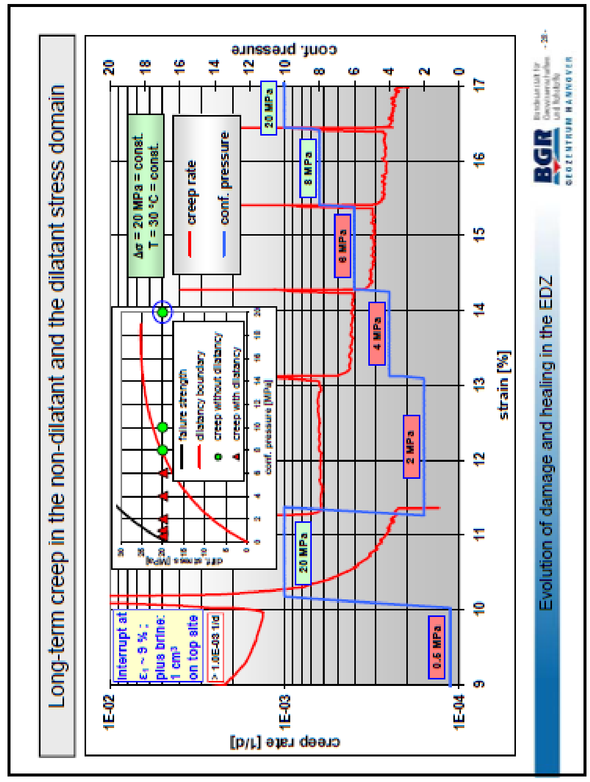

stress at failure [MPa]
strain at failure [%]
rock salt with instable second phase minerals (ph)
5.0E-06 // 20 %rh & 70 %rh
1.0E-06 // 20 %rh to 60 %rh
1.0E-06 // brine
1.0E-07 // 20 %rh
1.0E-07 // 50 %rh
1.0E-07 // brine
1.0E-07 // brine
1.0E-07 // 70 %rh
1.0E-08 // 20 %rh
1.0E-08 // 50 %rh
1.0E-08 // brine
1.0E-08 // 70 %rh
uniaxial strength and strain to failure in dependence on different humidity conditions
Evolution of damage and healing in the EDZ
BGR
GEOZENTRUM HANNOVER
- 23 -

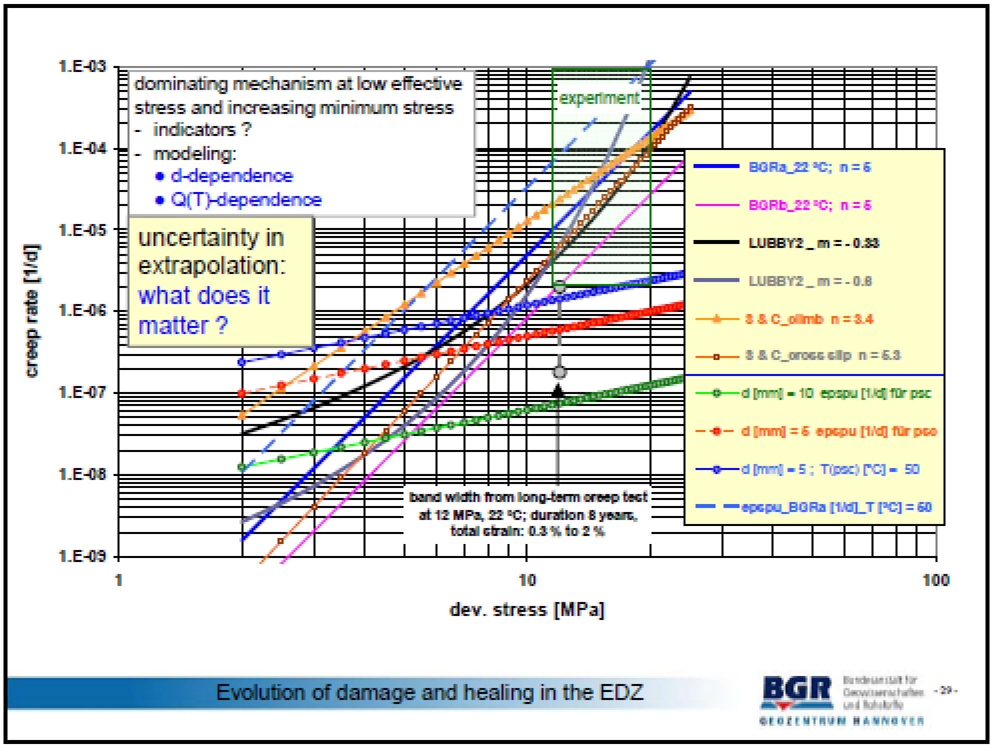

sig / sig_o
relax-time (t - to) [d]
File: 05035
Asse3/94_z2SP
T = 22 °C
Δε/Δt = 1.0E-08 1/s
humidity: 20 %rF
stress [MPa]
strain [%]
uniaxial strength testing
stiffness [GPa]
stress at start of relaxation
14.9 MPa_ 1. turn
17.9 MPa_ 2. turn
19.8 MPa_ 3. turn
21.7 MPa_ 4. turn
22.8 MPa_ 5. turn
23.9 MPa_ 6. turn
25.0 MPa_ 7. turn
26.0 MPa_ 8. turn
26.8 MPa_ 9. turn
26.8 MPa_10.turn
26.2 MPa_ 11. turn
23.0 MPa_12. turn
Evolution of damage and healing in the EDZ
BGR
GEOZENTRUM HANNOVER
- 24 -


relative Spannungsrelaxation
Zeit [d]
05049 20 %rF
05031 70 %rF
05030 70 %rF
Evolution of damage and healing in the EDZ
BGR
- 25 -


sig / sig_o
relax-time [d]
15 MPa_data (1. turn)
exp-function (1. turn)
15 MPa_data (2. turn)
exp-function (2. turn)
logarithmic law
power law
time dependent hardening
Evolution of damage and healing in the EDZ
BGR
- 26 -


Long-term creep in the non-dilatant and the dilatant stress domain
creep rate [1/d]
time [d]
conf. pressure
creep rate 00071
creep rate 00072
conf. pressure
Δσ = 20 MPa = const.
failure strength
dilatancy boundary
creep without dilatancy
creep with dilatancy
conf. pressure [MPa]
diff. stress [MPa]
20 MPa
10 MPa
8 MPa
6MPa
4MPa
2 MPa
1 MPa
0.5 MPa
~3.0E-04 1/d
Evolution of damage and healing in the EDZ
BGR
- 27 -


Long-term creep in the non-dilatant and the dilatant stress domain
creep rate [1/d]
strain [%]
conf. pressure
Interrupt at ε₁ ~ 9 %; plus brine: 1 cm³ on top site
> 1.0E-03 1/d
Δσ = 20 MPa = const.
T = 30 °C = const.
creep rate
conf. pressure
failure strength
dilatancy boundary
creep without dilatancy
creep with dilatancy
0.5 MPa
20 MPa
2 MPa
4 MPa
6 MPa
8 MPa
Evolution of damage and healing in the EDZ
BGR
- 28 -



dominating mechanism at low effective stress and increasing minimum stress
- indicators ?
- modeling:
• d-dependence
• Q(T)-dependence
uncertainty in extrapolation: what does it matter ?
experiment
band width from long-term creep test at 12 MPa, 22 °C; duration 8 years, total strain: 0.3 % to 2 %
BGRa_22 °C; n = 5
BGRb_22 °C; n = 5
LUBBY2 _ m = - 0.33
LUBBY2 _ m = - 0.8
S & C_climb n = 3.4
S & C_cross slip n = 5.3
d [mm] = 10 epspu [1/d] für psc
d [mm] = 5 epspu [1/d] für psc
d [mm] = 5 ; T(psc) [°C] = 50
epspu_BGRa [1/d]_T [°C] = 60
creep rate [1/d]
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1
10
100
dev. stress [MPa]
Evolution of damage and healing in the EDZ
BGR
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- 29 -

Geomechanical Assessment of the Barrier Integrity
2nd US-German Workshop on Salt Repository Research, Design and Operation
November 9 - 10, 2011 Peine, Germany

W. MINKLEY, IfG - Institut für Gebirgsmechanik GmbH, Leipzig

ABSTRACT: Salt formations are favoured for storage of radioactive waste due to their unique isolation capacity. Because their water content is extremely low, only solid state behaviour predominates with grain boundary diffusion. On the basis of natural analogues and the practical experiences of gas storage in salt caverns it can be concluded that undisturbed salt formation are impermeable. A loss of tightness becomes only possible if connectivity is created. Linked flow paths inside the salt barrier may be created under deviatoric stresses (1) if the acting stresses exceed the dilatancy boundary (= dilatancy criterion) or (2) at increased fluid pressure conditions if the acting normal stresses at the grain boundaries are lowered (= minimum stress criterion). The mechanically or hydraulically induced percolation bases on the same microphysical processes, i.e. the percolation of flow paths along discontinuities on a micro- or macroscopic scale (grain boundaries, bedding planes) after exceeding a threshold, which corresponds in both cases due to a removal of intergranular cohesion.

Implementation of this advantage, i.e. inherent tightness, in repository concepts of storage of radioactive waste in salt requires as a prerequisite that the barriers are dimensioned with a sufficient thickness, so that an entire inclusion succeeds. For long term warranty of this state, it has to be ensured that in the geological salt barrier under all acting stresses, i.e. convergence- or thermo-mechanical-induced, neither the dilatancy criterion nor the minimum stress criterion is violated. For the integrity of saliferous barriers, the minimum stress criterion is critical, because the dilatancy criterion is limited to the EDZ.

To demonstrate convergence-induced stress effects on geological barriers, the Asse mine represents a good example. Geomechanical calculations basing on an elasto-visco-plastic model with softening, yielded a significant stress relaxation of the rock salt barrier and damage in the vicinity of the upper level. In that area also micro-seismic activities are concentrated depicting the damage accumulation in the rock mass. On the upper levels where the rock salt thickness is less than 10 m the minimum principal stress is lower than the water pressure in this depth.

The actual rock-mechanical situation in the salt dome Bokeloh represents an example how the minimum stress criterion can be violated even in thick saliferous barriers in case of strong mining-induced processes. The calculated minimum stress on the boundary of the saliferous barrier is significantly lower than the fluid pressures measured with pressure build-up tests at the salt dome flank. Therefore, a passage of fluids became possible. After reduction of fluid pressure at the dome flank, there is a significant decrease of inflow in the mine. This shows that the percolation of saturated brine is stopped when the fluid pressure falls below the minimal principal stress and a sealing process of the salt barrier starts. The observed fluid inflow due to convergence-induced decrease of the minimum principal stress at the flank of a salt dome represents a unique large-scale test, which demonstrates that a singly violation of the minimum stress criterion suffices to suspend the barrier integrity. In other words, the impermeability of a saliferous barrier will be already lost if one of these two criteria (minimum stress criterion or dilatancy criterion) is violated.

As a consequence of the salt tightness, in the long-term after closure of a radioactive waste repository we have to consider the so-called gas frac scenario, if a generated gas pressure may exceed the lithostatic stress in the formation. For an assessment of the impact of increasing

gas pressures on the integrity of rock salt long-term gas injection tests in a German salt mine were performed. During the testing periods several pressure-step tests were performed. Slightly above the primary stress state a gas-percolation was observed. This breakthrough of gas into adjacent control drill holes was reversible. As demonstrated by the experimental tests, the flow of gas into the salt mass occurs on discrete flow paths.

The natural gas-frac analogue during the rock burst Voelkershausen offers a unique opportunity to study conditions of barrier integrity loss due to a real gas-frac. As a result of the strong dynamical event, the underlying salt barrier below the mining area lost its integrity. The rock burst "Voelkershausen 1989" was one of the strongest mining induced seismic events worldwide with a local magnitude of $M_L = 5.6$. Within a few seconds 3200 pillars in the carnallitic seam Thuringia were destroyed with a subsidence of 1 m and an impact on the surface. Fortunately, a protective effect was given by the thicker upper interbeds according to a multi-barrier system, which consists of approx. 180 m rock salt and ca. 40 m saliferous clay and clay stones.

With respect to the gas pressure at the base of the lower Werra-rock salt in the order of 7 MPa, the gas frac results due to the significant dynamic un-loading of the lower Werra rock salt. In the Feldatal-fault zone, where the Lower Werra-rock salt is thinned to less than 30 m, the minimum stress criterion was considerably violated due to the convergence drop in the mining field.

In the framework of a research project, the actual state of the underlying salt barrier has been investigated 18 years after the rock burst. For verification of the assumption of frac-healing, the former gas-frac zone has been inspected via a horizontal borehole, where open gas-bearings as well as recompacted fractures were found. The crack orientation corresponds fairly well with the calculated orientation of the major principal stress orientation.

In the natural scale frac conditions are only possible under the following two circumstances:

- Gas-frac due to an extremely fast gas pressure increase, i.e. an explosion
- Gas-frac during dynamic loading with a loss of confinement in the rock mass, e.g. during earth quakes or rock bursts.

The natural gas-frac analogue documents the recovery of barrier integrity in the salt mass after a dynamically induced gas-frac and demonstrates the capacity of rock salt for self healing.

Gas-production rates in a radioactive waste repository in salt will not be high enough to induce a macroscopic gas-frac, because the fluid pressure driven grain boundary opening will act as a safety valve.

For demonstrating the integrity of geological barriers it is necessary to describe the complex mechanical behaviour of saliferous rocks with suitable models to verify the barrier. Furthermore, the mechanical behaviour of bedding planes and discontinuities has to be considered as well. The elasto-visco-plastic constitutive law developed at the IfG with softening and dilatancy allows to describe the whole bandwidth of mechanical behaviour of various saliferous rocks.

As a consequence of the heat generation and the uplift of the salt, the primary stress state changes in the surrounding saliferous barrier of a final disposal site of high-level radioactive waste. One result of thermo-mechanical calculation is a violation of the minimum stress criteria on the leached surface of a salt dome. On the steeply dipping discontinuities or bedding planes the violation of the minimum stress criterium reached deeper.

In the flat bedded Zechstein salt formation in Germany one can find a natural geological multi-barrier-system, which has the advantages:

- claystone in the overburden
- salt clay as a protecting overlaying clay layer

- rock salt with bedding planes/discontinuities in a horizontal direction

With respect to the principle of the complete containment, salt formations have unique advantages for a nuclear waste repository:

- impermeability in undisturbed conditions
- tightness will only get lost in case of exceeding a threshold
- self-sealing ability and healing due to its visco-plastic behaviour

Germany offers excellent conditions in domal as well as in bedded salt formations.

Wolfgang Minkley

2nd US-German Workshop on Salt Repository Research, Design and Operation

November 9 - 10, 2011 Peine, Germany

Geomechanical Assessment of the Barrier Integrity

Wolfgang Minkley

IfG-Institute for Geomechanics GmbH, Leipzig, Germany

outline

- Isolation capability of salt rocks
- Loss of tightness of rock salt
- Convergence induced loading
- Gas-pressure induced loading
- Thermo-mechanical induced loading
- Outlook

Natural analogue: Long term storage capacity of high pressure fluids in salt

2004 - salt mine "Unterbreizbach"

CO_2-glacier after an underground gas-breakout

Isolation capability of salt rocks

- Conclusion

  On the basis of natural analogons and the practical experiences of gas storage in salt caverns it can concluded that

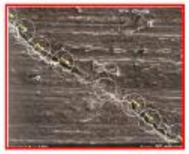
  undisturbed salt formations

  are impermeable !

Mechanically or hydraulically induced permeability

- Percolation of flow path along grain boundaries
  - deviatoric stresses induces development and connection of inter-crystalline cracks

    → dilatancy criterion



Crystal sliding
Alkan & Müller (2008)

  - fluid pressure driven grain boundary opening and connectivity

    → minimum stress criterion

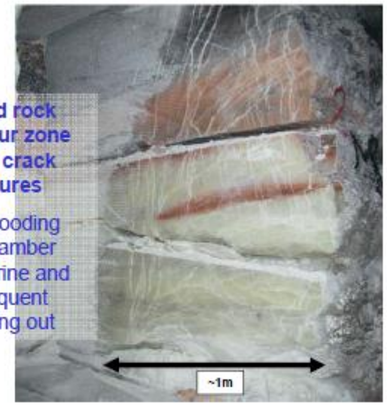
Gas injection
Popp et al. (2007)

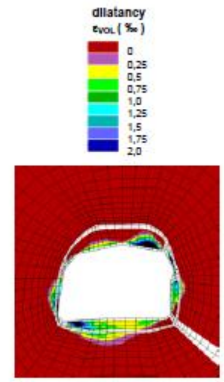
EDZ around a chamber in a salt mine

Damaged zone due to dilatant deformation

wetted rock contour zone along crack structures

after flooding the chamber with brine and subsequent pumping out





Calculation of damaging after 30 years

Loss of tightness of salt rocks

- Conclusion

  The mechanically or hydraulically induced permeability bases on the same microphysical processes, i.e. the percolation of flow paths along grain boundaries after exceeding a threshold, which correspond:

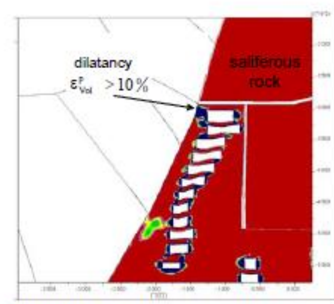
  - (1) at deviatoric conditions with the dilatancy boundary and
  - (2) at increased fluid pressures with the acting normal stresses respectively minimum stresses

  i.e. in both cases due to a removal of intergranular cohesion.

Case study (1) Asse 2: Violation of the dilatancy and minimum stress criterion

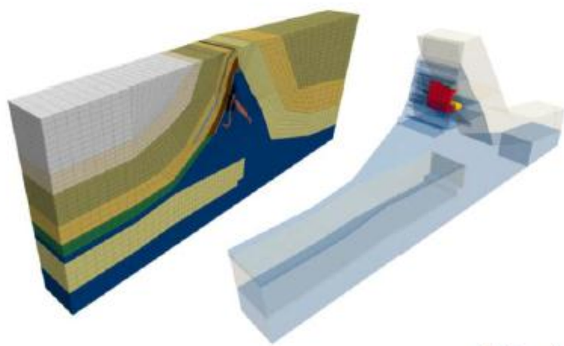
Inflow of water into the former salt-mine, used as URL

Recorded micro-seismic activities



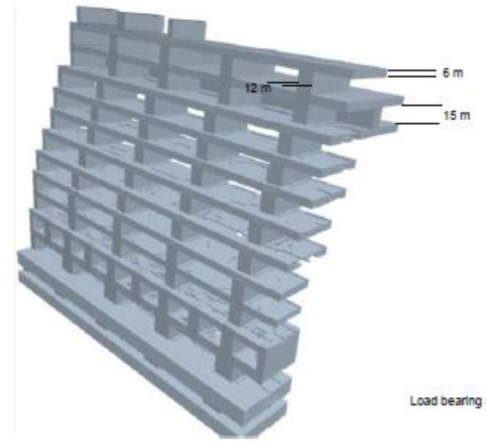
Calculated dilatant zones around the mining rooms at the southern flank of the Asse II mine

Case study (1) Asse 2: Violation of the dilatancy and minimum stress criterion
Inflow of water into the former salt-mine, used as URL



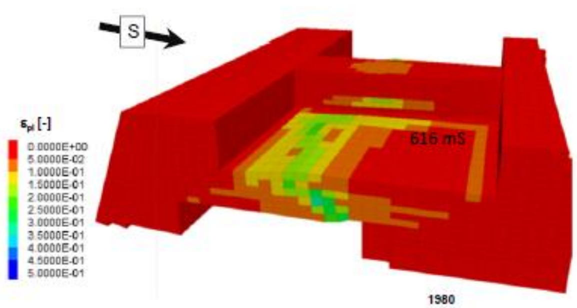
3D-Geomechanical Model

Case study (1) Asse 2: Violation of the dilatancy and minimum stress criterion
Inflow of water into the former salt-mine, used as URL



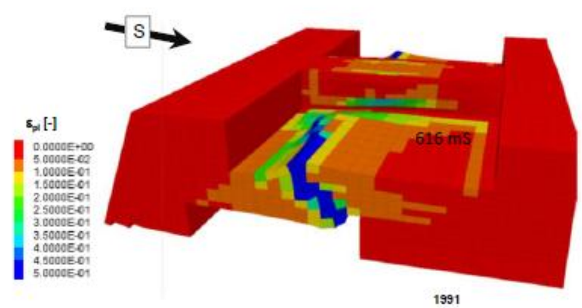
Load bearing system

Case study (1) Asse 2: Violation of the dilatancy and minimum stress criterion
Inflow of water into the former salt-mine, used as URL



Failure mechanism of the roof pillar

Case study (1) Asse 2: Violation of the dilatancy and minimum stress criterion
Inflow of water into the former salt-mine, used as URL



Failure mechanism of the roof pillar

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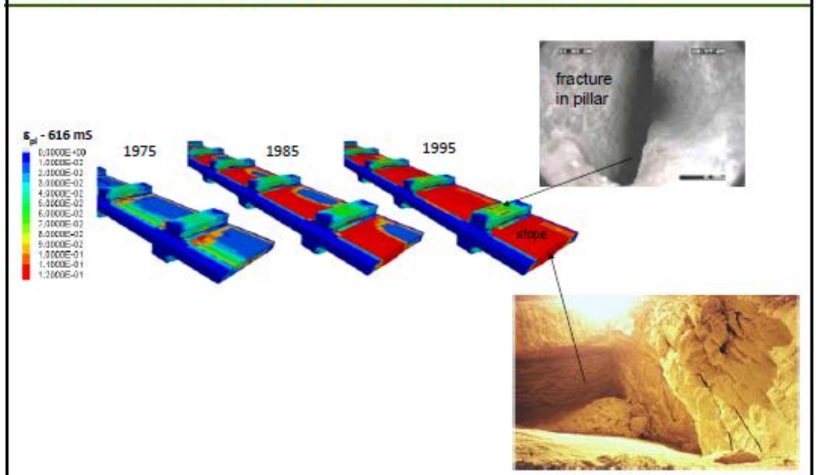
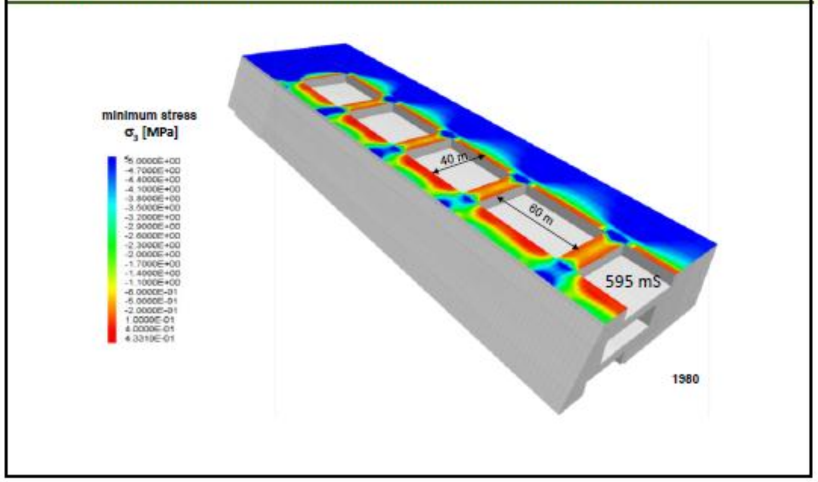
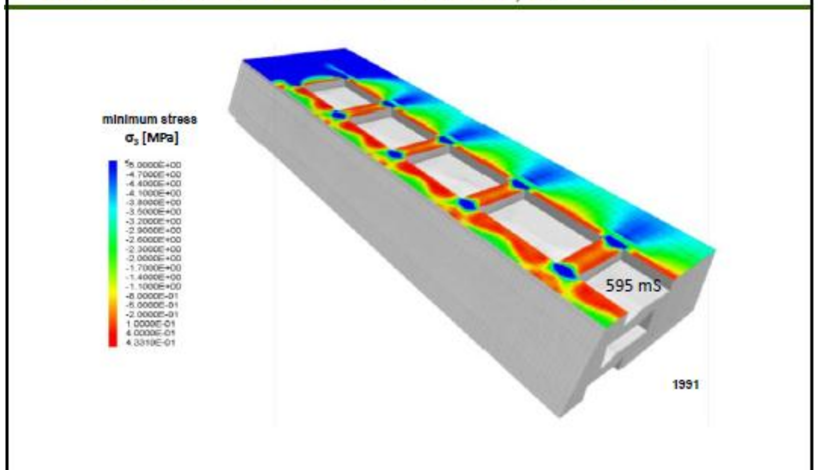


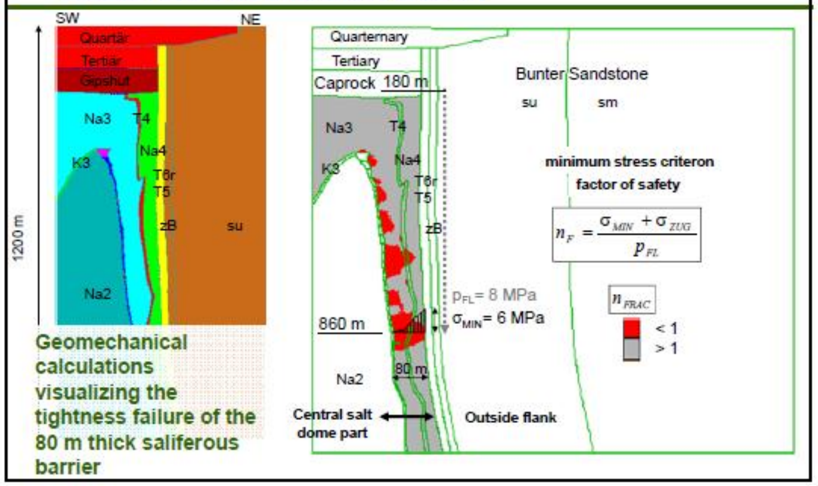
Case study (1) Asse 2: Violation of the dilatancy and minimum stress criterion
Inflow of water into the former salt-mine, used as URL



Case study (1) Asse 2: Violation of the dilatancy and minimum stress criterion
Inflow of water into the former salt-mine, used as URL

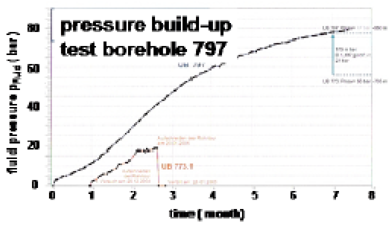


Case study (2) salt dome Bokeloh:
Violation of the Minimal stress criterion

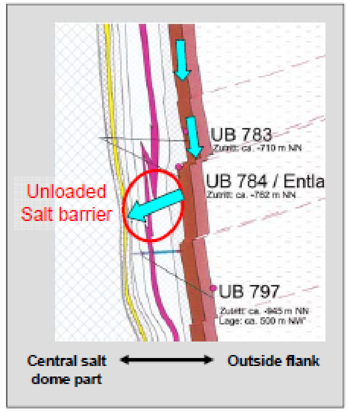


Experimental verification of hydraulic pressure built-up in the salt dome flank

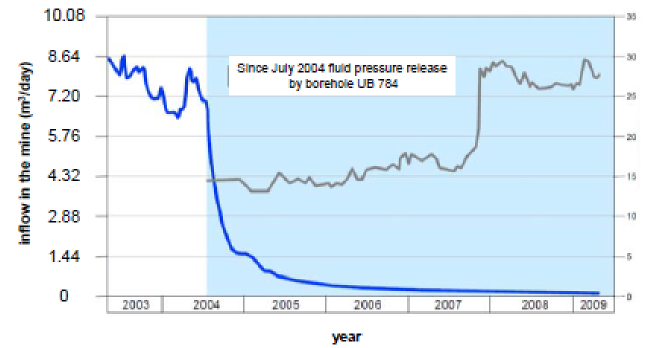
Hydraulic tests in bore holes at the salt dome flank demonstrate a hydraulic pressure of ~ 80 bar



Inflow of water into the mine



Decrease of inflow in the mine - sealing of the salt barrier after reduction of fluid pressure at the dome flank



Convergence-induced loading

- Conclusion

The impermeability of a saliferous barrier will already be lost if one of these two criteria:

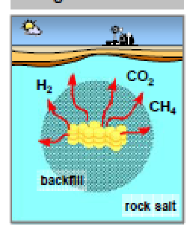
- (1) minimum stress criterion or
- (2) dilatancy criterion

is violated!

Note, most critical for the integrity of saliferous barrier is the minimum stress criterion because the importance of the dilatancy criterion is limited to the EDZ !

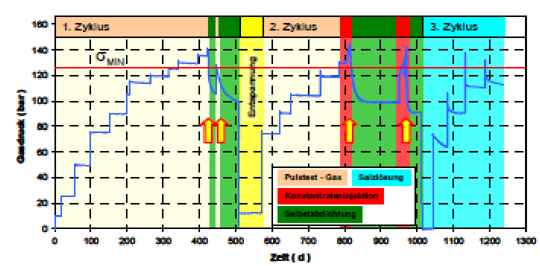
Barrier integrity of rock salt at gas pressure build-up

Long term



Gas production q_{gas}
- steel corrosion
- radiolysis
- bio-degradation

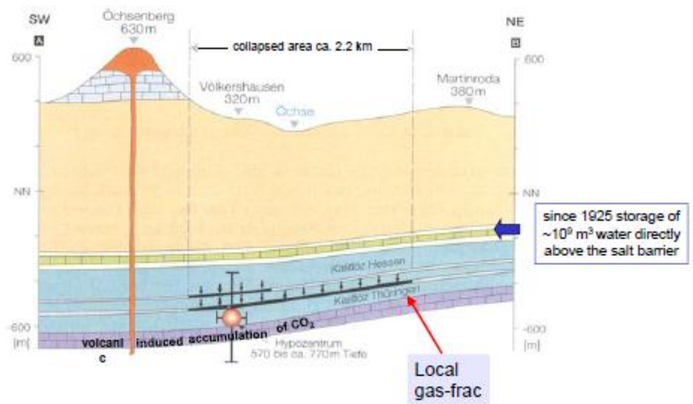
- The in-situ gas injection test



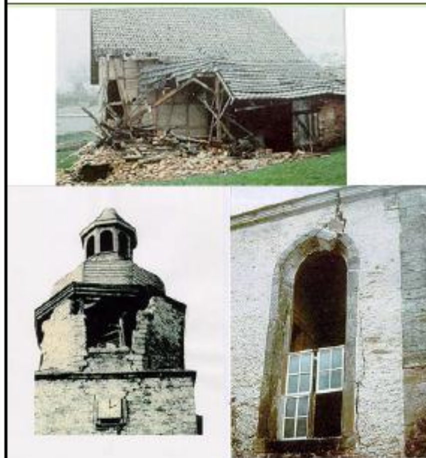
Pressure build-up with time
> Gas-frac risk <

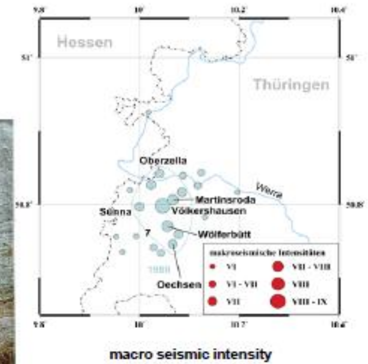
Research effort over the last 5 years
- *Comprehensive rock mechanical lab investigations*
- *Two In situ experiments in the Bernburg salt mine (D)*

Natural analogon:
Gas-frac during the rock burst Völkershausen 1989

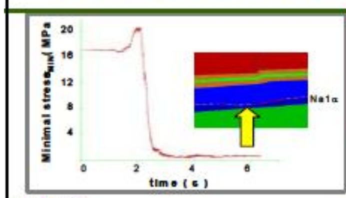


Rock burst Impact on the surface

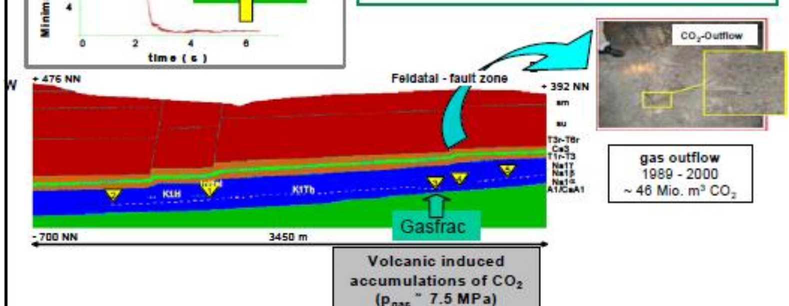




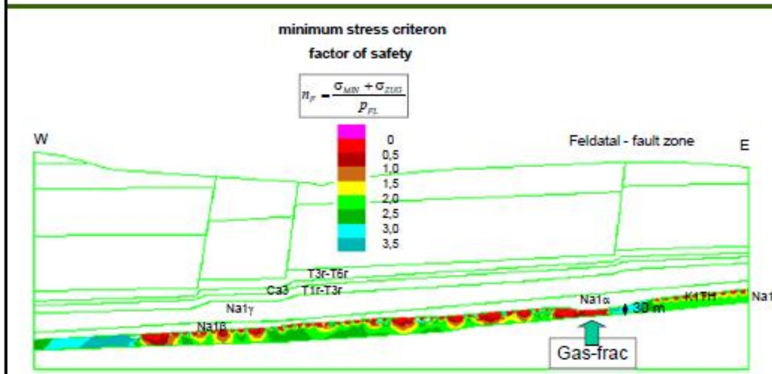
Impact on the geological salt barriers



As a consequence of the rock burst Völkershausen 1989 an gas breakthrough of CO_2 occurred in the lower rock salt barrier in the salt mine Merkers due to the unloading of the upper mine parts.

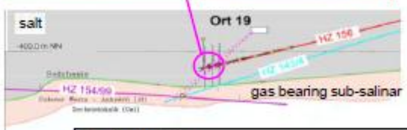


Impact on the geological salt barriers



$$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$$

In-situ testing in the former gasfrac zone

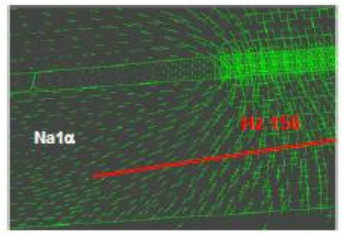


In-situ testing

250m long horizontal bore hole HZ156:

- Direct probing of the former gas-frac zone
- Hydrofrac testing
- Pressure build-up tests
- Gas-injection tests

- At least partial, but „real" healing is documented
- Only local gas reservoirs were found without connection to the gas bearing sub-salinar
- Recovery of minimal stress in the former gas-frac zone
- Gasfracs are oriented parallel to the direction of the maximal stress



Risk of gas frac in a saliferous barrier

- **Conclusion**

  In the natural scale gas frac conditions are only possible under the following two circumstances:

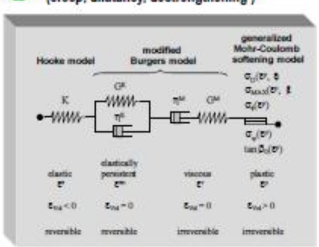
  - due to an extremely fast gas pressure increase, i.e. an explosion
  - during dynamic loading with a loss of confinement in the rock mass, e.g. during earth quakes or rock bursts.

  The natural gas-frac analogue documents the recovery of barrier integrity in the salt mass after a dynamically induced gas frac and demonstrates the capacity of rock salt for self healing.

  Gas-production rates in a radioactive waste repository in salt will not high enough to induce a macroscopic gas-frac because the fluid pressure driven grain boundary opening will act as a safety valve.

Geomechanical modeling demonstrating the integrity:
Constitutive models for salt rocks and imbedded weakness planes

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

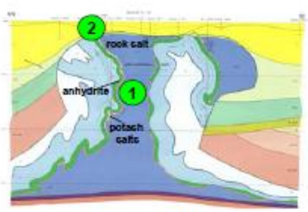


2 adhesive friction model for discontinuities and bedding planes with displacement-and velocity-dependent softening

adhesive friction model

$$\tau = \mu_K (1 + \mu_{ad}) \cdot \sigma_N + c$$

$$\mu_{ad} = f_{ad} \cdot \frac{w_{12}}{a(t) \cdot \sigma_r}$$

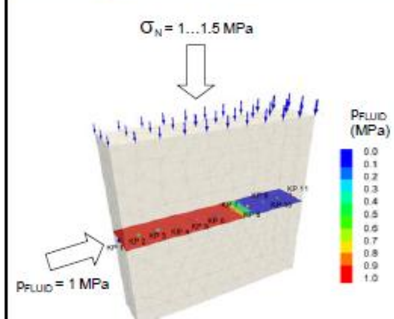


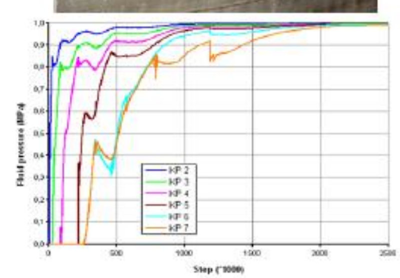
Constitutive models has to describe the mechanical behavior of saliferous strata witch consist mainly of:
-rock salt
-potash salts
-anhydritic rocks
-salt clay
-Claystone

and

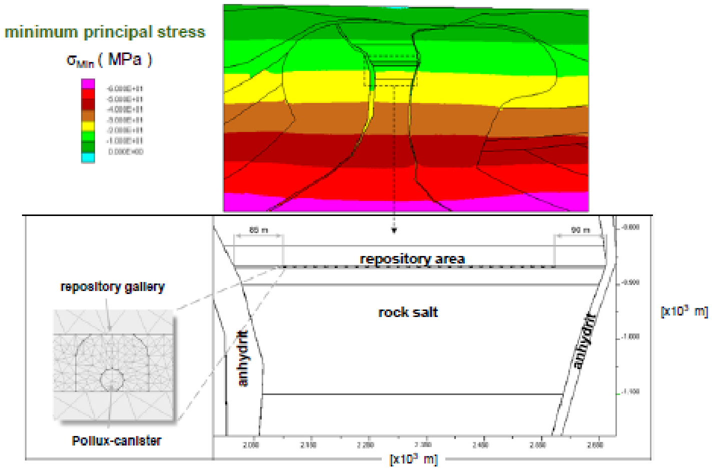
for discontinuities and bedding planes !

Numerical Simulation of fluid pressure driven flow along a bedding plane

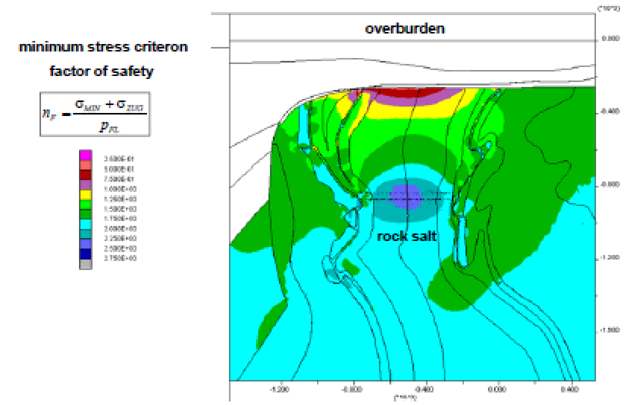




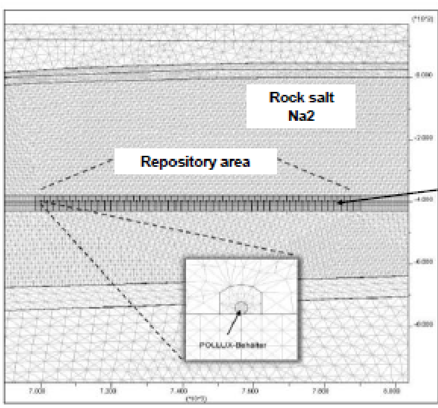
Geomechanical model: steep bedded deposit (salt dome)



Thermo-mechanical calculation of a final disposal in steep bedded deposits

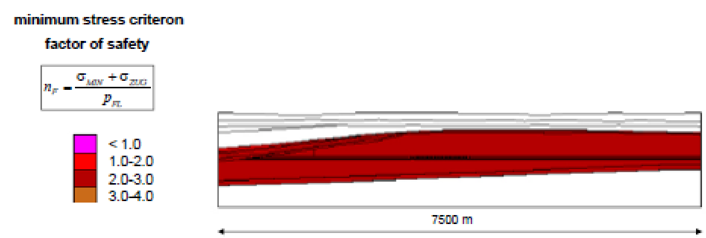


Layout for T-M coupled model calculation in flat bedded deposit



- Depth of emplacement horizon 700 m
- 50 backfilled drifts, height 3.7 m, width 4.5 m, pillar 13.5 m
- Material parameters and temperature boundary condition at POLLUX-containers in reference to project BAMBUS II

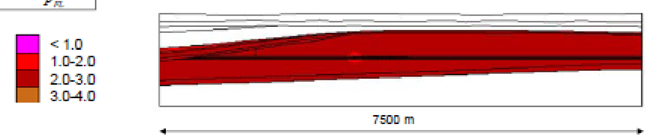
Thermo-mechanical calculation of a final disposal in a flat bedded deposit



Thermo-mechanical calculation of a final disposal in a flat bedded deposit

minimum stress criterion
factor of safety

$$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$$



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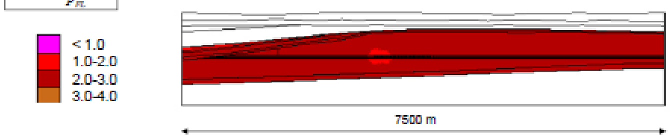

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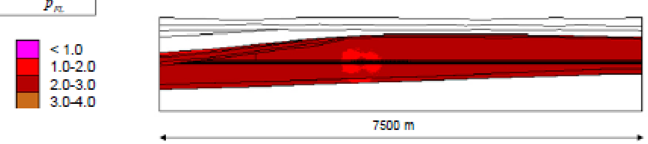

Thermo-mechanical calculation of a final disposal in a flat bedded deposit

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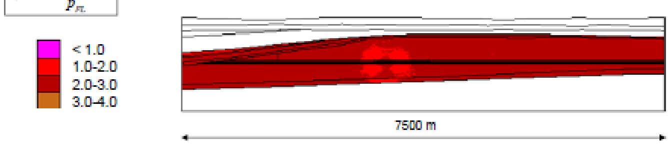
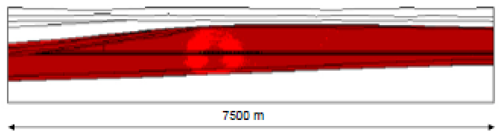


Thermo-mechanical calculation of a final disposal in a flat bedded deposit

minimum stress criterion
factor of safety

$$n_F = \frac{\sigma_{MIN} + \sigma_{ZUG}}{p_{FL}}$$

- < 1.0
- 1.0-2.0
- 2.0-3.0
- 3.0-4.0



Thermo-mechanical calculation of a final disposal in a flat bedded deposit

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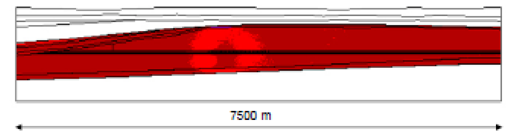

Thermo-mechanical calculation of a final disposal in a flat bedded deposit

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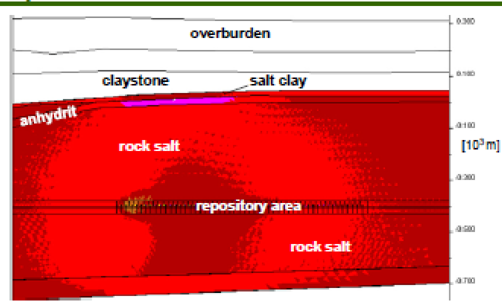
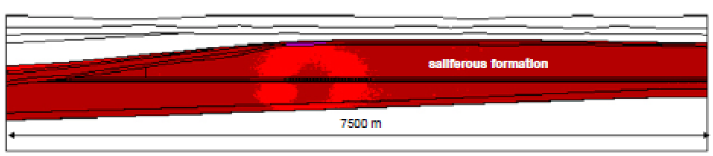


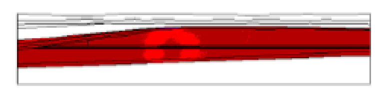


Main characteristics of steep bedded and flat bedded salt deposits

steep bedded deposit

- complex geological layout with folds
- steeply dipping seams up to the leached surface
- stiff anhydritic slabs
- thick rock salt layers in large depths

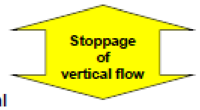
flat bedded deposit

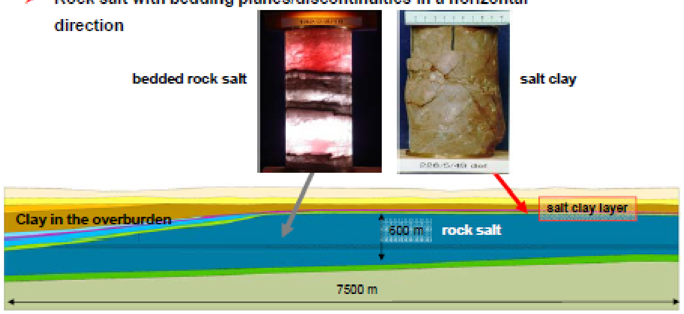


- simple geological layout
- geological multi-barrier system
- seams with great horizontal distance to the leached surface

Flat bedded salt deposits
- a natural geological multi-barrier-system

- **Advantages**
  - Clay layers in the overburden
  - Bedded intra-saliferous salt clay as additional protective shield
  - Rock salt with bedding planes/discontinuities in a horizontal direction





Outlook

- with respect to the principle of the complete containment salt formations have unique advantages for a nuclear waste repository
  - impermeability in undisturbed conditions
  - tightness will only get lost in case of exceeding a threshold
  - self-sealing ability and healing due to its visco-plastic behaviour
- Germany offers excellent conditions in domal as well as in bedded salt formations

Benchmark of TM(H) Modeling of Rock Salt

Andreas Hampel, Scientific Consultant, Mainz, Germany

Abstract

In recent decades, a large and detailed experimental and theoretical knowledge base has been compiled for the geomechanical behavior of rock salt. On this basis, several advanced constitutive models and procedures for the determination of salt type-specific parameter values and for the performance of numerical calculations have been developed. They are applied in numerical simulations for the design, stability analysis, and evaluation of the long-term behavior of underground openings in rock salt.

Some applications – e.g. the assessment and proof of integrity of the geological barrier around an underground repository for hazardous wastes, or the stability analysis of gas and oil storage caverns – require a particular high reliability and predictability of the results. Especially beyond experimentally accessible areas or intervals of boundary conditions, this can only be complied with advanced models that describe the relevant physical deformation mechanisms.

Between 2004 and 2010, the German Federal Ministry of Education and Research (BMBF) has funded two joint projects within its research program "Improvement of Tools for the Safety Assessment of Underground Repositories". The studies are currently being continued in another joint project (2010–2014) with a collaboration of the German partners with U.S. experts from Sandia National Laboratories. In this third project, the German partners are funded by the Federal Ministry of Economics and Technology (BMWi) within the program "Priorities of Future R&D Work on the Final Disposal of Radioactive Wastes".

The partners in the joint projects have been the following:

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

The general project objectives have been to document, check, and compare with benchmark calculations the constitutive models and modeling procedures of the partners, to validate the suitability and reliability of the models and procedures, to increase confidence in the results of numerical simulations performed with the models, and to enhance the acceptance of the results and conclusions. The results give also hints for the further development of the models.

The focus of project I was on the modeling of the relevant deformation phenomena in rock salt, i.e. transient and steady-state creep, the evolution of dilatancy and damage, short-term strength and long-term creep failure, post-failure behavior and residual strength. Each partner performed jointly defined benchmark calculations with his constitutive model(s) and numerical code(s). They were carried out with increasing complexity, starting with back-calculations of selected specific laboratory deformation tests, because in the laboratory the different deformation phenomena can be studied under various well-defined boundary conditions and – at least up to a

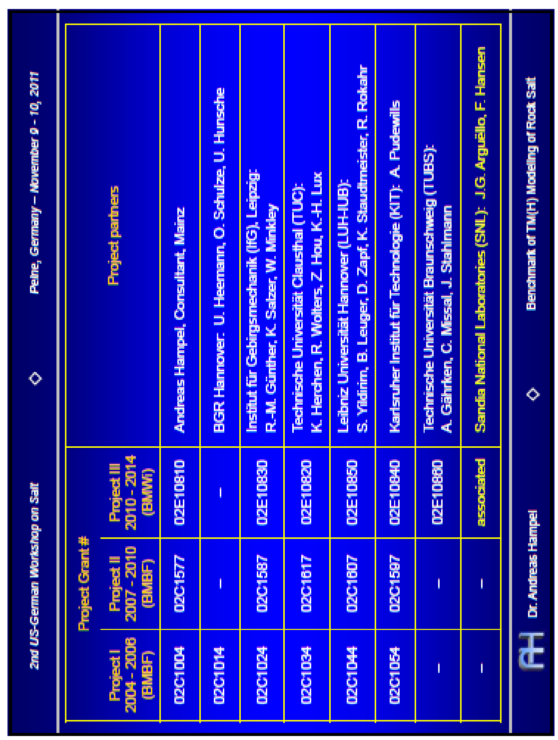
certain degree – independently from one another. Then, each partner performed 2-D calculations of simple, but typical underground structures, e.g. a highly loaded room-pillar situation.

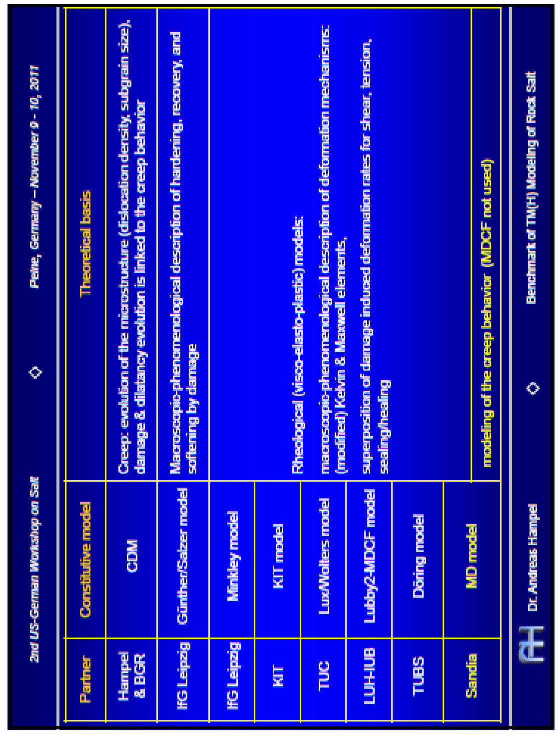
In project II, benchmark calculations of a 3-D section of a real salt mine were carried out. For this purpose, the Angersdorf mine in the "Leine" rock salt of Northern Germany was selected, because it has a relatively simple structure with a regular pattern of rooms and pillars, and because experimental data both from geomechanical laboratory tests and from surface subsidence measurements above the mine were already available at the start of the project. Within the project supplementary laboratory tests as well as in-situ measurements in the underground were carried out in order to get further data for the determination of salt type-specific parameter values and for comparisons with the simulation results. Each partner calculated the mine section with his constitutive model(s) and numerical code(s). The objective of this project was to check the applicability of the models to 3-D simulations of a real salt mine, and to compare the results with each other, with data of the surface subsidence above the mine, and with in-situ measurements of the minimum principal stress, pillar expansion rate, and the porosity (dilatancy) and permeability in the EDZ close to a pillar wall.

In the currently running project III, the studies are being continued with comparisons of the modeling of the thermo-mechanical behavior and of the damage reduction ("healing") of rock salt. Again, the benchmark comprises back-calculations of specific laboratory tests as well as simulations of in-situ structures. The modeling of the temperature influence on the deformation behavior is investigated by means of calculations of a heated borehole in the Asse II salt mine, and the results are compared with each other and with in-situ data from experiments of the Netherlands Energy Research Foundation ECN in that borehole. The modeling of healing of pre-damaged rock salt is studied with back-calculations of specific laboratory tests and with benchmark simulations of a drift that was excavated in 1911, and of which a 25 m long section was lined with a cast-steel tube in 1914 (the residual gap was filled with concrete). The simulation results of the partners will be compared with each other and with data from in-situ permeability measurements that were performed in the rock salt behind the bulkhead by GRS in the ALOHA2 project 85 years after the installation of the liner.

In project III, the Sandia National Laboratories are taking part, too. Both the Sandia experts and the German partners have substantial experience in the investigation of the deformation behavior of rock salt, in the development and application of constitutive models, and in the performance of numerical simulations. Therefore, these benchmark projects are well suited for further and enhanced joint research activities in these areas in the U.S. and in Germany for mutual benefit.

Andreas Hampel





Partner	Numerical Code(s)	Calculation Method
Hampel	FLAC & FLAC3D	Finite Difference
IfG Leipzig		
LUH-IUB		
TUC		
KIT	ADINA	Finite Element
BGR	JIFE	Finite Element
TUBS	FLAC3D, ANSYS	Finite Difference, Finite Element
Sandia	SIERRA Mechanics Code Suite (various coupled codes)	

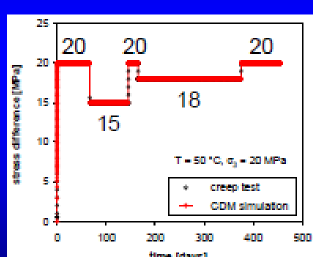
Three Joint Projects on the Comparison of Constitutive Models for Rock Salt

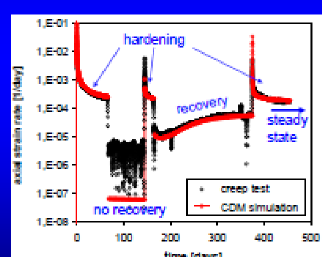
Project	Period	Title	Main Objectives
1	04/2004 – 11/2006	The Modeling of the Mechanical Behavior of Rock Salt: Comparison of Current Constitutive Models and Modeling Procedures	Document, check, and compare in detail the capabilities of the models to describe the relevant deformation phenomena in rock salt.
2	08/2007 – 07/2010	Comparison of Current Constitutive Models and Modeling Procedures with 3-D Calculations of the Mechanical Long-term Behavior of an Underground Structure in Rock Salt	Document, check and compare - the suitability of the models for the performance of 3-D simulations, - predictions of the future behavior, - the calculation of permeability of damaged rock salt with the models.
3	10/2010 – 01/2014	Comparison of Current Constitutive Models and Modeling Procedures with Model Calculations of the Thermo-mechanical Behavior and Healing of Rock Salt	Document, check and compare - the modeling of temperature influence on the deformation behavior of rock salt - the modeling of healing (sealing) of damaged rock salt with the models.

Document, check, and compare in detail the capabilites of the models to describe the relevant deformation phenomena in rock salt (1)

a) Each partner performed back-calculations of various creep tests from the laboratory

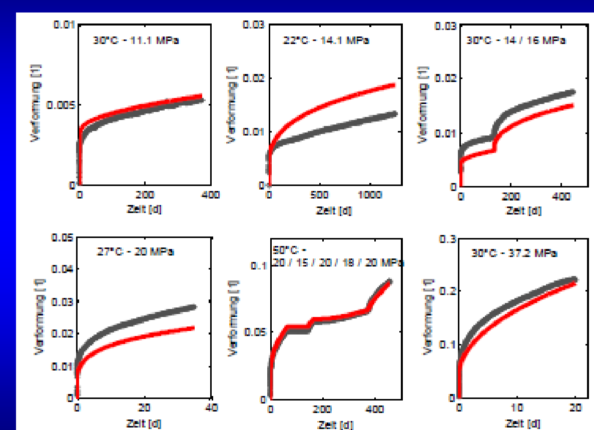
- Transient creep after a stress increase (hardening)
- Transient creep after a stress decrease (recovery)
- Steady-state creep





black: BGR creep test with rock salt from the Asse mine, red: CDM calculation of Hampel

Back-calculation of various creep tests with one unique set of salt type-specific parameter values



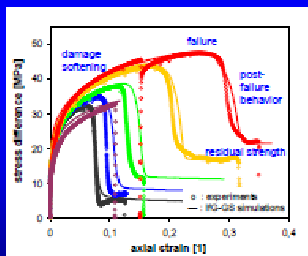
black: BGR creep tests with rock salt from the Asse mine

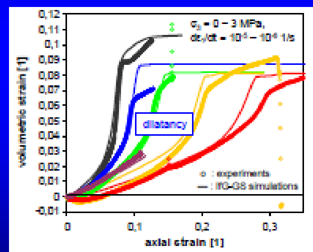
red: model curves (CDM simulation of Hampel)

Document, check, and compare in detail the capabilities of the models to describe the relevant deformation phenomena in rock salt (2)

b) Each partner peformed back-calculations of various strength tests from the laboratory

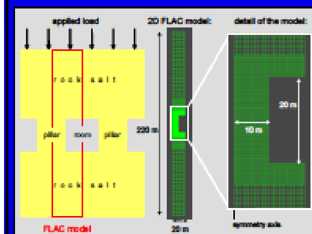
- evolution of damage, dilatancy (volumetric strains, porosity) above the dilatancy boundary
- short-term strength and long-term creep failure
- post-failure behavior and residual strength





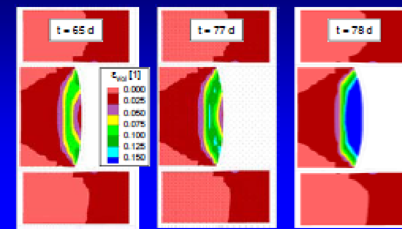
symbols: BGR strength tests with rock salt from the Asse mine, lines: IfG calculations with Günther/Salzer model

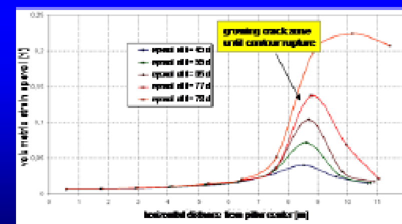
Each partner performed simulations of a typical room-pillar model structure



here: IfG simulation with the Günther/Salzer model

- high pillar load: 38.4 MPa



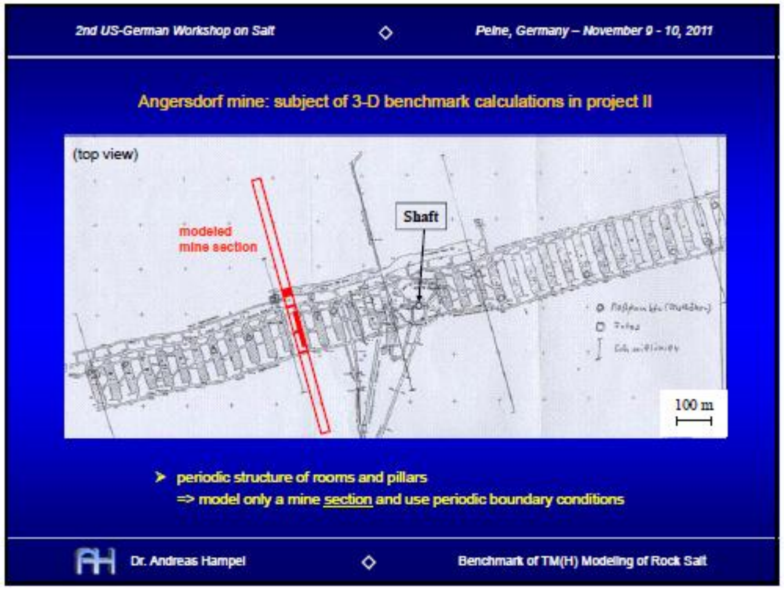


The modeling of the relevant deformation phenomena is also a basis for the description of …

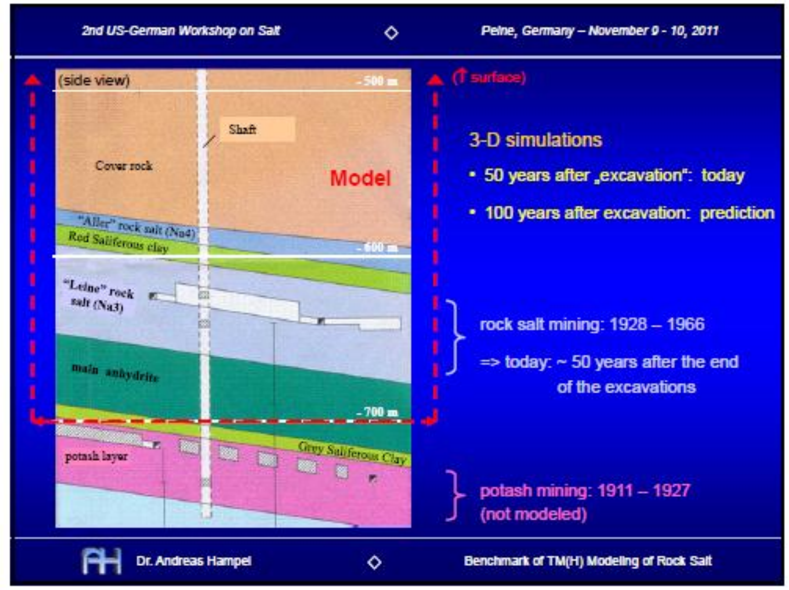
- … the thermo-hydro-mechanical coupling (THM)
- … the influence of a gas or fluid pressure on the opening and progress of (micro)cracks in rock salt (gasfrac, hydrofrac)
- … the closure (sealing) of microcracks and healing of damage below the dilatancy boundary (=> decrease of permeability)

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

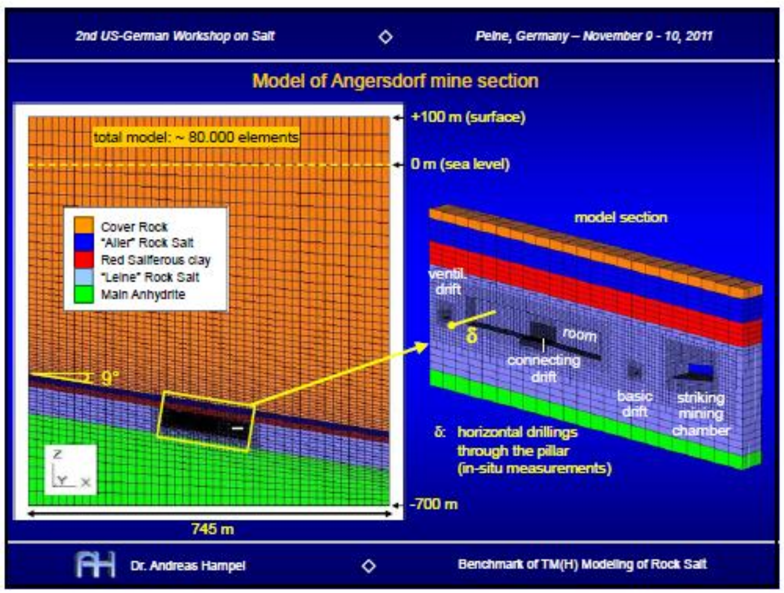
Project	Period	Title	Main Objectives
1	04/2004 – 11/2006	The Modeling of the Mechanical Behavior of Rock Salt: Comparison of Current Constitutive Models and Modeling Procedures	Document, check and compare the modeling of the relevant deformation phenomena in rock salt.
2	08/2007 – 07/2010	Comparison of Current Constitutive Models and Modeling Procedures with 3-D Calculations of the Mechanical Long-term Behavior of an Underground Structure in Rock Salt	Document, check and compare • the suitability of the models for the performance of 3-D simulations, • predictions of the future behavior, • the calculation of permeability of damaged rock salt with the models.
3	10/2010 – 01/2014	Comparison of Current Constitutive Models and Modeling Procedures with Model Calculations of the Thermo-mechanical Behavior and Healing of Rock Salt	Document, check and compare • the modeling of temperature influence on the deformation behavior of rock salt • the modeling of healing (sealing) of damaged rock salt with the models.



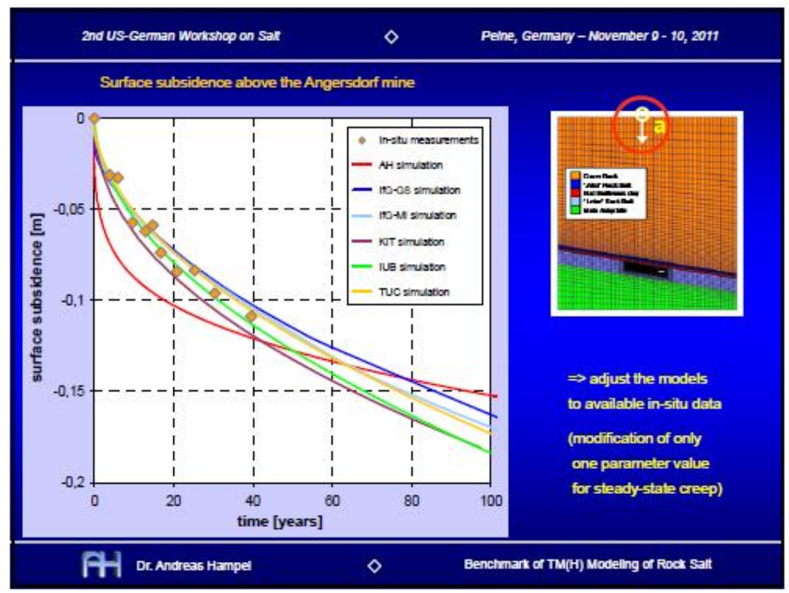
2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Angersdorf mine: subject of 3-D benchmark calculations in project II
(top view)
modeled mine section
Shaft
100 m
➤ periodic structure of rooms and pillars
=> model only a mine section and use periodic boundary conditions
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt



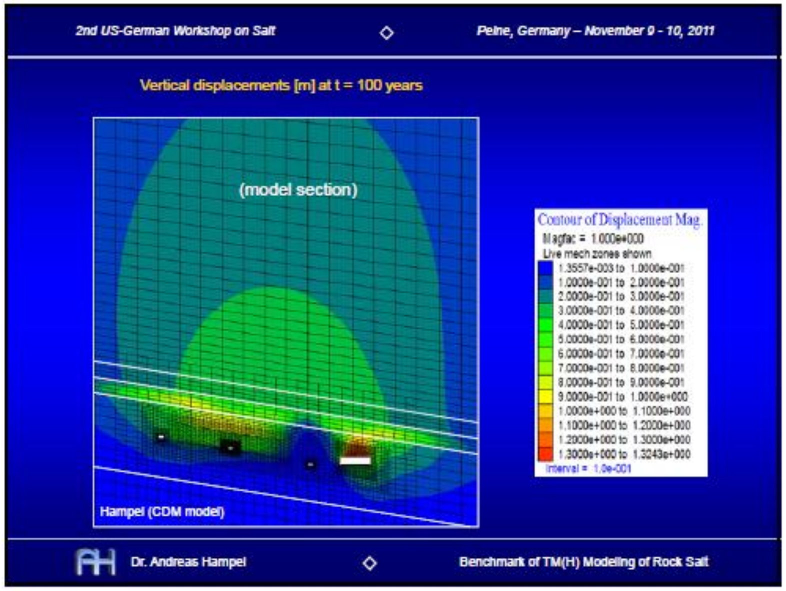
2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
(side view)
Shaft
Cover rock
Model
"Aller" rock salt (Na4)
Red Saliferous clay
"Leine" rock salt (Na3)
main anhydrite
potash layer
Grey Saliferous Clay
-500 m
-600 m
-700 m
(↑ surface)
3-D simulations
• 50 years after „excavation": today
• 100 years after excavation: prediction
rock salt mining: 1928 – 1966
=> today: ~ 50 years after the end of the excavations
potash mining: 1911 – 1927
(not modeled)
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt

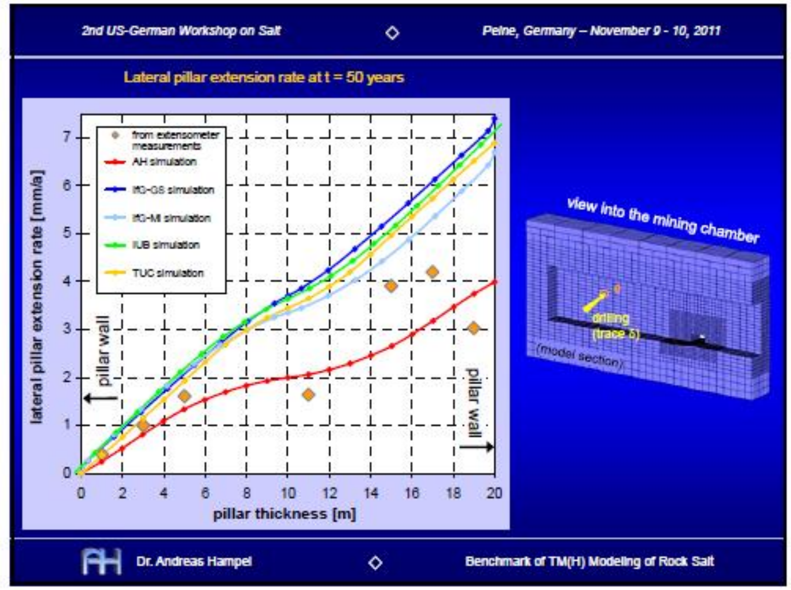


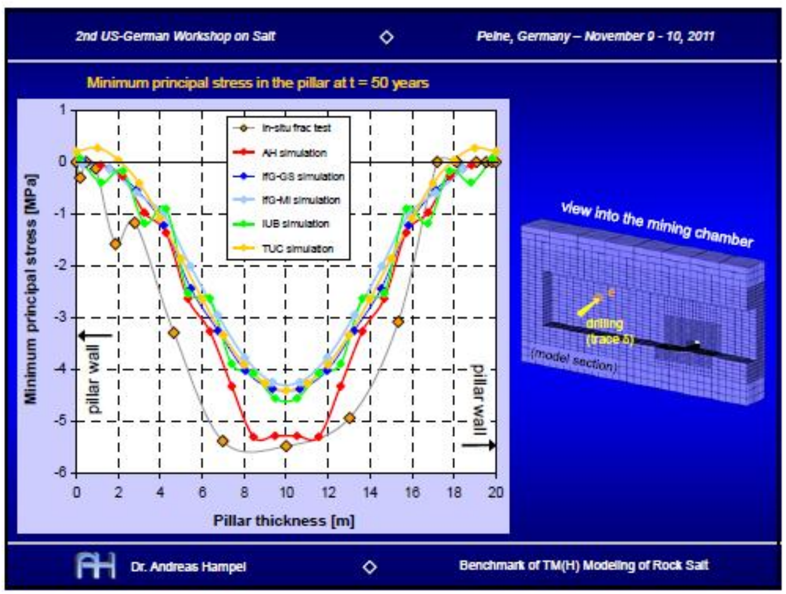
2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Model of Angersdorf mine section
total model: ~ 80.000 elements
+100 m (surface)
0 m (sea level)
Cover Rock
"Aller" Rock Salt
Red Saliferous clay
"Leine" Rock Salt
Main Anhydrite
9°
745 m
-700 m
model section
ventil. drift
δ
room
connecting drift
basic drift
striking mining chamber
δ: horizontal drillings through the pillar (in-situ measurements)
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt

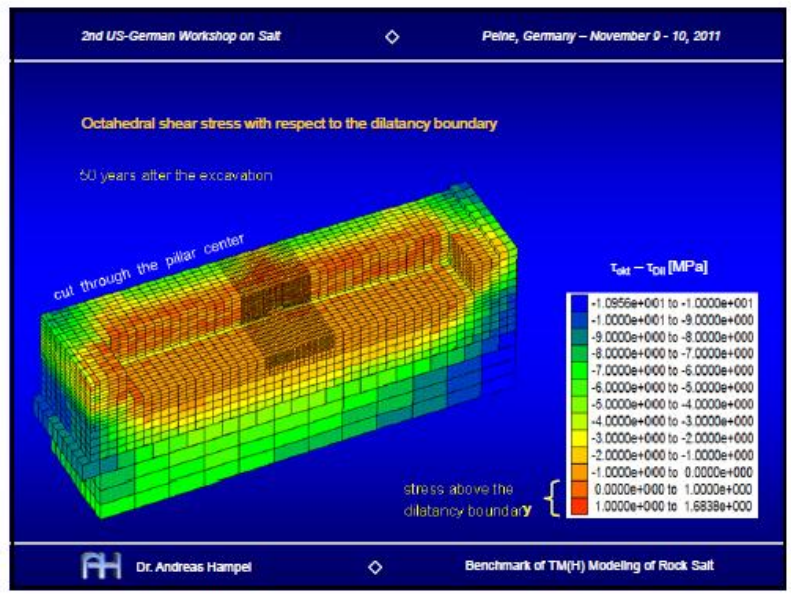


2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Surface subsidence above the Angersdorf mine
surface subsidence [m]
time [years]
0
-0,05
-0,1
-0,15
-0,2
0
20
40
60
80
100
in-situ measurements
AH simulation
IfG-GS simulation
IfG-MI simulation
KIT simulation
IUB simulation
TUC simulation
a
=> adjust the models to available in-situ data
(modification of only one parameter value for steady-state creep)
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt

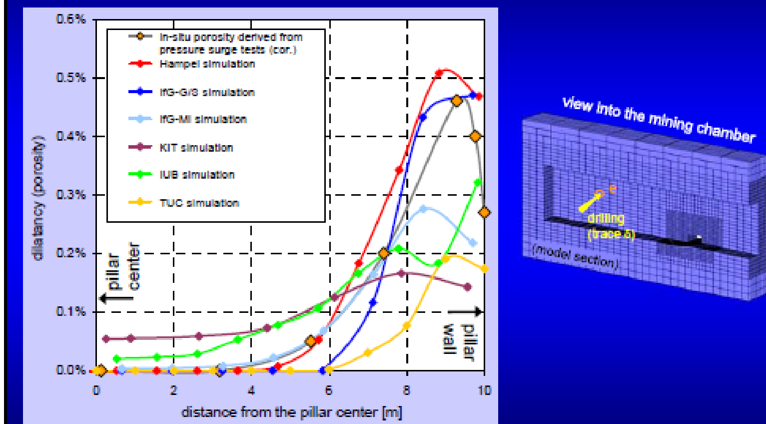

2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Vertical displacements [m] at t = 100 years
(model section)
Hampel (CDM model)
Contour of Displacement Mag.
Magfac = 1.000e+000
Live mech zones shown
1.3557e-003 to 1.0000e-001
1.0000e-001 to 2.0000e-001
2.0000e-001 to 3.0000e-001
3.0000e-001 to 4.0000e-001
4.0000e-001 to 5.0000e-001
5.0000e-001 to 6.0000e-001
6.0000e-001 to 7.0000e-001
7.0000e-001 to 8.0000e-001
8.0000e-001 to 9.0000e-001
9.0000e-001 to 1.0000e+000
1.0000e+000 to 1.1000e+000
1.1000e+000 to 1.2000e+000
1.2000e+000 to 1.3000e+000
1.3000e+000 to 1.3243e+000
Interval = 1.0e-001
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt


2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Lateral pillar extension rate at t = 50 years
lateral pillar extension rate [mm/a]
from extensometer measurements
AH simulation
IfG-GS simulation
IfG-MI simulation
IUB simulation
TUC simulation
pillar wall
pillar thickness [m]
view into the mining chamber
drilling (trace δ)
(model section)
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt

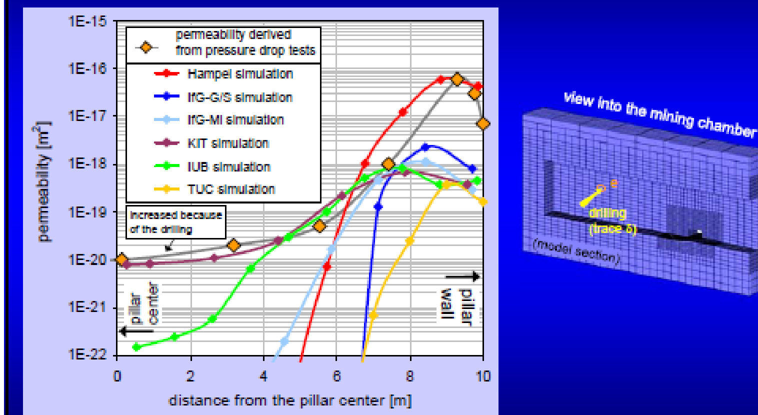

2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Minimum principal stress in the pillar at t = 50 years
Minimum principal stress [MPa]
in-situ frac test
AH simulation
IfG-GS simulation
IfG-MI simulation
IUB simulation
TUC simulation
pillar wall
Pillar thickness [m]
view into the mining chamber
drilling (trace δ)
(model section)
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt


2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Octahedral shear stress with respect to the dilatancy boundary
50 years after the excavation
cut through the pillar center
$\tau_{okt} - \tau_{Dil}$ [MPa]
-1.0956e+001 to -1.0000e+001
-1.0000e+001 to -9.0000e+000
-9.0000e+000 to -8.0000e+000
-8.0000e+000 to -7.0000e+000
-7.0000e+000 to -6.0000e+000
-6.0000e+000 to -5.0000e+000
-5.0000e+000 to -4.0000e+000
-4.0000e+000 to -3.0000e+000
-3.0000e+000 to -2.0000e+000
-2.0000e+000 to -1.0000e+000
-1.0000e+000 to 0.0000e+000
0.0000e+000 to 1.0000e+000
1.0000e+000 to 1.6838e+000
stress above the dilatancy boundary
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt

Dilatancy in the pillar at t = 50 years, compared with in-situ measurements



Permeability in the pillar at t = 50 years, compared with in-situ measurements



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

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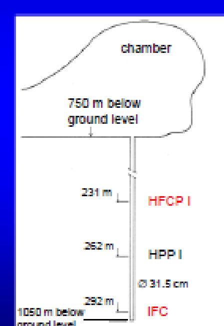
Joint Project 3 (10/2010 – 01/2014):

a) Modeling of the thermo-mechanical behavior of rock salt

- Performance and back-calculations of various specific laboratory creep and strength tests
- Simulations of ECN heater experiments in a deep 300 m long borehole in the Asse II salt mine



a.1) Isothermal free convergence (IFC)

18.12.1979 – 30.03.1982 (834 days),

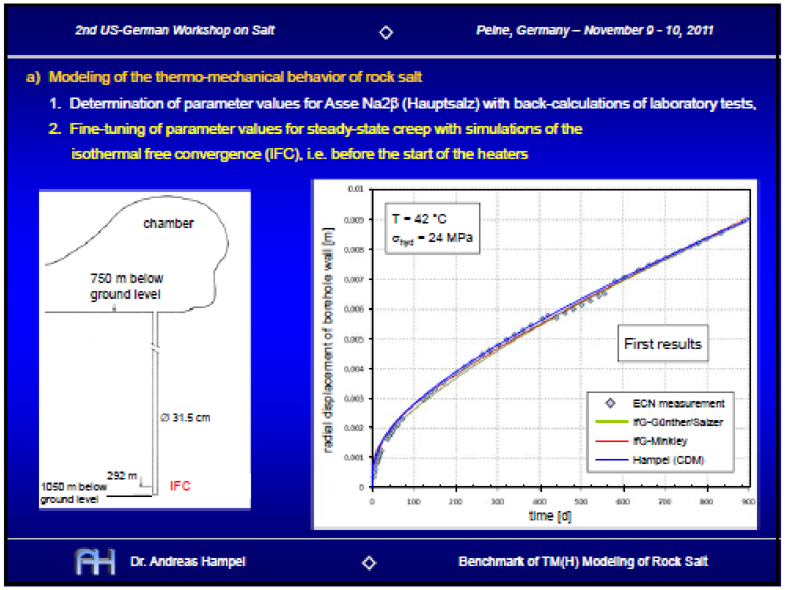
T = 42 °C, borehole depth: 292 m

a.2) Heated free convergence probe (HFCP)

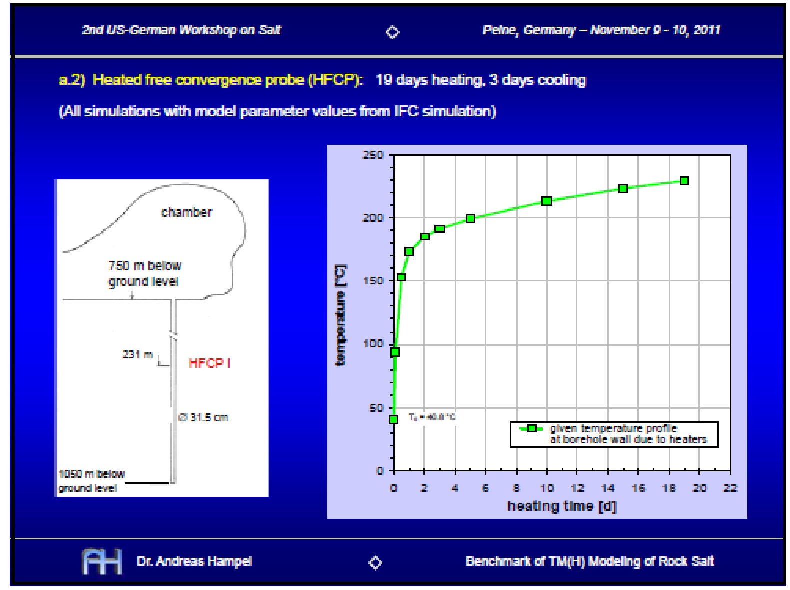
14.07.1983 – 22.08.1983 (23 days),

borehole depth: 231 m

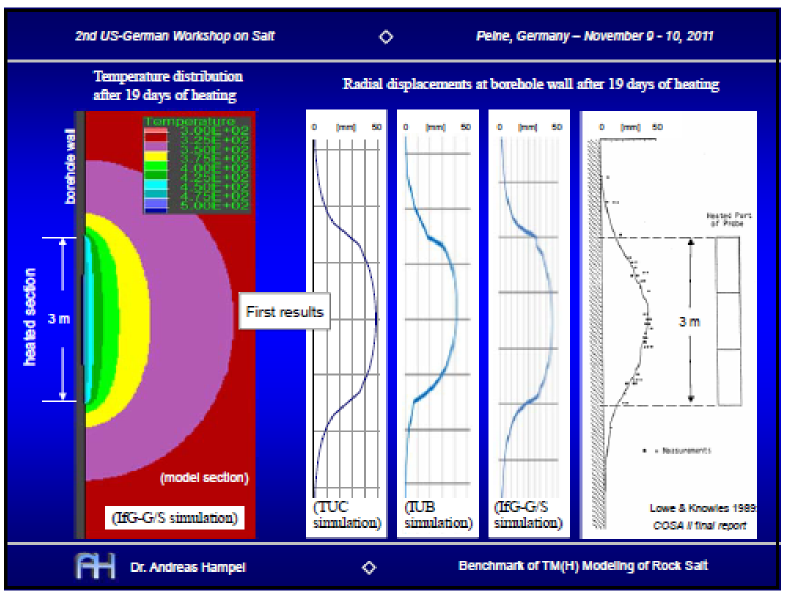
L.H. Vons, 1984: report ECN-84-35
J. Prij & A. de Ruiter, 1985: report ECN-85-31
M.J.S. Lowe & N.C. Knowles, 1989: *Final report of COSA II project*



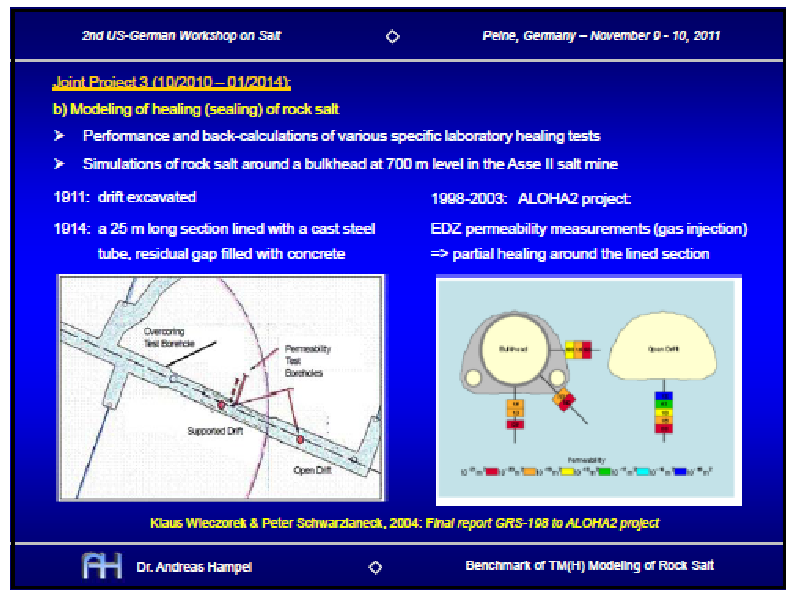
2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
a) Modeling of the thermo-mechanical behavior of rock salt
1. Determination of parameter values for Asse Na2β (Hauptsalz) with back-calculations of laboratory tests,
2. Fine-tuning of parameter values for steady-state creep with simulations of the isothermal free convergence (IFC), i.e. before the start of the heaters
chamber
750 m below ground level
Ø 31.5 cm
292 m
1050 m below ground level
IFC
T = 42 °C
σ_hyd = 24 MPa
First results
ECN measurement
IfG-Günther/Salzer
IfG-Minkley
Hampel (CDM)
radial displacement of borehole wall [m]
time [d]
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt



2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
a.2) Heated free convergence probe (HFCP): 19 days heating, 3 days cooling
(All simulations with model parameter values from IFC simulation)
chamber
750 m below ground level
231 m
HFCP I
Ø 31.5 cm
1050 m below ground level
temperature [°C]
heating time [d]
given temperature profile at borehole wall due to heaters
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt



2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Temperature distribution after 19 days of heating
Radial displacements at borehole wall after 19 days of heating
borehole wall
heated section
3 m
First results
(model section)
(IfG-G/S simulation)
(TUC simulation)
(IUB simulation)
(IfG-G/S simulation)
Lowe & Knowles 1989
COSA II final report
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt



2nd US-German Workshop on Salt
Peine, Germany – November 9 - 10, 2011
Joint Project 3 (10/2010 – 01/2014):
b) Modeling of healing (sealing) of rock salt
Performance and back-calculations of various specific laboratory healing tests
Simulations of rock salt around a bulkhead at 700 m level in the Asse II salt mine
1911: drift excavated
1914: a 25 m long section lined with a cast steel tube, residual gap filled with concrete
1998-2003: ALOHA2 project:
EDZ permeability measurements (gas injection)
=> partial healing around the lined section
Overcoring Test Borehole
Permeability Test Boreholes
Supported Drift
Open Drift
Klaus Wieczorek & Peter Schwarzianeck, 2004: Final report GRS-198 to ALOHA2 project
Dr. Andreas Hampel
Benchmark of TM(H) Modeling of Rock Salt

Conclusion

The partners' advanced geomechanical constitutive models for rock salt …

- … are based on different theoretical assumptions,
- … describe correctly and reliably the relevant deformation phenomena,
- … have to be adjusted to a specific salt type and location using reliable laboratory tests,
- … should be fine-tuned in addition by means of in-situ test data to increase precision,
- … are qualified for the performance of 3-D simulations of underground structures,
- … are validated tools for calculations of e. g.
  - the convergence of underground openings
  - the stress fields and the EDZ evolution around the openings
  - the porosity and permeability in the EDZ

  in good agreement with in-situ test data

Conclusion

The joint projects with the benchmark studies have yielded …

- … an approved tool for the check and validation of …
  - constitutive models,
  - procedures for the determination of salt type-specific parameter values,
  - procedures for the performance of numerical simulations,
- … many hints for the further development of the models and their implementations into numerical computer codes,
- … good basis for further collaboration on constitutive modeling, parameter determination, and performence of numerical simulations.

RESEARCH COLLABORATIONS IN (COMPUTATIONAL) GEO-MECHANICS

J. GUADALUPE ARGÜELLO

2ND US-GERMAN WORKSHOP ON SALT REPOSITORY RESEARCH, DESIGN, AND OPERATION

NOVEMBER 09-10, 2011

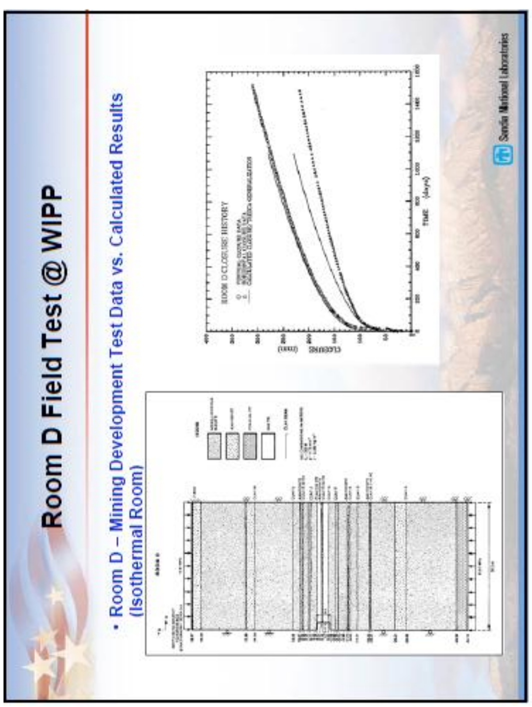
PEINE, GERMANY

ABSTRACT

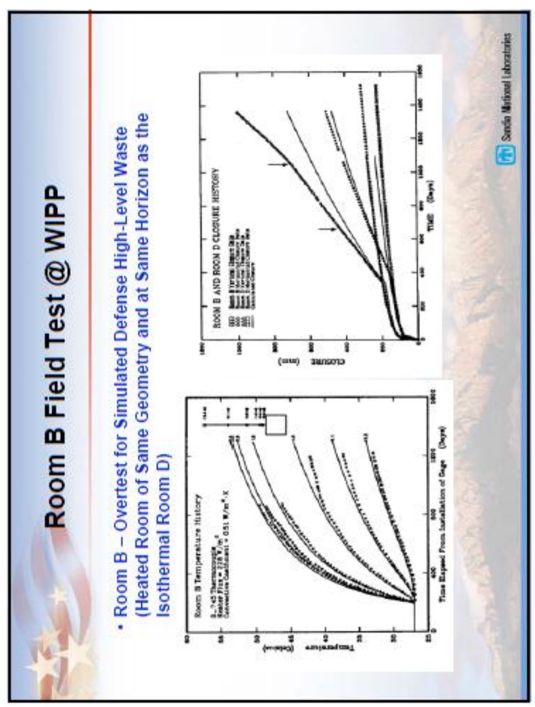
A brief overview of Sandia National Laboratories past geomechanics work in rock salt repositories is first presented, concentrating on the verification and validation (V&V) of the computational tools of the 80-90's timeframe. This validation of Sandia-developed tools against the various thermal-structural interactions (TSI) experimental rooms at the Waste Isolation Pilot Plant (WIPP) is reviewed. It is noted that one of the underground tests which appears to have never been validated against the computational tools of the time was Room H, the heated axisymmetric pillar test. It is offered up as a viable problem for a potential benchmarking exercise of current thermal-mechanical capability among the two countries.

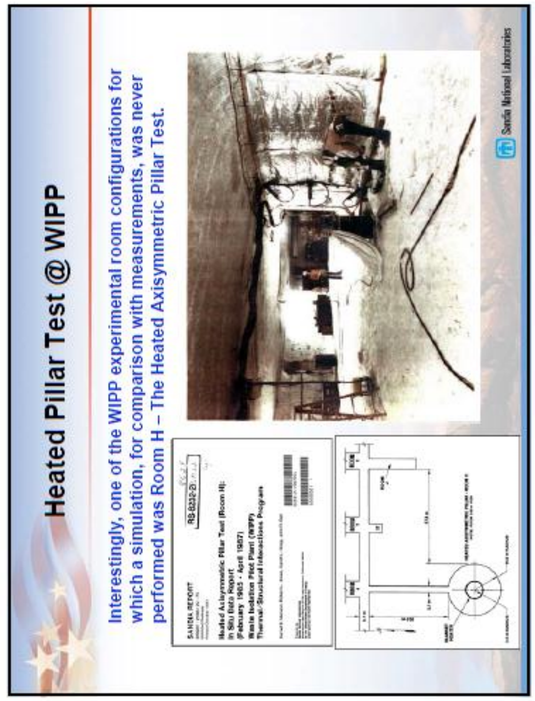
Since the 80's, there have been approximately 30 years of software and hardware advances. To take advantage of these advances, there is a next generation of coupled massively-parallel multi-physics capability being developed under a single computational framework at Sandia, known as SIERRA Mechanics. Sandia is developing this capability to support the Engineering Science mission, in general, and we are leveraging the capability to build the next generation of computing for coupled geomechanics simulations for a waste repository setting. An overview of SIERRA Mechanics is briefly presented. This is followed by a description and discussion of a specific demonstration problem of a coupled thermal-mechanical simulation recently performed to model a Generic Salt Repository for high level waste (HLW) using SIERRA mechanics and the Sandia-developed multi-mechanism deformation (MD) creep model. It is noted that constitutive modeling of salt is an important area of US-German collaboration.

A brief overview of a currently ongoing collaboration known as the "Joint Project on the Comparison of Constitutive Models for Rock Salt (III)" is then presented. The various target problems of this collaboration are reviewed and Sandia's modest efforts to-date on the project, due to budget constraints, are described and discussed. The WIPP TSI Room H, described above, is recommended as an additional target problem that both groups could also simulate for comparisons with each other and with the data under this Joint Project III collaboration.


Room D Field Test @ WIPP
• Room D – Mining Development Test Data vs. Calculated Results (Isothermal Room)
ROOM D CLOSURE HISTORY
CLOSURE (mm)
TIME (days)
Sandia National Laboratories


Additional Field Tests @ WIPP
Various other WIPP experimental configurations were also simulated for comparison with measurements*:
• Room G – Unheated Long Single Room
• Rooms A1-A3 – Heated Three-Room Complex with Overlapping Stress Fields (Early Closure of Mine-by)
• Room Q – Unheated Cylindrical Room
• Vertical Shaft V – Unheated Shaft at 612 m and 630 m Depth Locations
• Intermediate-scale Borehole Test (ISBT) – Unheated Borehole Located Through Room C1 and Room C2 Pillar
*Munson, D. E., "Constitutive Model of Creep in Rock Salt Applied to Underground Room Closure," Int. J. Rock Mech. Min. Sci., Vol. 34, No. 2, pp. 233-247, 1997.
Sandia National Laboratories


Room B Field Test @ WIPP
• Room B – Overtest for Simulated Defense High-Level Waste (Heated Room of Same Geometry and at Same Horizon as the Isothermal Room D)
Room B Temperature History
Temperature (Celsius)
Time Elapsed From Installation of Gage (Days)
ROOM B AND ROOM D CLOSURE HISTORY
CLOSURE (mm)
TIME (Days)
Sandia National Laboratories


Heated Pillar Test @ WIPP
Interestingly, one of the WIPP experimental room configurations for which a simulation, for comparison with measurements, was never performed was Room H – The Heated Axisymmetric Pillar Test.
SANDIA REPORT
Heated Axisymmetric Pillar Test (Room H): In Situ Data Report
Waste Isolation Pilot Plant (WIPP)
Thermal/Structural Interactions Program
Sandia National Laboratories

Current Collaboration

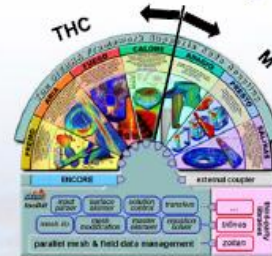
Next Generation of Analytical Tools – Coupled Multi-Physics

Sandia National Laboratories

SIERRA Mechanics

Present: State-of-the-Art integrates single physics codes to achieve coarse spatial and time scale simulation…

Future: SIERRA Mechanics leverages 10 years of ASC development providing:

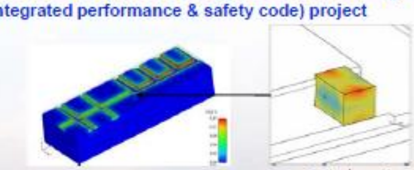


- Framework for coupled multi-physics simulations in a massively parallel environment
  - Scalability from 1 to thousands of processors on a variety of platforms
    - Launching point for fully integrated THCM coupling with adaptive solution control

Sandia National Laboratories

Next Generation of Coupled Simulations

- 30 years of software and hardware advances
- Sandia built a new generation of massively-parallel multi-physics capabilities into a single computational framework
- These tools simulate coupled geomechanics for a waste repository setting
  - LDRD (laboratory-directly research & development)
  - UFD (used fuels disposition campaign)
  - NEAMS Waste IPSC (nuclear energy advanced modeling & simulation waste integrated performance & safety code) project



Sandia National Laboratories

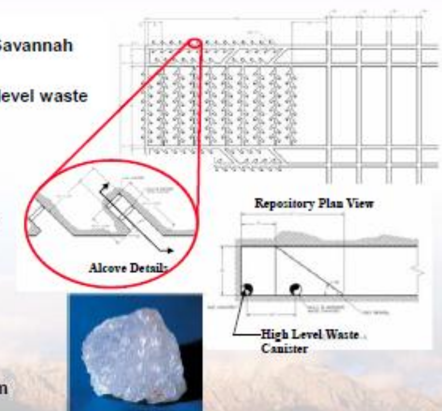
Sample Demonstration: Coupled Thermal-Mechanical Simulation of Generic Salt Repository

Sample Geometry:

- Configuration based on a 2008 Savannah River study
- Vitrified borosilicate glass high level waste canister with output 8.4 kW

Technical challenges:

- High Thermal Gradients
- Temperature dependent material properties
- Large Deformation Salt Creep behavior
- Contact modeling with heat conduction and load transfer
- Long duration simulation to room closure



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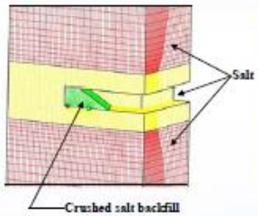
Sierra Mechanics Thermal-Mechanical Simulation of Generic Salt Repository



- Three-dimensional fully coupled thermal/mechanical analysis
- Massively Parallel Calculation - 96 processors
- Dissimilar meshes and domains for thermal and structural mechanics
- Contact surfaces used for both thermal and structural problems

Thermal Analysis Features:

- 904736 nodes / 864927 elements
- Contact surfaces used to accommodate heat conduction between contacting surfaces (alcove and haulage way)
- Re-computation of radiation view factors for deforming heated room surfaces

Structural Analysis Features:

- Quasistatic analysis with 294698 nodes / 279537 elements
- Large deformation, large strain formulation
- Nonlinear MD and power law creep models for salt
- Volumetric compaction model for the crushed salt
- Contact surfaces defined to allow arbitrary roof, rib, and floor contact
- Temperature dependent material properties

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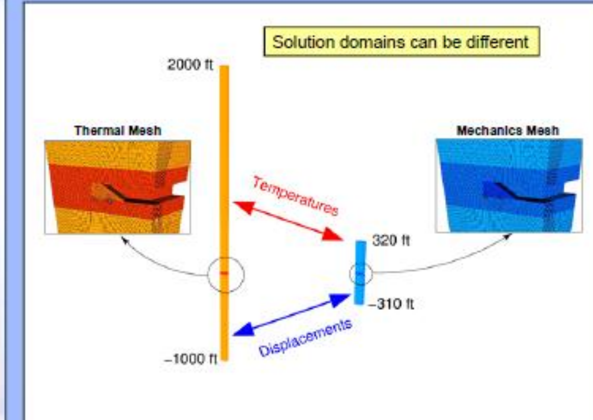
Schematic of Aria-to-Adagio Data Transfer Using Arpeggio



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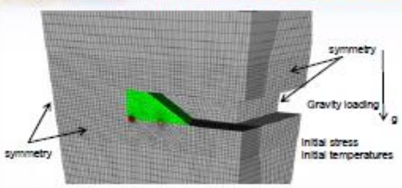
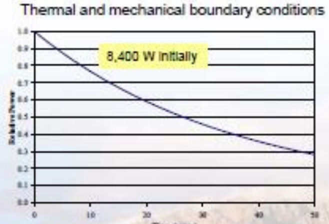
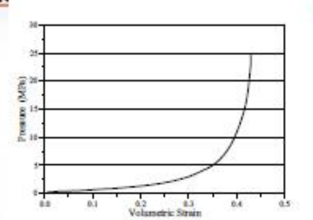
Generic Salt HLW Reposit... Problem Definition



Thermal and mechanical boundary conditions



Normalized power curve for HLW waste canister



Experimental pressure-volume strain curve for crushed salt at 200 C

Temperature dependent salt conductivity:

$$\lambda_{salt}(T) = \lambda_{300}\left(\frac{300}{T}\right)^{\gamma}$$

where:
λ_{300} = material constant, 5.4 [W/m/K]
γ = material constant, 1.14
T = temperature [K]

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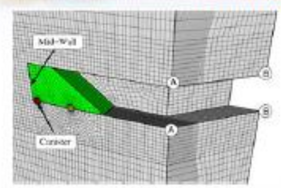
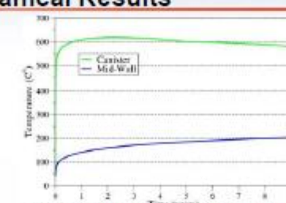
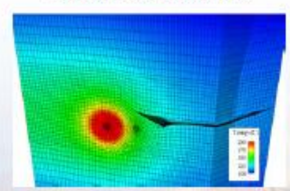
Thermal-Mechanical Results



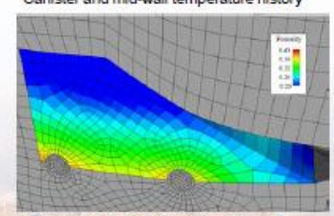
Output location definitions



Canister and mid-wall temperature history



Temperature contours at closure



Deformed shape of crushed salt backfill with contours of porosity

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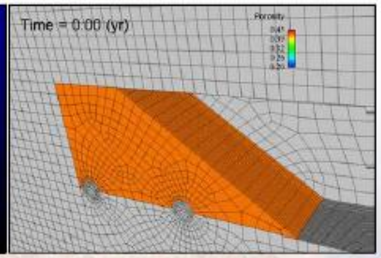
Closing Remarks and Observations on GSR

- Computational effort is in contact algorithm and integration of constitutive models
- Full MD model is more expensive than the PLC by a factor of 3 (using 2nd mechanism of the MD only for the PLC)
- Stand alone PLC model in Adagio is 3 times slower than using the 2nd mechanism in the MD model to represent PLC behavior (difference due to method of integration)

Repository Temperature Contours



Crushed Salt Backfill Porosity Contours

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Current Collaboration

Joint Project on the Comparison of Constitutive Models for Rock Salt

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Modeling Salt Behavior Correctly

- Salt constitutive modeling = important collaboration
- Need to assess the international capabilities
- Multi-mechanism Deformation (MD) model is currently in use
- Identify best features and deficiencies
- Examine potential development of our model & evaluate other existing models

Multi-mechanism deformation model:

$$\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i}$$

$$\dot{\varepsilon}_{ij}^{c} = F\,\dot{\varepsilon}_s \frac{\partial \bar{\sigma}}{\partial \sigma_{ij}}$$

$$F = \begin{cases} e^{\Delta[1-\zeta/\varepsilon_t^*]^2}, & \zeta < \varepsilon_t^* \\ 1 & \zeta = \varepsilon_t^* \\ e^{-\delta[1-\zeta/\varepsilon_t^*]^2} & \zeta > \varepsilon_t^* \end{cases}$$

$$\dot{\zeta} = (F-1)\dot{\varepsilon}_s$$

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Scope and Objectives

- Collaborate on advanced geomechanical constitutive models
- Salt specific parameter values and performance of numerical simulations
- Check the ability of the models to describe correctly the relevant deformation phenomena in rock salt under various influences
- Increase confidence in the results of numerical simulations and enhance the acceptance of the results
- Explore possibilities for the further development and improvement of the models

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Participants in Current Joint Project III

- The German project partners are each represented by:
  - Dr. Andreas Hampel, Scientific Consultant
  - Dr. Wolfgang Minkley, Institut für Gebirgsmechanik GmbH
  - Dr. Alexandra Pudewills, Institut für Nukleare Entsorgung, Karlsruher Institut für Technologie
  - Prof. Dr. Reinhard Rokahr, Institut für Unterirdisches Bauen, Leibniz Universität Hannover
  - Prof. Dr. Karl-Heinz Lux, Lehrstuhl für Deponietechnik und Geomechanik, Technische Universität Clausthal
  - Prof. Dr. Joachim Stahlmann, Institut für Grundbau und Bodenmechanik, Technische Universität Braunschweig
- Sandia National Laboratories

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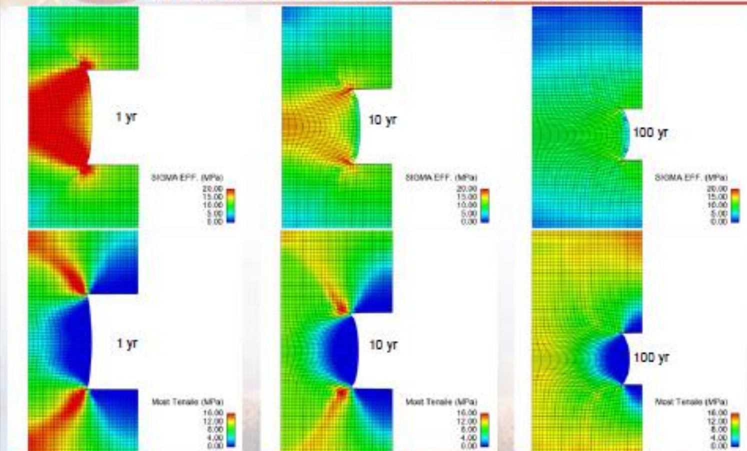
Requested Simulation from Joint Project I Room-Pillar Model Problem (12 MPa) – Fringe Plots



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Overview of Previous Joint Projects I & II (Prior to Sandia Participation)

Joint Project I (April 01, 2004 – November 30, 2006):

- Document the advanced geomechanical constitutive models of the project partners,
- Check & compare
  - the determination of salt type-specific parameter values,
  - the modeling of the relevant deformation phenomena

  with simulations of laboratory tests and of simple but typical underground structures.

Joint Project II (August 01, 2007 – July 31, 2010):

- Check & compare the suitability of the models for the simulation of a 3-D section of a real mine in rock salt. (Comparisons of the simulation results with each other and with in-situ data.)

Focus: Isothermal behavior and damage of salt

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Overview of Joint Project III – Current Project

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

Joint Project III (Oct. 01, 2010 – Sept. 30, 2013 (general) / Jan. 31,2014 (Hampel)):

- Check & compare the suitability of the models for the simulation of the thermo-mechanical behavior and damage reduction (sealing/healing) of rock salt (Comparisons of the simulation results with each other and with in-situ data.)

Focus: Thermo-Mechanical behavior and sealing/healing of salt

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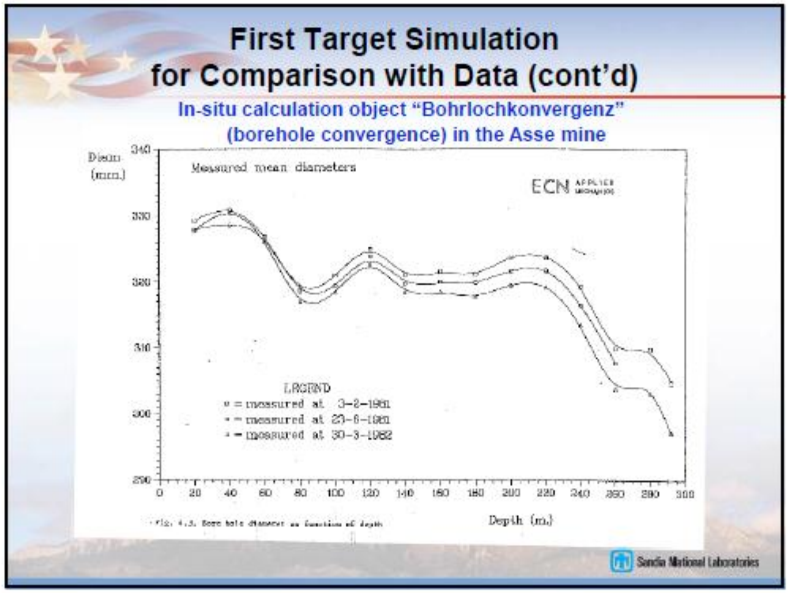
First Target Simulation
for Comparison with Data (cont'd)
In-situ calculation object "Bohrlochkonvergenz"
(borehole convergence) in the Asse mine
Diam
(mm)
Measured mean diameters
ECN
LEGEND
= measured at 3-2-1981
= measured at 23-6-1981
= measured at 30-3-1982
Depth (m)
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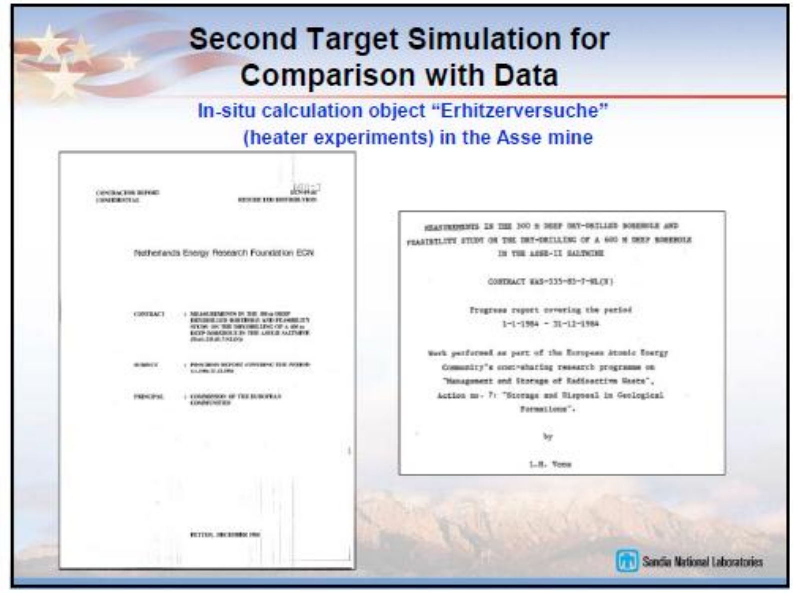
Second Target Simulation for
Comparison with Data
In-situ calculation object "Erhitzerversuche"
(heater experiments) in the Asse mine
Netherlands Energy Research Foundation ECN
Progress report covering the period
1-1-1984 - 31-12-1984
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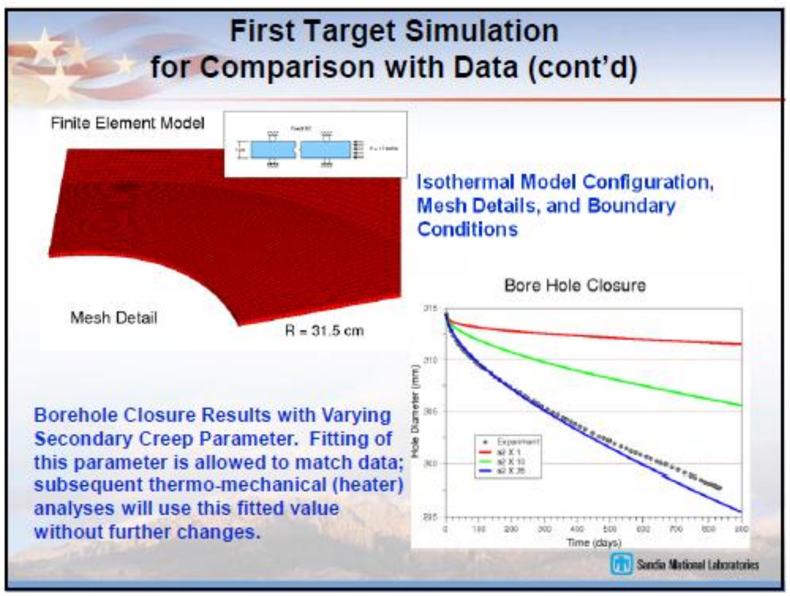
First Target Simulation
for Comparison with Data (cont'd)
Finite Element Model
Mesh Detail
R = 31.5 cm
Isothermal Model Configuration,
Mesh Details, and Boundary
Conditions
Bore Hole Closure
Hole Diameter (mm)
Time (days)
Experiment
a2 X 1
a2 X 10
a2 X 35
Borehole Closure Results with Varying
Secondary Creep Parameter. Fitting of
this parameter is allowed to match data;
subsequent thermo-mechanical (heater)
analyses will use this fitted value
without further changes.
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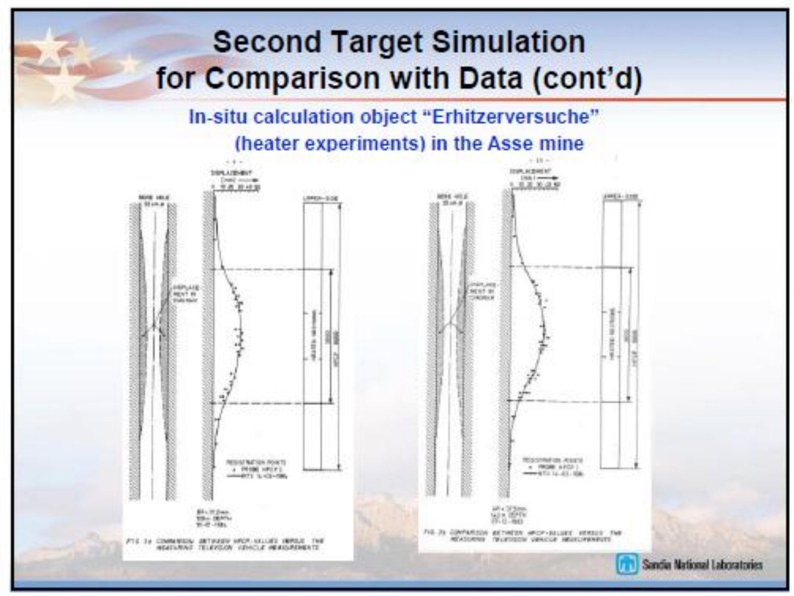
Second Target Simulation
for Comparison with Data (cont'd)
In-situ calculation object "Erhitzerversuche"
(heater experiments) in the Asse mine
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Session 5

IDENTIFICATION AND APPLICABILITY OF ANALOGUES FOR A SAFETY CASE FOR A HLW REPOSITORY IN ROCK SALT

U. Noseck, J. Wolf, A. Meleshyn

GRS, Theodor-Heuss-Str. 4, D-38122 Braunschweig, Germany

In Germany, a systematic review of the situation for final disposal of HLW in salt formations based on the state of the art in science and technology had been carried out within the R&D project ISIBEL. Following this review a new concept for a safety assessment is developed, in which the demonstration of the safe containment of the waste requires showing the integrity of the geological and geotechnical barriers. This concept is now applied and to some extent modified for the Preliminary Safety Analysis Gorleben (VSG).

In this context and based on the advanced state of the exploration results at Gorleben site, the role of analogues for a HLW repository in rock salt is currently re-evaluated in Germany. Particularly, it is elaborated how analogues can be used in the safety case to underpin the integrity of the geological and geotechnical barriers. Additionally – although of less relevance for the new safety concept – analogues for the assessment of release scenarios are considered. This compilation and evaluation comprises existing analogue studies but also the identification of FEPs, for which analogues would be suitable but are not available or at least not documented yet.

With respect to the integrity of the rock salt arguments from natural analogues can be used to underpin the long-term stability of salt rocks, the integrity against subrosion and diapirism, the impermeability of rock salt, namely that no pathways for fluids through the geological formation exist, as well as the mechanical and thermal stability of the rock formation. For each of these aspects examples from analogue studies are given.

For the integrity of the geotechnical barriers important aspects are the hydraulic resistance of containment providing barriers for shaft and drift sealings including the EDZ, the long-term stability of materials used for these barriers like salt concrete or bentonite as well as the compaction behaviour of salt grit backfill. For the geotechnical barriers only few analogues are identified so far. However, technical analogues like the bulkhead drift in the Asse mine showing the sealing of an EDZ around a lined drift after 85 years with well-defined initial and boundary conditions might be used in a more quantitative way, e.g. for model testing.

Concerning analogues for the assessment of release scenarios, degradation of glass and UO_2, retardation/precipitation of radionuclides in the near field under saline conditions, and retardation of radionuclides in the far field, i.e. the behavior in tertiary and quaternary sediment formations as found in the overburden of salt domes in Northern Germany are relevant aspects.

On the basis of this compilation and evaluation of existing analogue studies some issues of further interest were identified. This concerns the evaluation of information from other salt formations in the world with respect to their integrity. The identification and description of more analogues, which show that potential pathways at interfaces between rock salt and more competent formations like the main anhydrite are not hydraulically connected through the salt formation, because the anhydrite bands were broken by mechanical stress in the geological past, would be very beneficial. Further studies about the formation of temporally open fractures in rock salt enabling a limited inflow of brine, oil and gas should be evaluated to better understand

such events. Additionally, a further evaluation of studies on gas inclusions is recommended to e.g. achieve a better understanding of the origin of inclusions with high content of carbohydrates. Finally, exploration studies from oil industry where rock salt acted as trap might be used to further strengthen the argument of the impermeability of the formation are desired.
The current status of the work is described in *Wolf et al. 2011*.

Wolf, J.; Noseck , U.; Meleshyn, A. (2011): Anwendbarkeit von Natürlichen Analoga für den Langzeitsicherheitsnachweis für ein HAW-Endlager im Salzgestein. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig. To be published.

Identification and applicability of analogues for a safety case for a HLW repository in rock salt

U. Noseck, J. Wolf, A. Meleshyn

2nd US-German Workshop on Salt Repository Research, Design and Operation,
November 9-10, 2011 Peine, Gemany

Background and objectives

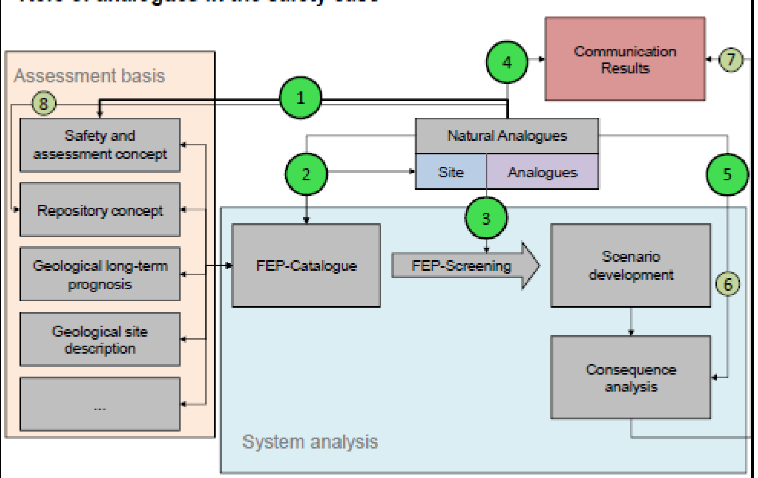
Analogue studies performed in Germany since ~1990

Now: Start of a systematic compilation and evaluation of how analogues can be used for the safety case of HLW/SF repository in rock salt

- How can analogues contribute to the assessment of safety?
  - Existing analogues
  - Analogues not identified (or not described in a useful way so far)
    → Identification of future work on analogues

- Focus on the safety and assessment concept from new developments in Germany
  - ISIBEL project, (VSG)
  - long-term safe containment by assessment of the geological and geotechnical barriers

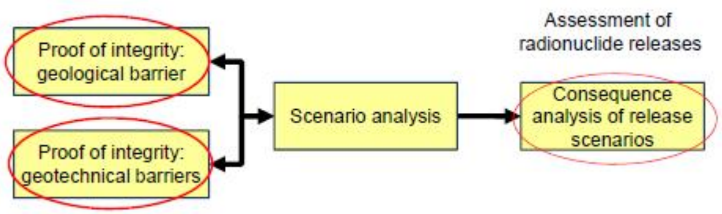
Role of analogues in the safety case



Role of analogues in the safety case

1. Underpinning the concept of deep geological disposal, e.g. through observations in U ore deposits
2. Identification and description of FEPs occurring at a disposal site, e.g. subrosion rate from analysis of the cap rock
3. Evaluation of the relevance of these FEPs in scenario development, e.g. exclusion of criticality
4. Explanation of the safety concept and relevant FEPs to the public
5. Model development: processes occurring in analogue systems, which are not relevant, which are dominating, spatial and temporal scale of these processes
6. Qualification of models and data, i.e. do PA models and databases describe the PA relevant processes observed in nature (e.g. BPM Studies)
7. Presentation and underpinning of FEPs, which positively affect Long-term safety, but not used in consequence analysis (Reserve-FEPs)
8. Further development of special options (use of new materials like Synrock)

Methodological approach of the post-closure safety case



Integrity of the geological barrier

Important aspects

- Long-term stability of salt rocks
- Probability of neotectonic events
- Subrosion and diapirism
- Pathways through the geological formation
- Mechanical stability of the rock formation
- Thermal stability of the rock formation
  - high temperatures (waste)
  - low temperatures (glacials)

Include „self analogues“

- If concrete statements on expected processes in disposal system are derived
- Gorleben as reference site

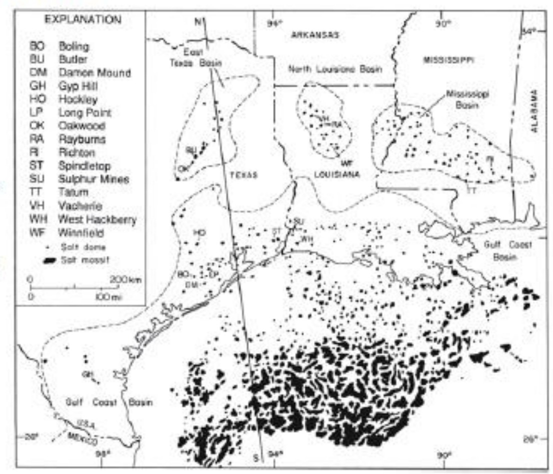
Long-term stability of salt formations

- In Northern Germany more than 200 salt formations
- Long-term existence of „water soluble“ salt (250 Mio y)
- Several glacials
  - area covered with >1000m thick glaciers
  - formation of deep channels

Salt formations world wide

Salt formations in other areas

- Well investigated, when used as oil reservoirs
- Transferability to be shown
- Worth to look at different conditions, e.g. below the ocean (Gulf of Mexico, Persia, Northern sea)



Subrosion and diapirism

- Salt becomes dissolved below surface from top of the salt dome.
- Low solubility minerals (anhydride or clayey material) are enriched → formation of the cap rock of the salt dome
- Crucial to exclude subrosion down to repository level
- Several influence factors (water chemistry, depth, diapirism, permeability, …)

Time frame	Geological situation	Subrosion rate [mm/a]
Malm-Cretaceous	Diapir stage, Cretaceous transgression	high
Tertiary	Postdiapir stage, deposition of covering layers	0.005 – 0.015
Quarternary, Pre-Elster	Postdiapir stage, Erosion of covering layers	0.1 – 0.2
Elster and Saale glacial	Postdiapir stage, glacial, formation of channels	0.2 – 0.4
Eem interglacial until recent	Postdiapir stage	0.01 – 0.05

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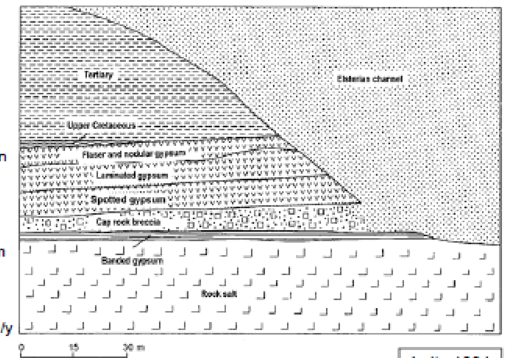
Subrosion: Example from Gorleben site

Detailed investigation of the cap rock
- 49 boreholes
- Dissolution of rock salt
- Residues of gypsum layers remain
  → Age decrease with depth
- Cap rock breccia during Elsterian glaciation (300 – 400 ky)

Estimation of subrosion rates from
- Thickness of the banded gypsum
- Content of gypsum and low soluble phases in the rock salt

Average subrosion rates: 0.04 mm/y



Jaritz 1994

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Water pathways in the geological barrier

German safety requirements (BMU 2010): It has to be shown that
- *the formation of secondary water pathways, which might lead to in- or outflow of evtl. contaminated brines within the isolating rock zone can be excluded, and*
- *Any pore water that may be present in the isolating rock zone does not participate in the hydrogeological cycle outside of the isolating rock zone as defined by water legislation.*

Arguments that no fluids from adjacent formations intruded into the salt formation can be derived from Natural Analogues:
- Mechanical behaviour of rock salt
- Chemical composition and isotope content of fluid inclusions (brines and gases)
- Trace element profiles (Br, Rb) in salt rocks

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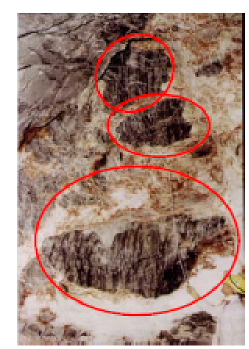
Behaviour of competent formations

Rock salt as incompetent material: Long-term unsealed fractures in the pure material can be excluded

Areas with high fraction of competent rocks more crucial
- Fractures at interfaces of competent / incompetent layers
- For Zechstein rock salt → main anhydrite most relevant

Competent layers embedded in incompetent material break under mechanical stress
- Several lab investigations
- Results from Gorleben exploration area

→ Inhibit continuous transport pathways



Evaluation of literature / Investigation of other sites to be done
- Investigation of Ara salt in Oman just published

Bornemann 2007
Foto: Bauer, DBE

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Brine inclusions

Identification, whether an interaction of formation water from overlying or adjacent rock formations occurred

At Gorleben site

- Larger fluid and gas inclusions are mainly found in anhydrite dominated rocks
- under lithostatic pressure (exclude hydraulic connection to overburden aquifers)
- Small fluid inclusions in halite crystals
  - detailed studies from *Herrmann et al.* at samples from different depths
  - two groups of solutions
    - NaCl dominated, low density and low bromide content
      - → impacted by re-crystallization in contact with unsaturated solutions
      - → found in upper 80 m of salt dome → glacial subrosion
    - $MgCl_2$ dominated, higher density and higher bromide content
      - → from late evaporation state (not influenced by formation water for >250 Mio years)
      - → found in 600 -1600 m depth

Gas inclusions

Results from Gorleben site

- Major fraction of gases originate from time of salt layer formation
- Only low migration of gases, limited to area of the main anhydrite during salt uplift

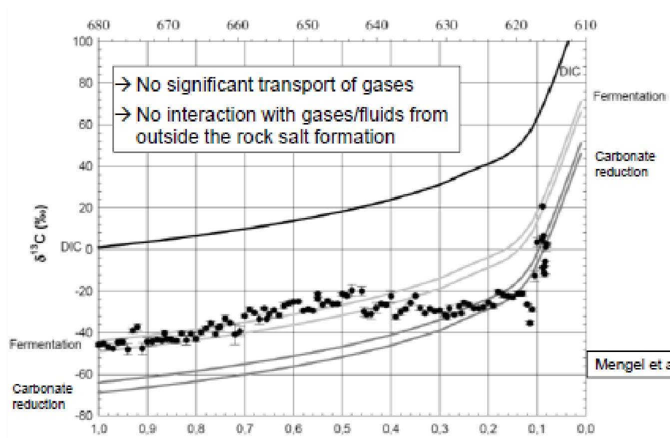
Example from salt formation at Zielitz site

- Analysis of the isotopes δ^2H, $\delta^{13}C$ in naturally occurring gases
- Distinction between inter- and intra-crystalline gases
- Identification of the origin of natural gases in evaporites
- Understanding of the migration behavior in the long term

$\delta^{13}C_{CH4}$ profile is characterized by

- Low values -45 ‰ to -50 ‰ in the lower halite
- Increase to +21 ‰ in the potash series at the top of the salt dome

Gas inclusions



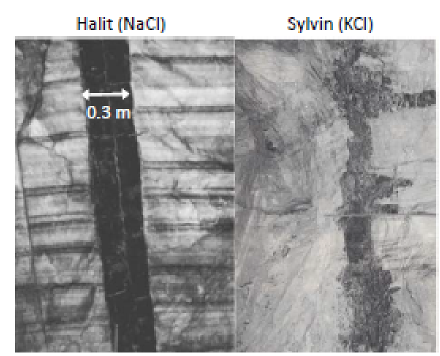
→ No significant transport of gases
→ No interaction with gases/fluids from outside the rock salt formation

Mengel et al. 2006

Thermal stability of rock salt

High temperatures

- Maximum temperature 200°C
- Investigations of heater experiments available
- Basalt intrusions in rock salt as analogues
- Not observed at Gorleben
- Investigated e.g. at Werra-Fulda deposits
  - material reaction and transport occurred
  - But restricted to few cm
  - much higher temperature
  - faster cooling



Knipping 1994

Low temperatures
→ cryogenic fractures (salt domes around Hanover)
→ filled by minerals
→ limited to upper 300 m of salt domes

Integrity of geotechnical barriers

Important aspects

- Hydraulic resistance of containment providing barriers
  - Shaft and drift sealings
  - Hydraulic resistance provided by the whole system (including EDZ)
- Long-term stability of materials used for these barriers
  - Salt concrete, bentonite,
  - Uncertainties in geochemical conditions of the inflowing solutions
- Compaction behaviour of salt grit backfill
  - Question of residual porosity

Hydraulic resistance of containment providing barriers

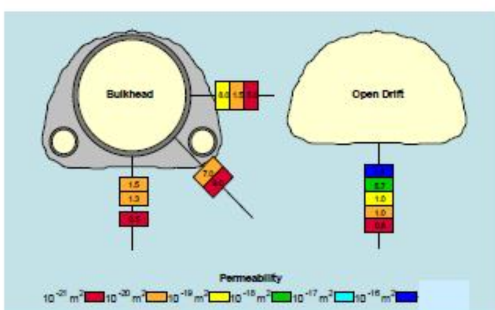
Self sealing of EDZ: Bulkhead drift in Asse mine

- 25 m long drift section equipped with liner of cast steel and residual void backfilled with concrete
- Investigation of permeability distribution around the drift (EDZ) and correlation between permeability and stress state in the long term

Hydraulic resistance of containment providing barriers

Self sealing of EDZ

Permeability distribution around the bulkhead and below the open drift



Hydraulic resistance of containment providing barriers

Permeability distribution around an open and the bulkhead drift after 85 years (measured by gas injection testing)

- Typical EDZ still present around the open drift
  - 1.5 m extension
  - Max. permeabilities: $2 \cdot 10^{-16}$ m² (measured below the drift)
- EDZ around bulkhead drift sealed to some extent
  - Max. permeabilities <10^{-18} m² (~10^{-20} m² below the drift)
  - Microstructural investigations: microfractures closed but not disappeared

Decrease of permeability at least by more than two orders of magnitude within 85 years

- Dry rock salt
- Rock temperature

Compaction behaviour of rock salt

Pilot study
- Characterization and definition of criteria for object selection, e.g.
- Aim: find samples with significant reduction of porosity (40% □ 10%)
- Geotechnical requirements: representative material, knowledge about initial state and history
- Model calculations: Kind of salt dome (no anhydrite veins: reduce convergence), depth (pressure, temperature), moisture content
- → suitable objects identified

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

Natural analogues for release scenarios

Stability of the waste matrix
- Behaviour of basaltic glasses in saline environment
- Behaviour of UO_2

Retardation of radionuclides in the near field (saline conditions)
- Distribution of trace elements in basaltic glass

Retardation of radionuclides in the far field
- Behaviour of radionuclides in tertiary and quaternary sediments
- Derivation of In-situ K_d-values from natural element distributions in sediments from the overburden (Gorleben, Morsleben)

Analogues for the integrity of the geological barrier

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

Outlook

Work to be continued
- Further evaluation of literature
- Evaluation of information from other salt formations
- Investigate topics with lacking knowledge / divergent opinions / new results
  - Broken competent formations
    - Hydraulic conductivity (3D profiles necessary)
    - Investigation in other salt domes
  - Further evaluation of work on gas inclusions
    - Origin of inclusions with high content of carbohydrates
  - Formation of temporally open fractures in rock salt and inflow of brine, oil, gas

- Identification of further analogues, e.g.
  - exploration studies from oil industry – rock salt as trap
  - Corrosion of iron under low water vapor pressures

Worse and Worst Case Analogues for Geologic Isolation of Heat-Generating Waste

ABSTRACT

Norbert T. Rempe, Carlsbad, New Mexico, USA
rempent@yahoo.com

One of several largely unexamined assumptions in geologic isolation of radioactive waste is that heat-generating waste presents a special threat that must be addressed by detailed and comprehensive investigations consuming enormous time and funds. More than half a century of international effort pursuing this path has yet to succeed with the operation of a repository for such waste.

Worse and worst case analogues, both natural and anthropogenic, present a more efficient approach to this issue. If analogues demonstrate beyond reasonable doubt that heat similar to or in excess of that generated by waste has not compromised the isolation capability of a host rock, then an outer safety envelope is established inside of which further study may be of continuing academic interest, but cannot be justified from the perspectives of practical safety, reasonable assurance of long-term performance, or fiscal prudence.

Deep wells produce toxic and combustible fluids (hydrocarbons) from >200°C hot reservoirs that have isolated these fluids for hundreds of millions of years.[1] The surface temperature of used fuel canisters, by comparison, may range from ~140 to ~240°C for <100 years.[2]
Fossil hydrothermal systems indicate that mineral alteration resulting from the flow of hot fluids through fractures extends only a few centimeters from the fracture wall into the matrix.[3]

Igneous intrusives and underground nuclear detonations provide extreme samples of upper bounding analogues. Contact metamorphic aureoles near igneous dikes, solidified from magma at original temperatures between 800 and 1 200°C, rarely extend further laterally than several centimeters to a few meters. Rock salt adjacent to dikes remains impermeable even to gas for at least tens of millions of years as demonstrated by pockets of CO_2 under high pressure in German and U.S. potash mines. Radionuclides have for at least 50 years demonstrably not migrated from many cavities created by underground nuclear detonations.[4]

The conclusion is therefore inescapable: Observations of natural and engineered analogues provide sufficient confidence that geologic isolation of heat-generating radioactive waste will have negligible effects on the confinement capability of the host rock.

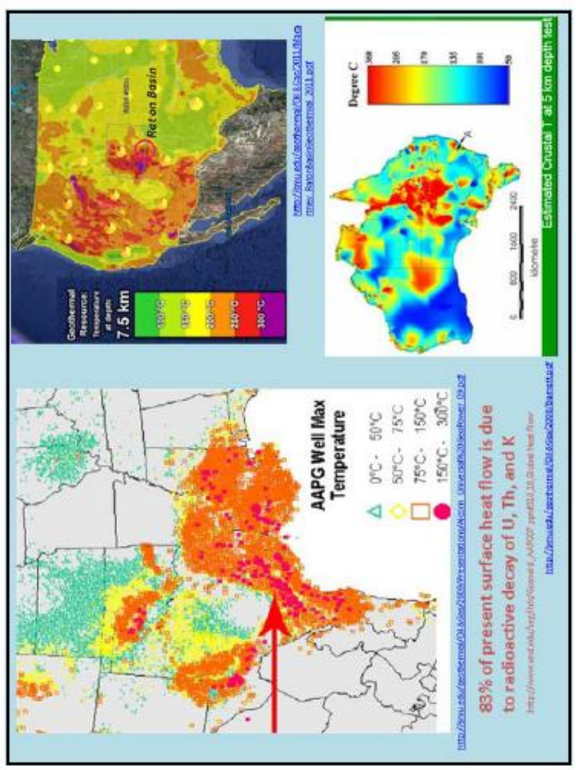
1. B. Borak and G.M. Friedman, "Textures of Sandstones and Carbonate Rocks in the World's Deepest Wells (in excess of 30,000 ft. or 9.1 km): Anadarko Basin, Oklahoma," *Sedimentary Geology*, **29**, 133-151 (1981).
2. P.V. Brady et al., Deep Borehole Disposal of High-Level Radioactive Waste, Sandia Report SAND2009-4401 (2009).
3. A.M. Simmons and J.S. Stuckless, Analogues to Features and Processes of a High-Level Radioactive Waste Repository Proposed for Yucca Mountain, Nevada, USGS Prof. Paper 1779 (2010). http://pubs.usgs.gov/pp/1779/pdf/PP1779.pdf

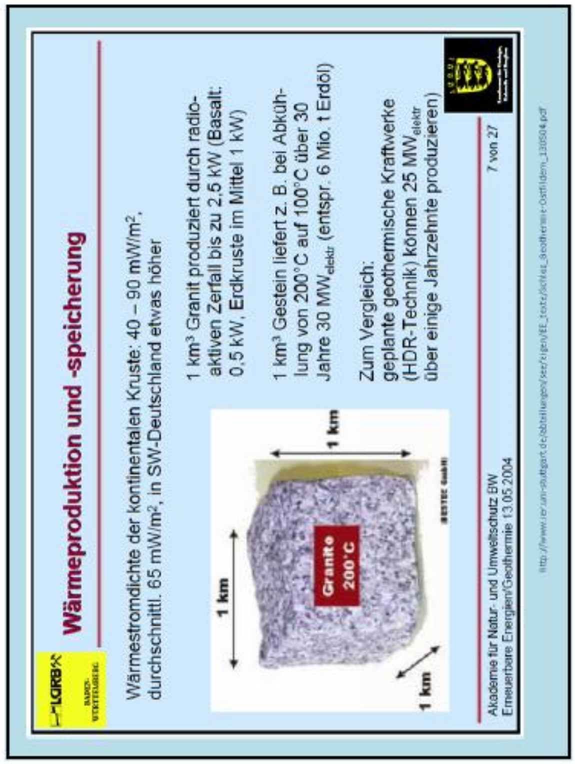
4. N.T. Rempe, Engineered and Natural New Mexico Analogues for Geologic Isolation of Heat Generating Waste in Rock Salt, Proc. High-Level Waste Management Conference, Albuquerque, NM (2011).

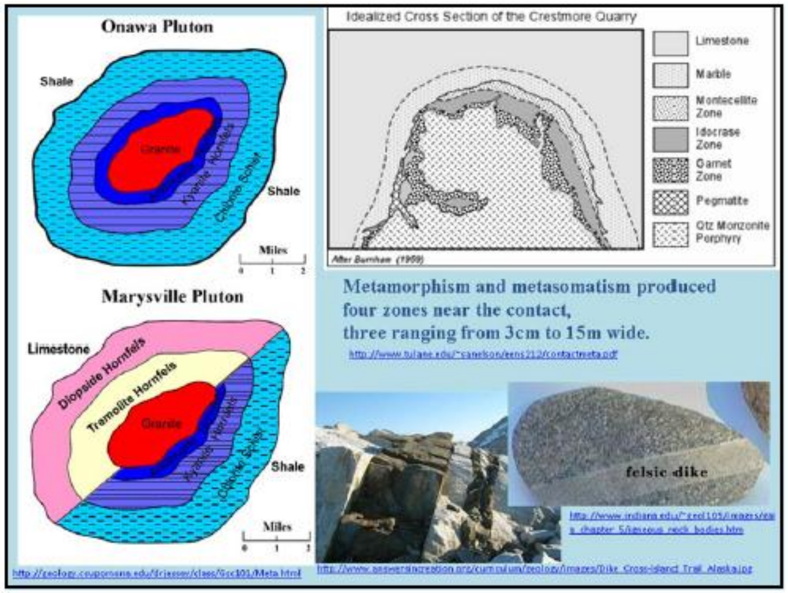
ng(o)3

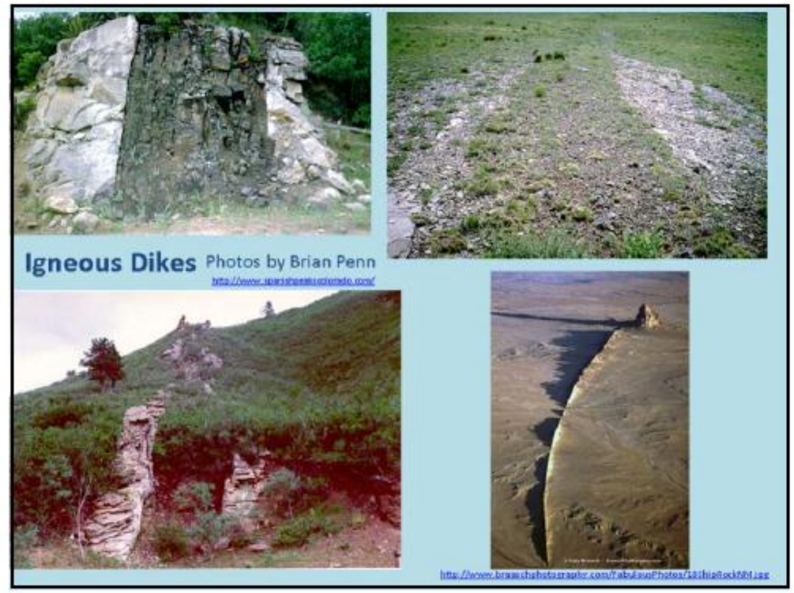

Worse and Worst Case Analogues for Geologic Isolation of Heat-Generating Waste
Norbert T. Rempe, Carlsbad, NM, USA
rempent@yahoo.com
ng(o)3

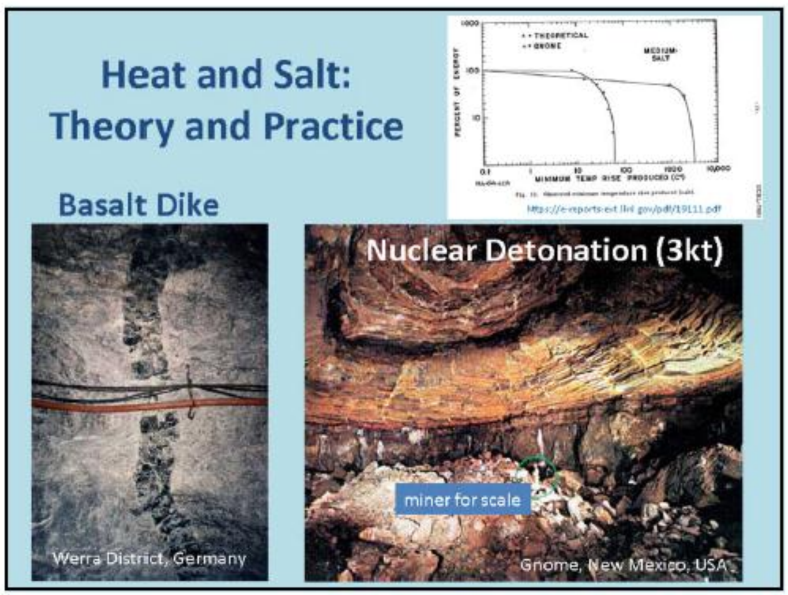

ὁ δὲ ἀνεξέταστος βίος οὐ βιωτὸς ἀνθρώπῳ (Socrates)
the unexamined life is not worth living (for a proper human being)
Common unexamined assumptions in radioactive waste sequestration:
The fascinating impressiveness of rigorous mathematical analysis, with its atmosphere of precision and elegance, should not blind us to the defects of the premises that condition the whole process (T. C. Chamberlin, 1899)
Liquid waste must be solidified before geologic disposal
New excavations are better than old mines
Known mineral resource areas should be avoided
Radioactivity is more insidious than chemical toxicity
Heat generating waste presents special threats
We must understand everything "perfectly"
down below the yocto (10-24) scale
up above the nth dimension
before deciding to do anything
Your system is perfectly designed to give you the results you're getting
(W. Edwards Deming)
ng(o)3

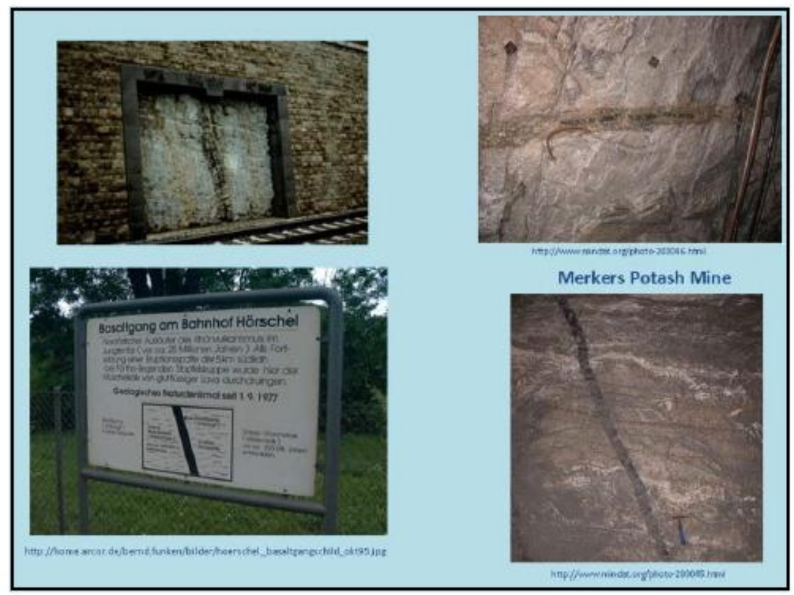

AAPG Well Max Temperature
0°C - 50°C
50°C - 75°C
75°C - 150°C
150°C - 300°C
83% of present surface heat flow is due to radioactive decay of U, Th, and K
Geothermal Resource: Temperature at depth
7.5 km
Raton Basin
Degree C
Estimated Crustal T at 5 km depth test


Wärmeproduktion und -speicherung
Wärmestromdichte der kontinentalen Kruste: 40 – 90 mW/m², durchschnittl. 65 mW/m², in SW-Deutschland etwas höher
1 km³ Granit produziert durch radioaktiven Zerfall bis zu 2,5 kW (Basalt: 0,5 kW, Erdkruste im Mittel 1 kW)
1 km³ Gestein liefert z. B. bei Abkühlung von 200°C auf 100°C über 30 Jahre 30 MWelektr (entspr. 6 Mio. t Erdöl)
Zum Vergleich:
geplante geothermische Kraftwerke (HDR-Technik) können 25 MWelektr über einige Jahrzehnte produzieren)
1 km
1 km
1 km
Granite 200°C
Akademie für Natur- und Umweltschutz BW
Erneuerbare Energien/Geothermie 13.05.2004
7 von 27

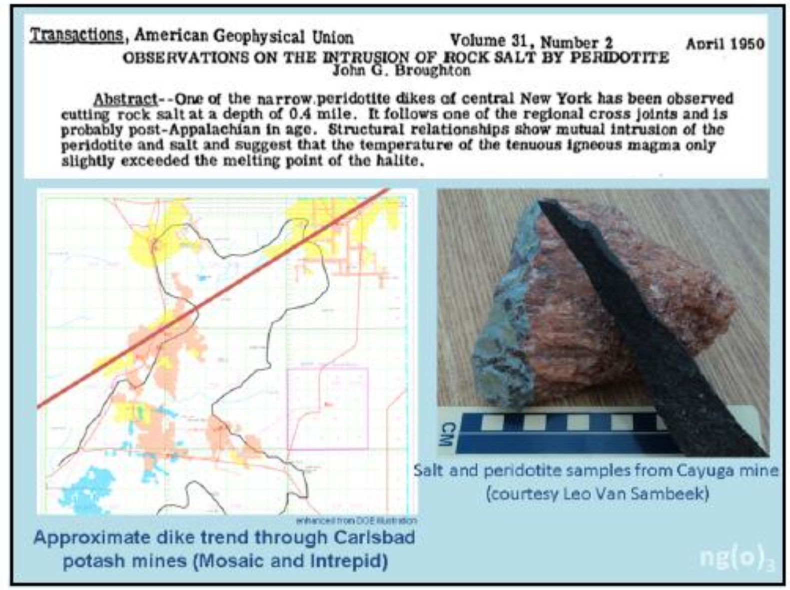

Onawa Pluton
Shale
Granite
Kyanite Hornfels
Chlorite Schist
Shale
Miles
Marysville Pluton
Limestone
Diopside Hornfels
Tremolite Hornfels
Granite
Shale
Miles
Idealized Cross Section of the Crestmore Quarry
Limestone
Marble
Montecellite Zone
Idocrase Zone
Garnet Zone
Pegmatite
Qtz Monzonite Porphyry
After Burnham (1959)
Metamorphism and metasomatism produced
four zones near the contact,
three ranging from 3cm to 15m wide.
felsic dike


Igneous Dikes Photos by Brian Penn


Heat and Salt:
Theory and Practice
Basalt Dike
THEORETICAL
GNOME
MEDIUM-SALT
PERCENT OF ENERGY
MINIMUM TEMP RISE PRODUCED (C°)
Nuclear Detonation (3kt)
miner for scale
Werra District, Germany
Gnome, New Mexico, USA

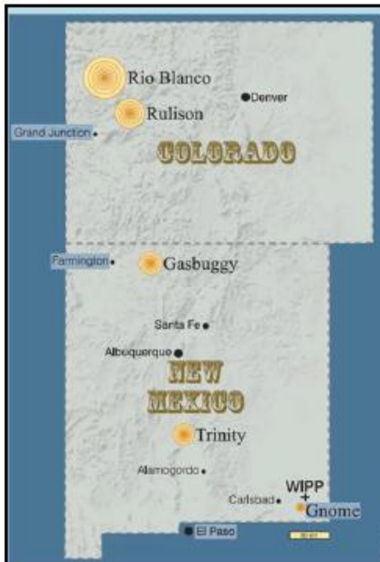

Basaltgang am Bahnhof Hörschel
Merkers Potash Mine

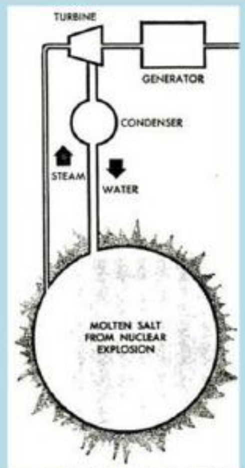

Lecture Notes in Earth Sciences
24
Bernhard Knipping
Basalt Intrusions in Evaporites
Springer-Verlag
1989
Dike width 30 cm, contact zone <2 cm wide
Dike in Merkers potash mine


Transactions, American Geophysical Union Volume 31, Number 2 April 1950
OBSERVATIONS ON THE INTRUSION OF ROCK SALT BY PERIDOTITE
John G. Broughton
Abstract--One of the narrow peridotite dikes of central New York has been observed cutting rock salt at a depth of 0.4 mile. It follows one of the regional cross joints and is probably post-Appalachian in age. Structural relationships show mutual intrusion of the peridotite and salt and suggest that the temperature of the tenuous igneous magma only slightly exceeded the melting point of the halite.
enhanced from DOE illustration
Approximate dike trend through Carlsbad potash mines (Mosaic and Intrepid)
CM
Salt and peridotite samples from Cayuga mine (courtesy Leo Van Sambeek)
ng(o)3


polyhalite
potash ore
dike
leached contact zone ~20' wide
Igneous dike in Intrepid potash mine, Carlsbad, NM
dike ~30' wide


New Mexico
Santa Fe
Gnome-Coach Site
Lovington
Hobbs
Eunice
Carlsbad
Loving
Gnome-Coach Site
New Mexico
Texas
Jal
Kermit
Wink
Monahans
Pecos
Miles
Shaft
Surface Ground Zero
Depth (feet)
Alluvial Deposits
Gatuna Formation
Dewey Lake Redbeds
Forty-Niner Member
Magenta Dolomite Member
Rustler Formation
Tamarisk Member
Culebra Dolomite Member
Los Medaños Member
Leached Member
Salado Formation (Halite)
Shot Point 1,183 Feet Below Ground Surface
Plug
Drift (Tunnel)
200
400
600
800
1,000





Edward Teller, "We're Going to Work Miracles"
Popular Mechanics, **113**, 3, p.100, March 1960

Thank you for giving me the opportunity

to make our minds play

"outside the box"

ng(o)$_3$

Auxiliary Information

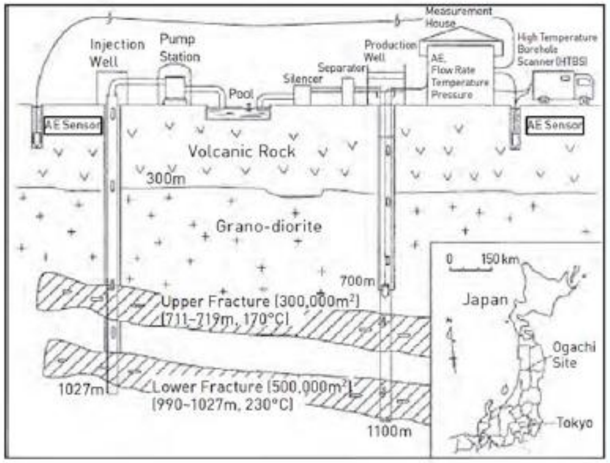


Figure 4.11 Illustration of the Ogachi HDR experiment (Kitano et al., 2000).

High-performance geothermal cement

CaP Cement (Calcium Aluminate Phosphate cement)

- CO_2 resistant
- Not subject to corrosion
- Not subject to strength retrogresion
- Does not shrink
- Good bonding properties
- Tested @ 700 F

Basic Geothermal Reservoir Types

- Steam
  - 450-470ºF
- Steam/Water
  - > 450ºF
- High Temperature Water
  - < 350ºF
- Low Temperature Water
  - < 350ºF
- Very Low Temperature Water
  - < 212ºF

CLASSIFICATION:

- Low temp. (< 90ºC or 194º F)
- Moderate temp (90º-150º C or 194º- 302º F)
- High temp. (> 150ºC or 302º F)

Geo-Heat Center Oregon Institute of Technology

Current Well Logging Tools

Tool	Max. Temp.	Max. Depth
One (1) Truck mounted electric line system	150°C	4 km
Two (2) Slick-line computer tools	400°C	8 km
Multiple portable temperature systems	200°C	up to 1 km

One can estimate the pre-drilling formation temperature by observing the way bottom-hole temperature changes over time after the well has been shut.

Bottom-hole Temperature Data

Mobile 999 OCS-G7863 Well #1

	Run	Time Circulation Stopped	Time Logger On Bottom	Sub-bottom Depth (m)	Shut-in Time	BHT (°C)
section 1	1	6/24/87 2:00	6/24/87 10:30	3197	8:30	92.2
	2	6/24/87 2:00	6/24/87 15:00	3197	13:00	96.7
section 2	1	8/17/87 13:00	8/18/87 2:15	5682	13:15	154.4
	2	8/17/87 13:00	8/18/87 21:30	5682	32:30	168.9
section 3	1	12/24/87 21:00	12/25/87 11:14	6999	14:14	197.8
	2	12/24/87 21:00	12/25/87 23:00	6999	26:00	205.6
	3	12/24/87 21:00	12/26/87 15:00	6998	42:00	208.9
section 4	1	1/31/88 21:30	2/1/88 10:26	7295	12:56	210.0
	2	1/31/88 21:30	2/1/88 15:00	7291	17:30	211.1
	3	1/31/88 21:30	2/1/88 22:00	7296	24:30	213.9

The pre-drilling (true) formation temperature can be higher than the reported BHT by anywhere between 3° C to 30° C.

gets increasingly warmer. Worldwide, *the geothermal gradient* (the rate at which the temperature increases with depth), averages about 15°F per 1,000 feet of depth below the surface. The increase has to be added to the average annual temperature at the surface. Calculating the temperature of a reservoir at 5,000 feet in the Powder River Basin of Wyoming, for example, would be the 65°F average surface temperature plus 5 × 15°F, or 140°F. Offshore, at depths of around 5,000 feet, the water temperature is about 33°F, so the temperature at the bottom of a well 25,000 feet below sea level would be about 333°F.

Variations abound. For example, near hot spots like Yellowstone Park, the subsurface temperature is warmer. Where the Earth's crust is being pushed beneath a continental plate and the temperature has not yet adjusted, it is cooler.

letters to nature

The temperatures of oil and gas formation in the sub-surface

T. M. QUIGLEY & A. S. MACKENZIE

Much has been written about the influence of time and temperature on the formation of oil and gas in the sub-surface[1-5]. However, a majority of previous publications have used a very simple formula to calculate the kinetics of a chemical reaction—usually referred to as the Lopatin approach[6-8]—which we believe is incorrect. Other more sophisticated schemes have generally used laboratory experiments as their primary calibrants[9]. Because reaction rates in the laboratory are at least seven orders of magnitude faster than those in nature, their relevance to sub-surface oil and gas formation is unclear, and can only be assessed provided geochemical data from deep boreholes are available[10,11]. We have calibrated a kinetic scheme that describes oil and gas formation using geological samples that have been heated under both natural and laboratory conditions. These equations predict that in the sub-surface the influence of time is not great, and that most oil is formed between 100 and 150 °C; and most gas between 150 and 220 °C.

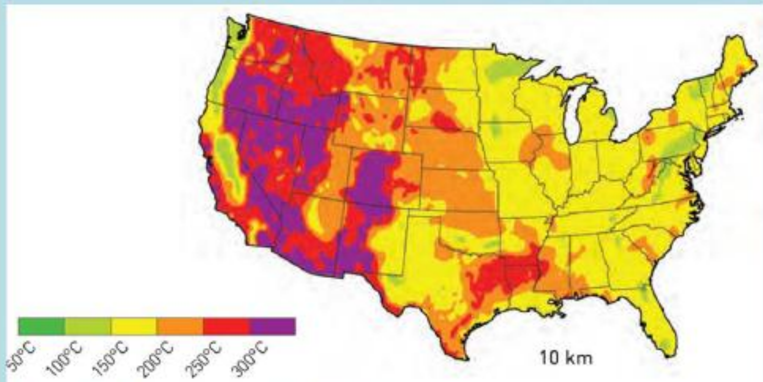


Figure 1.5 Temperatures at a depth of 10 km.

- Develop robust downhole tools to measure temperature, pressure, flow rate, and natural gamma emissions, capable of surviving in a well at temperatures of 200°C or higher for long-term monitoring.

MIT 2006

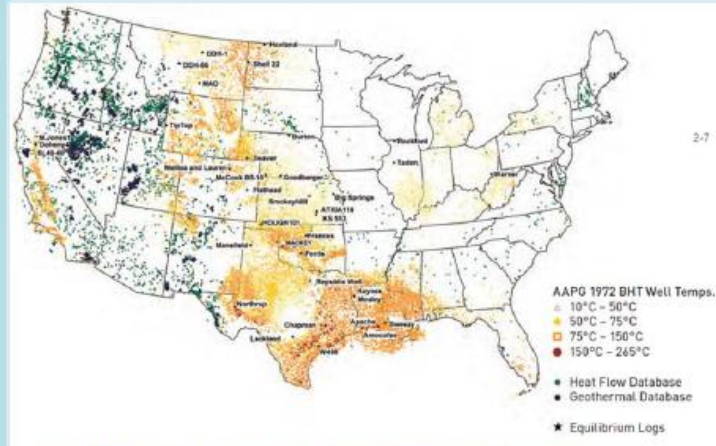


Figure 2.2 All BHT sites in the conterminous United States in the AAPG database. BHT symbols are based on depth and temperature (heat flow is not available for all of the sites, so some were not used for preparation of the Geothermal Map of North America). The named wells are the calibration points. The regional heat flow and geothermal database sites are also shown.

2-7

MIT 2006

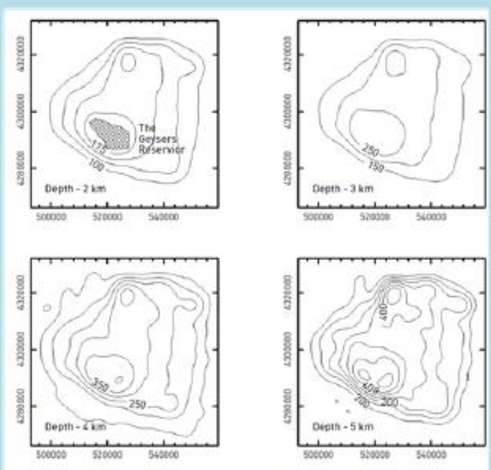


Figure 2.11 Temperatures at depths of 2 to 5 km in The Geysers/Clear Lake thermal area (Erkan et al., 2005).

MIT 2006

Some areas of oil and gas development have relatively high temperatures at routinely drilled depths for hydrocarbon production. For example, parts of east and south Texas and northwest Louisiana are characterized by temperatures in excess of 150°C (300°F) at depths of 4 to 6 km (13,123 ft to 19,684 ft) (McKenna and Blackwell, 2005; McKenna et al., 2005) (see Figure 2.7).

Data from BHT and high resolution log segments in wells in south Texas indicate temperatures of more than 200°C (400°F) at 5 km (16,000 ft). In east Texas, temperatures are more than 150°C in the depth range of 3.5 to 4 km (11,000 to 13,000 ft). And, in northwest Louisiana, BHTs and equilibrium temperature logs document temperatures of 120-160°C at only 3 km (10,000 ft).

MIT 2006

...tools are available for use on logging cable for up to about 300°C...Resistivity, sonic, gamma, and density neutron tools are available for use at or above 260°C and 20 MPa pressures (Sarian and Gibson, 2005).

Downhole mechanical tools (packers, etc.) can be equipped for reliable service up to about 250°C...

Sandia...has contributed to the development of a drillable inflatable packer...that can be used at high temperatures. Although the packer is not retrievable, it is drillable after the stimulation is finished. Similar noncommercial packers have been used successfully at Soultz.

MIT 2006

Manufactured chemically stable proppants can provide acceptable long-term fracture conductivities at 8,000+ meters and temperatures of 250°C.

...there are alternatives that can provide adequate proppant transport rheology for periods of 72 hours at temperatures of 220°C. However, viscosity begins to decrease at about 175°C for most high-temperature fluids.

Downhole electric submersible pumps are available for temperatures up to 175°C.

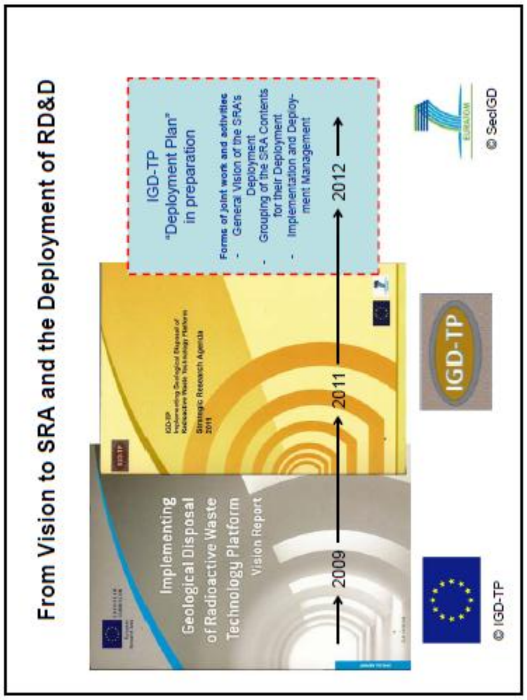
MIT 2006

...as the price of oil and gas increases, the search for new U.S.-based reserves will extend into deeper formations with higher temperatures and pressures.

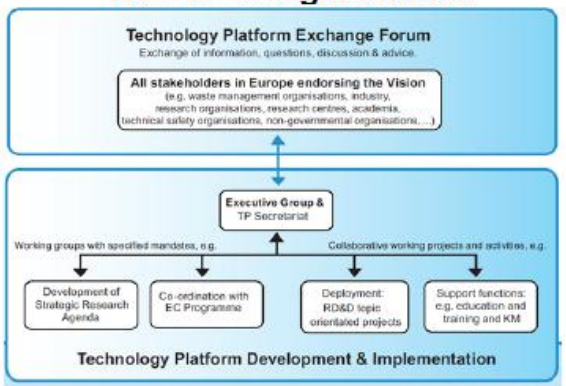
Capability limits (both temperature and pressure) have increased significantly...for oil and gas wire-line logging equipment, downhole mechanical tools, and hydraulic fracturing materials. These limits are expected to continue increasing...as oil and gas explorers and producers progress into more severe environments.

MIT 2006

Basics on the Deployment of RD&D Projects, important to the IGD-TP Vision
By Wernt Brewitz, Walter Steininger, Siegfried Köster (BMWi) (No Abstract)



IGD-TP's organisation



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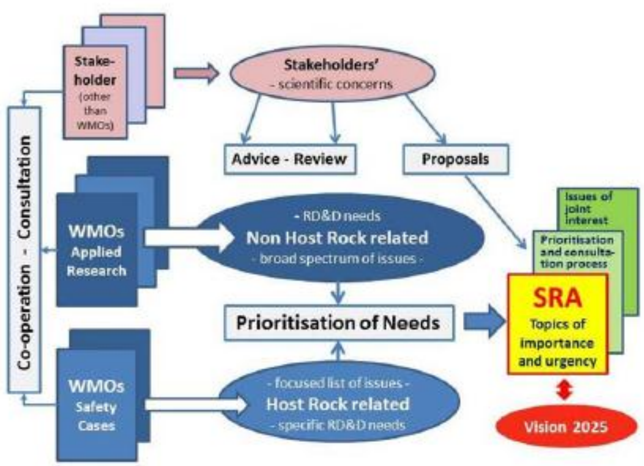
Scientific and technical basis for the SRA

- Waste Management Programs & Conceptions
  - HLW disposal concepts - state of advancement - time frames - etc
- International & National Framework Conditions
  - regulations - legal requirements - safety standards - etc
- State-of-the-Art
  - radioactive waste management - engineering - sciences - RD&D
- **WMOs needs for**
  - licensing - construction - operation - final closure
  - confidence building - public acceptance
  - training and education

6

Main tasks on the road to the SRA



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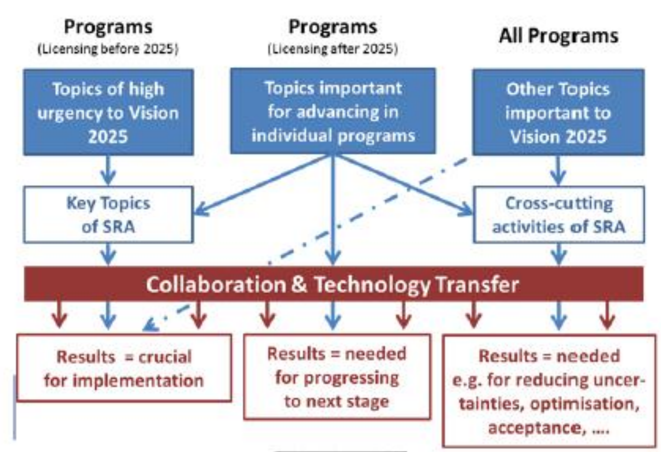
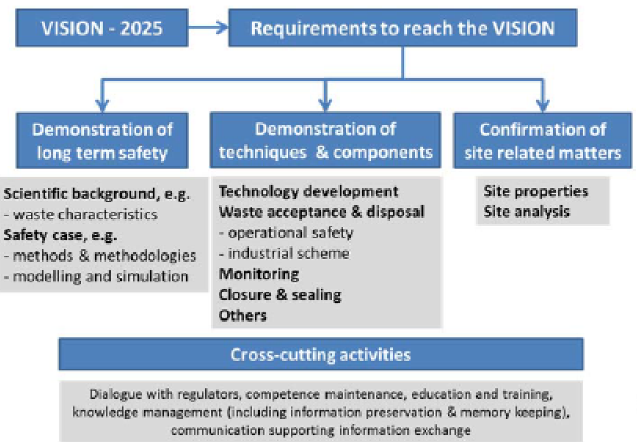
Co-operation of the participating WMOs



8

Needs for implementing geological disposal at an advanced Stage



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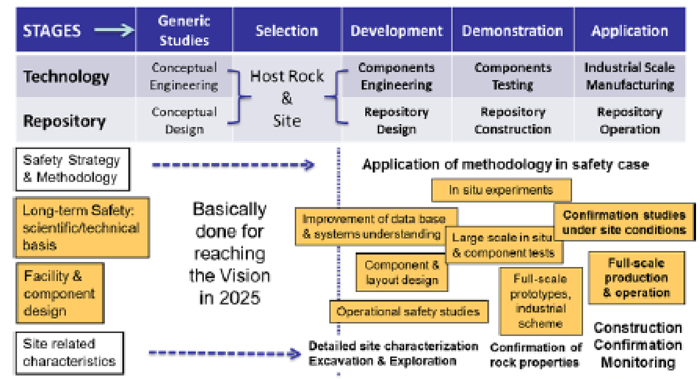
The path to implementation of geological disposal and its RD&D tasks



10

Ways and means to reduce uncertainties

- Criteria based site selection
- Thorough site investigation & characterization
- Adaptation of disposal concept to site conditions
- Experiments on safety related issues
- Investigation of processes relevant to repository performance
- Demonstration of disposal techniques
- Natural analogue studies
- Repository system's performance analysis
- Scenario based safety assessment studies

11

Key elements of the prioritization process

- Acknowledgement of the state-of-the-art
- Systematic approach in the identification of
  - RD&D issues
  - key topics of common interest
- Stepwise procedure in the prioritization of topics (importance, urgency)
- Transparency and traceability of procedure
- Monitoring of decisions
- Monitoring of stakeholders concern / advice

12

Structure of the **Prioritization Process**

1) Checking of WMOs programs for their specific RD&D issues and compilation of the issues important to WMOs
2) Overall classification of main areas of issues in view of their importance to Vision 2025
3) Detailed analysis of major trends in RD&D with identification of common interests and common needs *(Brussels seminar: check up and input from stakeholders)*
4) Definition of key topics and prioritisation of topics for vision related strategic RD&D *(Paris exchange forum: consultation of participants, information of stakeholders)*
5) Finalization of the Strategic Research Agenda, followed by the development of the deployment plan
6) Governance, strategy and methods for the deployment of urgent and important topics as identified in SRA (RD&D projects, working groups, information exchange) *(Helsinki exchange forum - Nov. 29, 2011: consultation of participants, information of stakeholders)*

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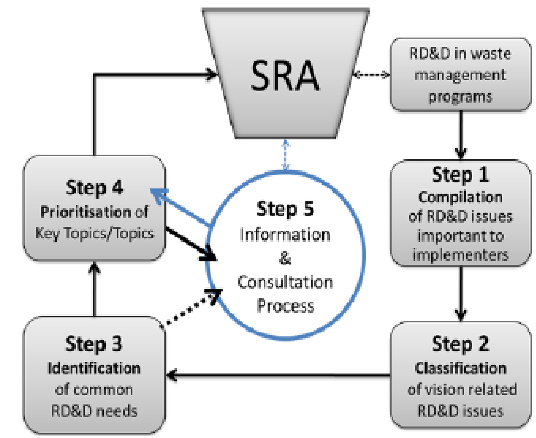
13



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14

Key Topics – the basis of the SRA

- Safety case
- Waste forms and their behaviour
- Technical feasibility and long-term performance of repository components
- Development strategy of the repository
- Safety of construction and operation
- Monitoring
- Governance and stakeholder involvement

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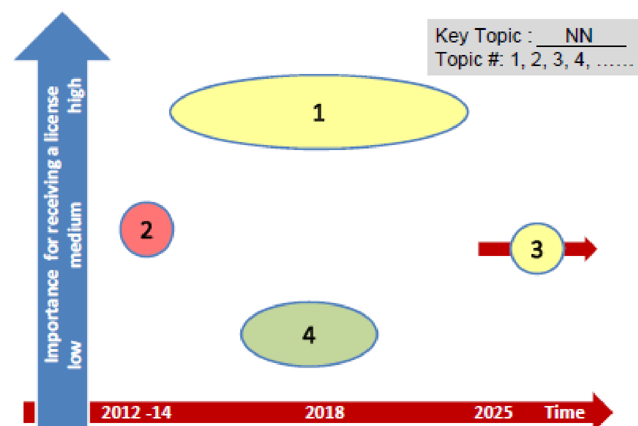
15



Importance: #1 high, #2 medium, #3 medium, #4 low;
Urgency: #1 until operation starts,
#2 as soon as possible,
#3 after start of operation,
#4 before licensing starts

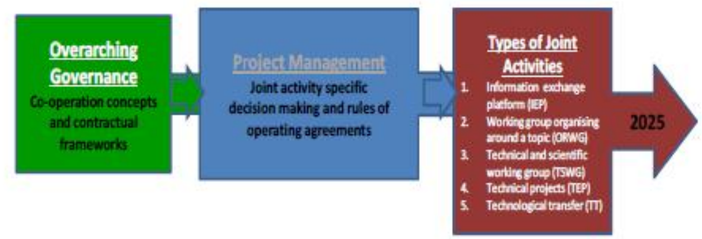
16

Cross-cutting issues are important
- relevant to every program, at any stage -

- Dialogue with regulators,
- Competence maintenance,
- Education and training,
- Knowledge management (incl. information preservation, memory keeping),
- Communication and other activities supporting information exchange.

17

Basics of a Deployment Strategy
(as proposed by the Deployment WG)



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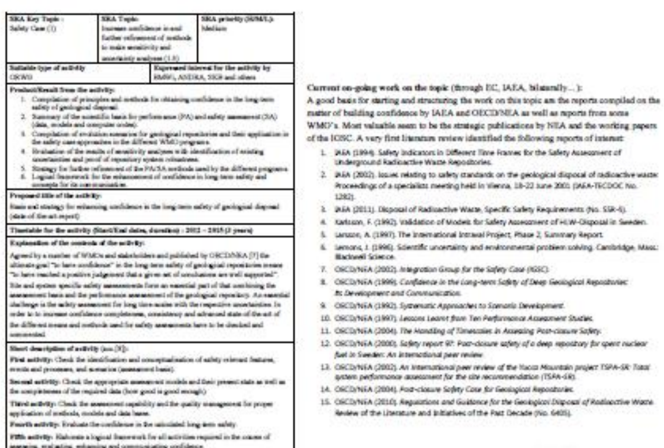
Example for an Outline of Activity (Information Sheet)



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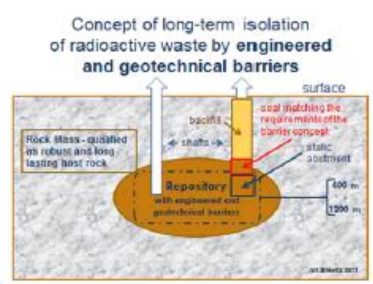
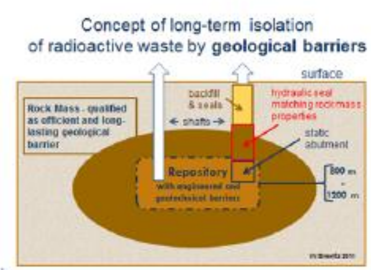
An Important Topic is Plugging and Sealing





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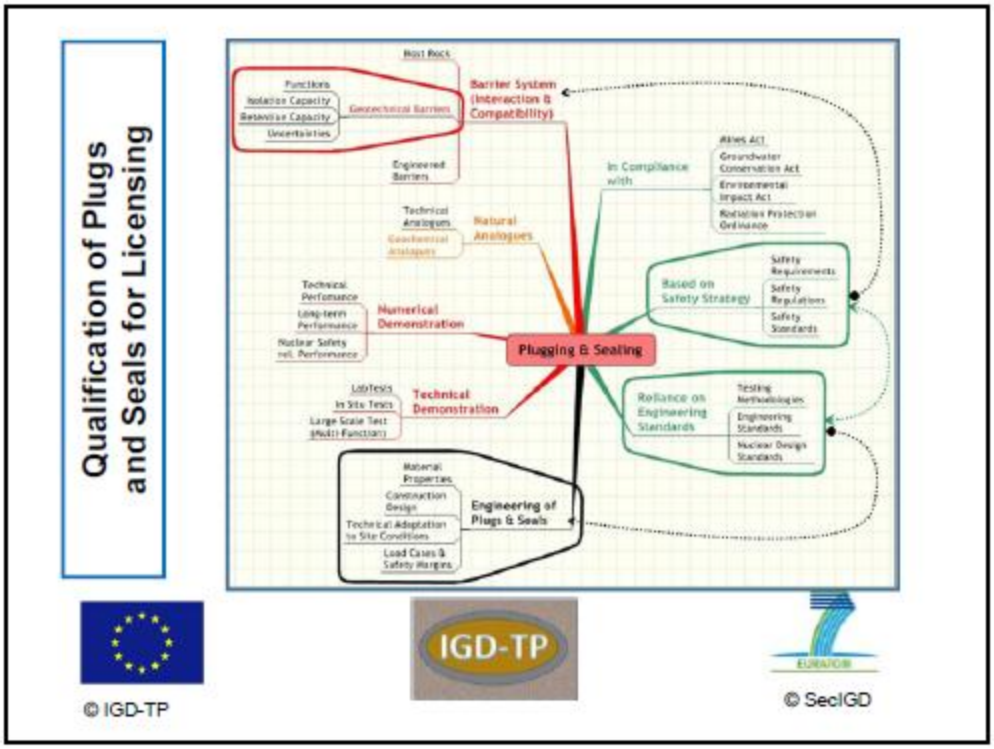

Qualification of Plugs and Seals for Licensing
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Functions
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Uncertainties
Geotechnical Barriers
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Technical Analogues
Natural Analogues
Technical Performance
Long-term Performance
Nuclear Safety rel. Performance
Numerical Demonstration
Plugging & Sealing
LabTests
In Situ Tests
Large Scale Test (Multi-Function)
Technical Demonstration
Material Properties
Construction Design
Technical Adaptation to Site Conditions
Load Cases & Safety Margins
Engineering of Plugs & Seals
In Compliance with
Mines Act
Groundwater Conservation Act
Environmental Impact Act
Radiation Protection Ordinance
Based on Safety Strategy
Safety Requirements
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