PROCEEDINGS OF THE 9th US/GERMAN WORKSHOP ON SALT REPOSITORY RESEARCH, DESIGN, AND OPERATION

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March 20, 2019

Dear colleagues and friends,

We mourn the loss of our esteemed colleague Jörg Hammer, who passed away suddenly and unexpectedly on February 28, one day after his 61 birthday, after a short and severe disease.

Jörg Hammer was a nationwide and internationally well-respected geologist who started his scientific career after finishing his studies at the Mining school in St. Petersburg with a diploma in mining geology. After that, he moved to Bergakademie Freiberg, where he carried out his thesis in the field of mineralogy and geochemistry, followed by his habilitation in the special field of geochemistry and petrology. In 2002, he started at the BGR as a scientific employee and in 2008 he undertook the responsibility for a working group as division head. His main working field was focused on geological explorations for a nuclear waste disposal site and storage caverns. Alongside his salt research, clay and crystalline rocks came to the fore of his projects in recent years. He worked intensively with colleagues in Germany and abroad investigating different host rocks for nuclear waste deposal. Jörg made his greatest contributions advancing salt science over much of his career. The US/German Workshop was an ideal and very helpful platform for him to intensify his salt research. His contributions to this important topic are huge and indispensable. With Jörg's support, many new projects were initiated. In his unforgettable and friendly manner, he shared his knowledge in the process of defining the research frontier.

In his professional life, he cultivated not only scientific contacts, but also personal friendships with the people working with him. He is irreplaceable for all of us and leaves an unbelievably big gap. We will miss his friendly, sympathetic and optimistic character. His suggestions, his constant willingness to help, his unique sense of responsibility and his engagement in supporting the young academics will not be forgotten.

Our thoughts are with his family.

Summary

The 9th US/German Workshop on Salt Repository Research, Design, and Operation organized by the Project Management Agency Karlsruhe (PTKA), Karlsruhe Institute of Technology (KIT) was held in Hanover, Germany on September 10-11, 2018. The workshop was preceded on September 7 by the 8th Annual Meeting of Nuclear Energy Agency (NEA) Salt Club and was succeeded on September 12-14 by the 9th Conference on the Mechanical Behavior of Salt. All meetings were hosted by the Federal Institute for Geosciences and Natural Resources (BGR). Fifty-eight participants not only from the US and Germany but also from The Netherlands, Poland, Austria, and Switzerland representing federal and governmental agencies, universities, research groups, and private companies attended the workshop.

Since the workshop's reinitiation in 2010, activities, results, and the advances of the international collaboration during each event have been published in the form of Proceedings. In this way the labor of ongoing partnerships on well-established investigations as well as emerging research issues are not only well documented but also made available to a larger community.

During the 2-day workshop, participants presented and discussed the state of the art during sessions which are summarized in respective chapters in this document:

- Joint Project WEIMOS (Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgs-mechanischen Modellierung für die HAW-Endlagerung im Steinsalz / Joint Project: Further development and qualification of rock mechanics modeling for final storage of HAW in rock salt) – Chapter 2
- Engineered Barrier Systems (concepts, materials, and demonstration) – Chapter 3
- Bedded, Pillow, and Domal Salt Repositories – Chapter 4
- Design Aspects – Chapter 5

Detailed information on each topic can be found in the appendices of the document where all of the abstracts and presentations as well as the technical agenda and a list of participants are available.

Chapter 2 reviews the progress of the ongoing research within the WEIMOS collaboration effort. In this chapter, recent laboratory results on the shear strength of salt/clay and salt/anhydrite interfaces are described. The chapter includes results from numerical models of canister compaction under room closure considering a new canister design and the effects of clay seams. Furthermore, this chapter reports first results from microstructural investigations by optical and scanning electron microscopy on WEIMOS-relevant core samples tested in low deviatoric stress conditions.

Chapter 3 focuses on Engineered Barrier Systems. A variety of sealing materials applied in different test sites is addressed. The key issues are the formation of cracks within the seal and gaps on the seal/salt interface as well as the overall performance of the sealing materials in terms of permeability and porosity. The subjects of discussion in this chapter extend to the application of dynamic compaction technology, material optimization, and a laboratory approach to analyzing sealing systems of cut salt bricks. Finally, the chapter reports on pilot applications of drift seals in the Asse and Morsleben sites in Germany.

Chapter 4 compares contemporary considerations of bedded, pillow and domal salt for repository purposes. Comparison of salt formations remains an ongoing concern for the US/German workshops because essentially all geological formations are being reconsidered at some level. Salt formations possess many common positive attributes for repository performance, independent of the geologic setting. In the current workshop, comparisons emphasized two key questions concerning anisotropy and geomechanical modeling.

Chapter 5 encompasses the workshop's presentations and discussions on Design Aspects. It reports on case studies concerning the characteristics of clay-salt complexes and the implementation of retrievability requirements. Furthermore, the chapter includes final results from the Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept Project (KOSINA) and an update on the evolving situation at the Waste Isolation Pilot Plant (WIPP) in the United States. These concern the current status and possible future events at the WIPP site, characteristics of clay-salt complexes in salt diapirs, and concepts of radioactive waste retrieval for different disposal strategies such as drift disposal, borehole disposal, piling, and slope dumping. The chapter also emphasizes results from the KOSINA project. KOSINA is a joint undertaking of the BGR, Society for plant and reactor safety (GRS), Institute for Rock Mechanics (IfG), and DBE TECHNOLOGY[1] funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The contribution of the KOSINA collaborators to the workshop includes results from generic geological modelling, technical repository concepts, a presentation of Safety and Demonstration Concept, numerical simulations on barrier integrity, and the respective analysis of radiological consequences.

Chapter 6 concludes the activities on technical, scientific and collaborative levels of the 9th US/German Workshop on Salt Repository Research, Design, and Operation. These provide solid bases for supporting a collaborative research agenda, which will be developed and reported upon at the 10th US/German Workshop on Salt Repository Research, Design, and Operation in 2019.

[1] DBE TECHNOLOGY GmbH became BGE TECHNOLOGY GmbH on 21st June 2018.

Acknowledgements

The 9th US/German Workshop on Salt Repository Research, Design, and Operation was organized by the Project Management Agency Karlsruhe (PTKA), Karlsruhe Institute of Technology (KIT), BGE TECHNOLOGY, and Sandia National Laboratories. The workshop was held at the BGR in Hanover, Germany, on September 10-11, 2018. Participants owe special thanks to Michael Bühler and his team, Wilhelm Bollingerfehr, and Sean Dunagan for their considerable work organizing this workshop, and to Sandra Fahland and her team for the arrangements and the hospitality at the BGR venue.

The authors of these Proceedings are indebted to all participants for their collaboration efforts and are profoundly grateful for the excellent contributions of the presenting authors and their co-authors. The organization, assembly and the editing of these Proceedings would not have been possible without the valuable efforts of Frank Hansen, Sandra Fahland, Georgios Maniatis, Wenting Liu, Britta Frenzel, and Anja Gerlach.

During the 2-day workshop, participants presented and discussed the state of the art of salt repository research, design, and operation. These Proceedings document the workshop's activities, results, and advances in summarizing chapters. We sincerely acknowledge the significant efforts of all authors who wrote the corresponding chapters of this document:

Contributing Authors		
Chapter	**Title**	**Authors**
Chapter 1	INTRODUCTION	G. Enste, S. Fahland, and F. Hansen
Chapter 2	WEIMOS PROJECT	A. Hampel, B. Reedlunn, M. Mills, and S. Sobolik
Chapter 3	ENGINEERED BARRIER SYSTEMS	N. Müller-Hoeppe, K. Wieczorek, and J. Aurich
Chapter 4	BEDDED, PILLOW, AND DOMAL SALT REPOSITORIES	T. Popp, J. Hammer, and F. Hansen
Chapter 5	DESIGN ASPECTS	W. Bollingerfehr
Chapter 6	CONCLUDING REMARKS AND OUTLOOK	G. Enste, M. Bühler, W. Bollingerfehr, F. Hansen, and S. Dunagan.

The US/German Workshops are made possible by federal/ministry funding as outlined by a Memorandum of Understanding between the United States (US) Department of Energy (DOE), and the German Federal Ministry for Economic Affairs and Energy (BMWi). Special thanks are extended to RESPEC who made it possible for Frank Hansen to attend, contribute, write, and edit these Proceedings.

Going forward, the Proceedings will be compiled by the hosting organization. That means in 2019, RESPEC (US) will compile the Proceedings.

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Acronyms

BCT	Bell Canyon Test
BGE	Bundesgesellschaft für Endlagerung mbH (BGE) (Federal Company for Radioactive Waste Disposal (Germany))
BGE TECHNOLOGY	BGE TECHNOLOGY is a wholly owned subsidiary of the (German Federal Company for Radioactive Waste Disposal (BGE)
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources (Germany))
BMWi	Bundesministerium für Wirtschaft und Energie (German Federal Ministry for Economic Affairs and Energy)
CRZ	containment-providing rock zone
DBE TECHNOLOGY	Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE Technology is a wholly owned subsidiary of German Company for Construction and Operation of Waste Repositories (DBE))
DOE	US Department of Energy
DRZ	damaged rock zone
EDZ	excavation damaged zone
ELSA II	Schachtverschlüsse für Endlager für hochradioaktive Abfälle – ELSA-Phase 2: Konzeptentwicklung für Schachtverschlüsse und Test von Funktionselementen von Schachtverschlüssen“ (Shaft sealing systems for final repositories for high-level radioactive waste (ELSA) – phase 2: concept design for shaft seals and testing of the functional elements of shaft seals)
FEPs	features, events, and processes
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Society for plant and reactor safety) GmbH
HLW	high-level radioactive waste
HAW	high-activity radioactive waste
IfG	Institut für Gebirgsmechanik (Institute for Rock Mechanics)
KIT	Karlsruhe Institute of Technology
KOSINA	Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept

LAUS	Large Aperture Ultrasonic System
LUH	Leibniz Universität Hannover, Germany
NEA	OECD Nuclear Energy Agency
PA	Performance Assessment
PTKA	Project Management Agency Karlsruhe
QA	Quality Assurance
R&D	research and development
RGI	Radiologischer Geringfügigkeits-Index (index of marginal radiological impact)
SaltMech IX	9th Conference on the Mechanical Behavior of Salt
SEM	Scanning Electron Microscopy
SNL	Sandia National Laboratories
SSSPT	Small-scale seal performance tests
TUBAF	Technische Universität Bergakademie Freiberg, Germany
TUBS	Technische Universität Braunschweig, Germany
TUC	Technische Universität Clausthal, Germany
US/USA	United States/United States of America
WEIMOS	Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz (Collaborative project: Further development and qualification of rock mechanicsl modeling for final storage of HAW in rock salt).
WIPP	Waste Isolation Pilot Plant
WP	Work Package
3D	three-dimensional

Proceedings of the 9th US/German Workshop on Salt Repository Research, Design, and Operation

1 Introduction

Germany and the United States have collaborated on salt research, especially directed toward nuclear waste repositories, since the late 1960s. Most of this collaboration was of a special nature and involved principal investigators working on unique problems. However, since Germany ended its moratorium in 2010, coordination of salt repository research has taken on a more formal and consistent foundation. Annual workshops have assembled representatives of federal and governmental agencies, universities, research groups and private companies to address a coordinated research and technical agenda.

The 9th US/German Workshop on Salt Repository Research, Design, and Operation was held in Hanover, Germany, on September 10-11, 2018, and accommodated more than 50 participants. Synchronizing the workshop with the 8th Annual Meeting of Nuclear Energy Agency (NEA) Salt Club and the 9th Conference on the Mechanical Behavior of Salt (SaltMechIX) at the venue of the Federal Institute for Geosciences and Natural Resources (BGR) underlines the workshop's significance within a larger salt community.

As always, it is not possible to focus on all contemporary developments in salt repository research, design and operation. Therefore, the key subjects at the 9th US/German Workshop included selected issues regarding geomechanics; numerical investigations; operational safety; engineered barrier systems; and the comparison of bedded, pillow and domal salt repositories.

Continuing the practice established since reinitiation of the workshops, these Proceedings include the summary of presentations and discussions and document the workshop's activities, results and advances. Detailed information can be found in the appendices of this document, which includes abstracts, presentations, the technical agenda, and a list of participants.

2 WEIMOS Project

Historically, thermomechanical modeling of rock salt behavior was based on phenomenological descriptions of mostly no more than steady-state creep. Mismatches between modeling results and in-situ test data were commonly compensated by tuning model parameter values: e.g., a modification of elastic modulus, that was not in accordance with experimental data. This engineering approach eventually allowed better agreement with field-test data. However, in numerical simulations for safe disposal of heat-generating high-level radioactive waste (HLW) in geological salt formations, the validity of long-term extrapolations up to one million years based on such engineering approaches is questionable.

Parallel to enormous advances in computational capabilities in the last two to three decades, significant progress has been achieved in laboratory techniques and basic micromechanical understanding of salt deformational processes. The fundamentals of deformation led to development of advanced constitutive or material models that include descriptions of further mechanical phenomena like transient creep, evolution of damage and dilatancy, creep failure and short-term strength, residual strength, damage reduction and healing, and tensile damage. Today, the highly nonlinear thermo-mechanical behavior of salt is described with state variables that take into account the dominant physical mechanisms and their interrelations.

A reliable description of these phenomena provides a solid basis for calculations of several processes,such as the evolution of the damaged rock zone (DRZ) after excavation of shafts, drifts, and rooms in salt, the convergence and closure of underground openings, the compaction of backfill materials, the damage reduction in the DRZ resulting from creep of salt against backfill and closure systems, and the restoration of long-term tightness, in the containment providing rock zone (CRZ). Therefore, reliable constitutive models are required for all phases of an HLW repository in geological salt formations from initializing stages of research, design, and operation, to the post-operational phase and safe long-term isolation of hazardous wastes.

In three joint projects between 2004 and 2016, salt scientists and modeling experts from different institutions performed detailed and comprehensive studies comparing advanced constitutive models and modeling procedures. The work included several systematic series of precise lab tests with different types of salt, recalculations of the tests and determinations of characteristic, salt-type-specific parameter values and simulations of various typical (real) underground situations in salt. The projects demonstrated that the models are generally able to describe the various deformation phenomena in salt correctly. In some cases, the close collaboration of the experts has also helped improve the models and identify open questions that require more experimental investigations and a further development of the rock-mechanical modeling. This is now pursued in joint project WEIMOS (Lüdeling et al. 2018) by the following partners:

- Dr. Andreas Hampel, Hampel Consulting, Mainz, Germany (coordinator)
- Institut für Gebirgsmechanik GmbH (IfG), Leipzig, Germany
- Leibniz Universität Hannover, Germany (LUH)
- Technische Universität Braunschweig, Germany (TUBS)
- Technische Universität Clausthal, Germany (TUC)
- Sandia National Laboratories (SNL), Albuquerque and Carlsbad, NM, USA.

The challenges of HLW disposal in the underground cannot be met by single countries alone. The collaboration of the German partners with US colleagues from Sandia within the project WEIMOS provides a forum for an ongoing and thorough exchange of knowledge and experiences in salt research and geomechanical modeling for mutual benefits. The German partners are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and managed by the Project Management Agency Karlsruhe (PTKA). The international collaboration is conducted under a framework agreement between the German BMWi and the US Department of Energy (DOE).

The identified research areas for further investigations and improvements of the rock-mechanical modeling are formulated in the following four work packages (WP):

WP 1: Deformation behavior at small deviatoric stresses
WP 2: Temperature and stress dependence of damage reduction and healing
WP 3: Deformation behavior resulting from tensile stresses
WP 4: Influence of inhomogeneities (layer boundaries, interfaces) on deformation

The current status of the modeling and progresses achieved in WEIMOS are demonstrated with simulations of a complex three-dimensional (3D) model in WP 5:

WP 5: Virtual demonstrator

WP 6 contains all administrative actions:

WP 6: Administrative work

At the 9th US/German Workshop, recent results and the current status of research in WP 1 to WP 5 were reported. Furthermore, the motivation for a proposed extension of the WEIMOS project until Sept. 2021 and the suggested research was introduced. At the end of the WEIMOS session, results from SNL's simulations of canister compaction at WIPP were presented as an example for the application of the geomechanical modeling.

WP 1: Small deviatoric stresses

Most regions around underground openings in salt deform under the influence of small deviatoric stresses. In WEIMOS, this was demonstrated with simulations of the current uplift rate in a generic salt dome (Popp & Hansen 2018). Small stresses determine long-term creep closure of drifts and rooms, compaction of backfill materials, damage reduction and healing of salt in the DRZ, and restoration of tightness of the geotechnical barrier. Therefore, reliable long-term extrapolations of creep of natural rock salt with constitutive models require a well-derived experimental database and an understanding of the acting deformation mechanisms.

Although numerous creep tests with various types of salt from many different locations were performed in the past, creep rates at natural rock temperatures (25-40°C) and small deviatoric stresses (< 5 MPa) could not be confidently measured. In this range, steady-state creep rates are in the order of 10^{-11} to 10^{-13} 1/s and thus below resolution limits of conventional lab tests. Some uniaxial creep tests were performed in this range (Bérest et al. 2018; Popp & Hansen 2018). However, the results show large scattering, and influences of damage, dilatancy, and humidity cannot be excluded.

In WEIMOS, the true creep of intact salt shall be examined with well-controlled triaxial lab tests. IfG has constructed three new creep test rigs with a high-resolution capacitive displacement measurement system, isolated from floor vibrations and located in a climate-controlled chamber ensuring high temperature stability ($\Delta T = \pm 0.2$°C). A remote readout and logging system removes the necessity of entering the chamber during a test. Currently (Sept. 2018), calibration of the equipment is in progress.

Parallel to the construction of the new equipment, a pretest was conducted in an existing test rig with a 130-day-long initial isostatic compaction phase. With such a reconsolidation, any predamage from remnants of the DRZ in the drilled cores or from specimen preparation shall be removed. Surprisingly, the axial strain in the pretest was still slightly changing even after 100 days. This might be a hint that consolidation takes much longer than previously anticipated and commonly conducted.

The newly developed IfG test plan for the extension of the WEIMOS project comprises an initial reconsolidation phase of 100 days at a higher temperature. Then, two triaxial test series in the new IfG test rigs are planned with various deviatoric loadings between 1 and 6 MPa and a confining stress of 20 MPa. The deviatoric test phases start at 80°C to gain more deformation and thus a closer approach to the true steady-state creep rate, followed by two temperature changes to 60 and 30°C with no new transient creep phases. Each test series will take approximately 400 days.

Microstructural analyses by SNL of unloaded and loaded samples have started to identify the dominant deformation mechanisms in the range of small deviatoric stresses. The approach to perform these investigations must be of great care and include the following procedures. First, the sample cores are cut in half by a low damage isomet saw to produce one portion for single grain cleavage chip investigations, and another for making thin sections to study grain boundaries. To obtain single grains, the sample is gently disaggregated to avoid artificial damage. The single grain is cleaved to attain a cleavage chip for etching, thereby highlighting the grain microstructure. The cleavage chip is etched by immersion in a solution saturated with lead chloride in methanol, followed by rinsing in butanol to discontinue the etch, before drying completely. The etching technique is a delicate procedure and can be affected by several factors such as solution quality, time of immersion, agitation in etchant, effectiveness of stopping rinse, and drying efficiency. Successful etched cleavage chips reveal insights into subgrain size, free dislocation density, and deformation mechanisms associated with stress and/ or temperature that are examined under optical and scanning electron microscopes.

Thus far, two WIPP core samples from multistage creep experiments by IfG have been investigated: samples TCC21 and TCC23. Photomicrographs of etch cleavage grains from each sample are shown in Figure 2.1, where test conditions for each are noted in the caption, respectively. The differences between their microstructure in terms of subgrain sizes and free dislocation density can be seen. TCC21 has remnant, small subgrains along the 110 planes, with glide bands emanating from the upper left to the lower right of the photo. The subgrains are also quite tangled and there are a multitude of free dislocations. TCC23 on the other hand displays a larger subgrain structure with clear and defined boundaries. Free dislocation density is also lower as they have moved to the subgrain boundaries, thereby indicating more recovery. The microstructural differences are explained by the creep deformation at different temperatures and the amount of strain each sample experienced. TCC21 reached a maximum strain of 1.7E-03 during testing at 25 and 60°C, where the total strain in TCC23 was almost an order of magnitude higher at 1.1E-02 and the temperature was 80°C. Hence, TCC23 had a more recovered substructure, while TCC21 was still in the middle of recovery and had not reached steady-state creep.

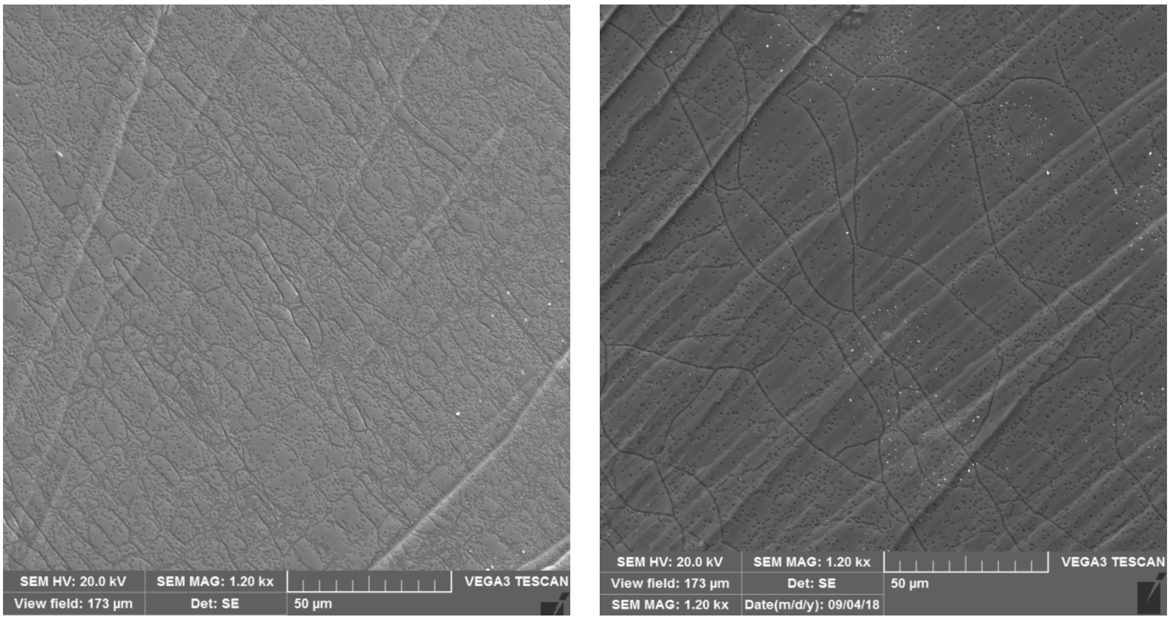


Figure 2.1: Scanning Electron Microscopy (SEM) photomicrographs at 1200X of etched cleavage chips from low deviatoric creep tested samples, TCC21 (left): σ_3 = 20 MPa, Δσ = 6→4→2 MPa at 25°C and Δσ = 2 MPa at 60°C, TCC23 (right): σ_3 = 20 MPa, Δσ = 8→6→4→6 MPa at T = 80°C.

These preliminary investigations yield promising results, especially since deformation mechanism(s) at low deviatoric stresses can be difficult to distinguish in the native salt substructure. Future work will evaluate and estimate free dislocation density, measure subgrain sizes, and investigate grain boundaries from thin sections of the remaining samples in the project scope. The lab tests and microstructural investigations will yield a basis for a more reliable modeling of salt deformation at small deviatoric stresses.

WP2: Damage reduction

Generally, "damage" involves the formation of microcracks and results in volumetric strains (dilatancy), increased permeability, and reduced load-bearing capacity. Damage reduction reduces dilatancy and permeability by the closure of opened microcracks, and "healing" subsequently restores mechanical strength through a recovery of cohesion by regeneration of bonds between microcrack surfaces.

Damage reduction and healing processes are important to the safety analysis for radioactive waste repositories, specifically in simulations of the restoration of tightness in the excavation damaged zone/damaged rock zone (EDZ, DRZ), and thus in the thermomechanical integrity analysis for the demonstration of the containment-providing rock zone (CRZ). Establishment of generally accepted healing approaches in the constitutive models may help demonstrate more realistically the long-term performance of geological and technical barriers and, thereby, enhance confidence in the salt barrier robustness. Thus, reliable experimental data are of urgent need for developing improved healing approaches.

The laboratory tests for the influence of temperature and stress state on damage reduction and healing in this WP are performed by the partner TUC (Herchen et al. 2018). At the workshop, the healing test technique, test program, and recent results were presented.

Finally, a new test program was introduced that shall be conducted in the proposed extension of the project. It was developed by the partners based on the recent results and experiences. The tests will be performed by TUC in the new test rigs with Asse salt and WIPP salt at different stress conditions and different temperatures.

WP 3: Tensile stresses

Around underground openings in salt, tensile strength and tensile damage processes play dominant roles for the development of microcracks and progressive damage in the EDZ. Typical failure modes such as spalling are closely related to tensile damage. In addition to pure mechanical effects, i.e. due to rock convergence, tensile stresses may also be generated by thermal processes: e.g., due to temperature changes in a heat-generating radioactive waste repository or due to a temperature drop in a gas cavern if highly compressed gases are squeezed out.

In WEIMOS, the simulation of tensile damage with the constitutive models of the partners was studied and compared in calculations of several typical examples: a bending beam, a Brazilian test, a heated and then cooleddown borehole wall section, and the converging Room D at WIPP (Lüdeling et al. 2018). The examples demonstrate the capability of the used constitutive models. They can describe not only the characteristics of a viscoplastic material behavior: i.e., three creep phases in combination with the strength and dilatancy behavior, but also tensile effects.

While all modeling results are plausible, a series of 30 triaxial tests with different confining stresses σ_3 = 0.2…5 MPa is planned for the extension of the WEIMOS project. It will yield a basis for the further development of the modeling, parameter determinations, and more reliable quantitative results. For example, the dependence of tensile strength on damage shall be investigated with samples that are predamaged in compression up to different levels of dilatancy ε_{vol} = 0.5…3 %, and then subjected to direct shear tests.

WP 4: Layer boundaries, interfaces

The influence of layer boundaries, interfaces, clay seams or stringers, and contact surfaces on the convergence of underground openings became readily visible during the simulations of Rooms D and B from WIPP in the previous Joint Project III. Here, some differences in the horizontal convergence between the simulation results and the in-situ measured data were partially explained with the influence of local sliding between rock salt and clay seams. Differences in the vertical convergence between the simulation results and the in-situ measured data were partially attributed to a separation between rock salt and an anhydrite layer above the room ceiling. Neither phenomenon was considered in the calculations in Joint Project III because of the lack of experimental data.

Munson et al. (1989), Munson (1997), and Rath & Argüello (2012) considered a shear response of nine clay seams in their simulations of Rooms D and B (treated as sliding material interfaces) by assuming a single coefficient of friction of μ = 0.2 for all seams. However, this assumption was not based on measurements. Rath & Argüello (2012, p. 18) refer to Munson et al. as follows: “Historically, this value has been interrogated, demonstrating that values ranging from 0.4 to 0.2 result a change in vertical closure of 10% and a change in horizontal closure of about 5% (Munson et al. 1989). Also, all clay seams are homogenous in the numerical treatment of contact surfaces; that is, there is no variance in friction value with regard to each clay seam."

In this WP, direct shear tests on several samples have been performed for SNL by RESPEC in their laboratory in Rapid City, South Dakota. They tested samples with clay seams, halite/anhydrite contact surfaces, halite/polyhalite contact surfaces, and plain salt samples without an interface for comparison. Some plain salt samples were extracted close to the drift wall (< 50 cm), while others were extracted from deeper into the wall (≥ 50 cm). The series of laboratory direct shear tests were performed on several samples of materials from the Permian Basin in New Mexico. In addition, several Canadian clay seam samples were used for test method development. The test plan and recent results were presented at this workshop by Steve Sobolik. The tests were conducted at several normal and shear loads up to the expected in situ premining stress conditions. Intact shear strength values were determined for all the test samples along with residual values for the majority of the tests.

Several general observations can be made from the results of these tests. First, the overall testing technique is good; the application of shear in the RESPEC direct shear machine is assumed to be only minimally affected by bending moments in the application of shear. Two indications that the test setup might not be ideally rigid include the observation that the fractures all tend to occur at an angle to the direction of shear in a "top down" mode, indicative of the presence of some bending moment, and radial cracks in grout in some of the tests might indicate an incomplete rigidity of the sample within the shear box. RESPEC was able to obtain peak and residual stress curves from most of the samples.

The residual shear stress (strength) measurements are plotted as a function of applied normal stress in Figure 2.2 for six different sample types. A Mohr-Coulomb law was fit to each data set to produce the solid colored lines, the strength of cohesion $S_{0,}$ and angle of internal friction φ in Figure 2.2.

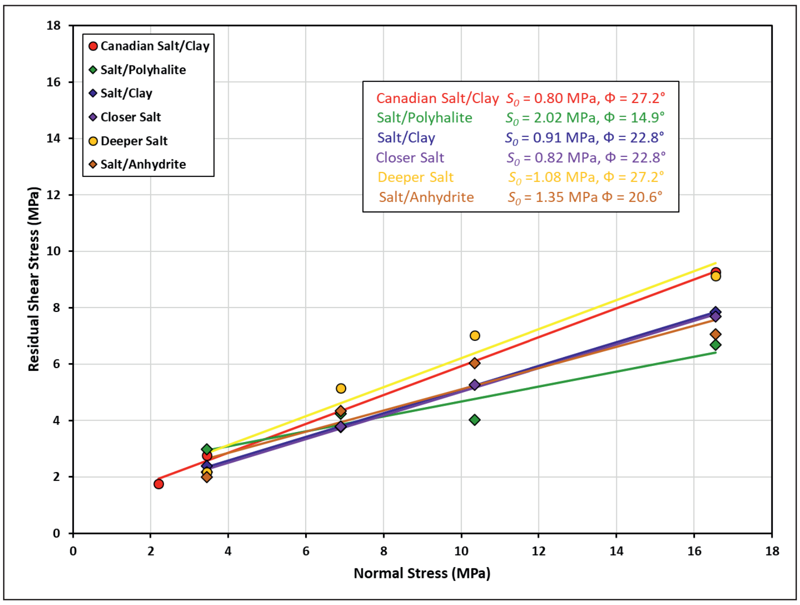


Figure 2.2: Residual shear strength curves, post-fracture, from intact tests for all samples.

Among the conclusions from these results, the most important is that the halite-clay contacts were much stronger than anticipated. Posttest inspections of these samples found that salt crystals were intrinsic to the structure of the seam, which probably increased the shear strength as compared to a more typical clay seam from the WIPP site. The in situ clay seams at the WIPP site have been observed to exhibit noticeable slip, and these in situ seams have also been observed to be less structurally integrated with the surrounding salt. In addition, the water content of the clay in the test samples may be much less than other in situ clay seams because of the length of time they have been exposed to ventilating air. In another observation, the stiffnesses of the samples were much higher than anticipated. Finally, consistent behavior was observed among different samples on intact tests.

Following the presentation of these results at the US/German workshop, several additional steps will be pursued toward completion of this series of tests. A few tests for which there were noticeable testing problems or that the data seem to be outliers will be redone with new samples from the same cores. Sandia National Laboratories (SNL) will begin development of a constitutive model based on test results. However, because the halite/clay interfaces tests to date were much stiffer and more integrated than perhaps has been observed at the depths of the WIPP site, RESPEC will develop several samples of salt that will include a manufactured clay seam, probably made of bentonite, which may be less stiff than the current samples. SNL and RESPEC will evaluate the costs and time required to modify the direct shear machine to operate at much slower shear velocities, in the expectation that a shear response curve without a distinct peak load may be obtained for these interfaces.

Besides the shear behavior, the modeling of the evolution and reduction of damage, dilatancy, and permeability in the excavation damaged zone/damaged rock zone (EDZ, DRZ) in contact zones between rock salt and geotechnical sealing elements is not yet well understood and should be investigated as well.

WP 5: Virtual Demonstrator

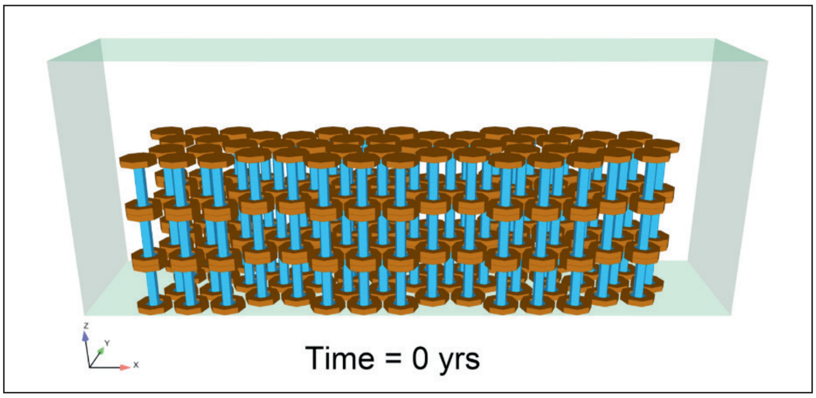
In this WP, a complex 3D model is calculated 1) with the existing material models and 2) after the studies in WPs 1 to 4 with the improved tools. The partners have chosen a main drift with a sealing system as an example. At first the open drift is calculated for 30 years, then a sealing system is introduced, and the subsequent phase is calculated for another 70 years. The plug is modeled in a simplified manner since the focus is not on the behavior of the sealing element. Test simulations are performed by all partners to improve the 3D discretization for FLAC3D, reduce numerical issues, and find appropriate locations and quantities for the evaluation and comparison of simulation results. With the model, the influence of small deviatoric stresses on the long-term evolution of stresses and strains and the reduction of damage and dilatancy behind the plug are studied. Besides the anhydrite and polyhalite layers, it is planned to introduce an additional interface: e.g., a clay seam, that crosses the wall of the drift, to study the phenomena of WP 4. Furthermore, the influence of different temperatures or a temperature gradient on the simulation results shall be studied.

Because tensile damage (WP 3) is not a major process in this model, a second demonstration model for the simulation has been suggested for the extension of the project. This model focuses on the evolution of slab separation above a drift, see Figure 2.3.

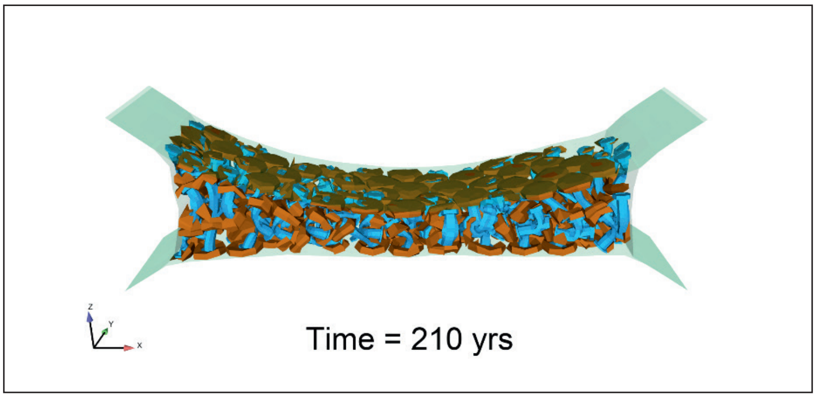
Figure 2.3: For the second demonstration model, a drift with slab separation above the sealing was suggested. The photo shows a crack above a drift at WIPP.

Simulations of Canister Compaction at the Waste Isolation Pilot Plant

Joint Project WEIMOS strives to improve constitutive models for rock salt. One important application of these models is canister compaction. Once canisters are placed underground in a WIPP disposal room, the surrounding rock salt compresses the canisters over several centuries, thereby isolating the waste from the biosphere. Although canisters at WIPP have been traditionally modeled as a homogeneous solid material, a new canister design under consideration consists of a thin-walled, 17-cm-diameter, stainless-steel pipe and plywood within a 55-gallon drum. These new canisters are structurally anisotropic and susceptible to buckling during compaction, which prompted the need to discretely model the individual canisters, including the pipe and plywood within each drum (see Figure 2.4a). Sierra/Solid Mechanics' explicit dynamics capability is well suited to modeling the pervasive contact and severe plastic deformation as the canisters compress, but the timestep is typically about a microsecond. To avoid this limitation, the rock salt viscoplasticity was sped up by several orders of magnitude (while verifying that the kinetic energy was negligible), thereby squeezing hundreds of years into seconds. Short-duration geomechanical events such as rock falls were not considered in these calculations. An example compaction prediction is shown in Figure 2.4b, where the canisters clearly deformed in a nonuniform and highly complex manner. These high-fidelity simulations will help SNL assess the nuclear waste isolation process and evaluate whether the risks of an adverse event are acceptably low.



a) Undeformed canisters



b) Deformed canisters

Figure 2.4: Several rows of canisters with stainless-steel pipes in blue and plywood in brown. (The surrounding rock salt and 55-gallon drums are not shown for visualization purposes.)

3 Engineered Barrier Systems

3.1 Overview

Backfilling and sealing of salt repositories have been topics of interest for US/German collaborators for many years. Crushed salt backfill made of mine-run salt has been investigated for decades due to its great potential to reestablish the natural rock salt barrier by reconsolidation in the long term. The state of knowledge on crushed salt backfill was broadly discussed at the US/German Workshop in 2017. As performance assessment applications (PA) involve long time periods and the prediction of crushed salt reconsolidation is affected by uncertainties, it is preferred to take measures to lessen performance uncertainties. Two presentations to resolve the question were provided by the technical staff of Technische Universität Bergakademie Freiberg (TUBAF) and TUC.

Until the crushed salt is reconsolidated enough to assume the barrier function, additional plugging and sealing measures are necessary to prevent brine intrusion from the overburden into the salt repository. At the US/German Workshop 2016, a historical overview was given on the German seal and dam structures for which extensive knowledge has been gained covering the time period from German mine work in the early 1900s to today´s pilot seals, which were specifically constructed to demonstrate their capability to seal waste repositories in salt. Two of them are still under investigation and recent results were presented by technical staff of Federal Institute for Geosciences and Natural Resources (BGE). The historical overview on plugging and sealing measures and the experience gained was complemented from the US perspective by technical staff of SNL. The present state of knowledge was summarized and design bases for a generic HLW salt repository in the US were addressed. Finally, aspects of the planning and construction of drift seals in the Asse mine, where routine operation is running, were contributed by staff of BGE and BGE TECHNOLOGY.

3.2 Backfill and Salt Bricks

Crushed mine-run salt was investigated as backfill material for a radwaste repository in salt in the past. From natural and technical analogues, it was concluded that reconsolidated crushed salt takes over the barrier function if its porosity meets the same range of 0.1 – 1% as intact salt. Thus, the time span needed to achieve sufficiently low porosities is of interest because the time span significantly affects the robustness of sealing measures. Experiments showed different reconsolidation rates depending on the moisture content of the backfill. Therefore, measures to reach low porosities instantaneously after emplacement and additives to accelerate compaction at least in a specific section are evaluated. Within the research and development (R&D) Project Shaft sealing systems for final repositories for high-level radioactive waste (ELSA) – phase 2: concept design for shaft seals and testing of the functional elements of shaft seals (ELSA II), compaction of crushed salt-clay-water-mixtures with high compaction energy was investigated at field-test scale in order to minimize the initial porosity and to accelerate the compaction rate. Using a Terra Mix impulse compaction unit characterized by a falling weight of 9,000 kg, a falling height of 15 cm to 120 cm, a single hit energy of 0.013 MJ to 0.053 MJ, an initial total porosity in the range of 14% – 8% could be achieved for the preferred mixture STM-2. Exemplary permeability measurements verified an improvement of the hydraulic properties under realistic conditions and showed an effective permeability to gas below 10^{-17} m².

An alternative approach to reduce the initial porosity from the very beginning is to use cut salt bricks to construct a sealing system made of salt stonework. The gaps are filled with crushed salt. After a number of successful laboratory tests, a large-scale pilot plant was designed to analyze sealing systems of cut salt bricks (Figure 3.1). In the meantime, the test device has been constructed and preliminary tests to calibrate it and to check its functionality have been performed. Numerical calculations to assess the mechanical load-bearing behavior of the salt stonework accompanied the calibration tests.

Figure 3.1: Test device for the large-scale pilot plant (left) and stonework made of salt bricks (right)

3.3 Plugging and Sealing

Because only loosely emplaced mine-run crushed salt has been investigated for backfill so far, additional shaft and drift seals were designed to avoid brine inflow from the overburden shortly after repository closure. According to salt mining experience, suitable sealing materials comprise various types of concrete – salt concrete and Sorel concrete – as well as clay/bentonite and asphalt. A brief historical overview on sealing and plugging measures regarding salt repositories in the US was given starting with the borehole plugging program in the 1970s. Four plugs were installed in the ERDA No. 10 drillhole applying different grout mixtures situated at depths between 1351 m and ground surface. Sample analysis however was limited, and the purpose of the plugging experiment was not documented, unambiguously. Within the Bell Canyon Test (BCT) in the AEC-7 borehole, originally an exploratory borehole 5 miles northeast of WIPP site, a plug was installed in anhydrite at a depth of 1370 m. From preparatory grouting studies two candidate grouts, BCT-1F (saltwater grout), and BCT-1FF (freshwater grout) were identified. Based on laboratory tests for permeability and bond strength push-out tests, the freshwater grout BCT-1FF was chosen for emplacement. It is notable that saltwater grout BCT-1F showed poor bonding to anhydrite in lab tests. The purposes of the experiment were to demonstrate a pressurized cementitious borehole seal that exhibited an expected low permeability and to execute a plug seal that bonded well with the host rock by virtue of cement that was properly set and cured. Within small-scale seal performance tests (SSSPT) (Finley & Tillerson 1991; Knowles & Howard 1995), several test series in different configurations (Figure 3.2) were performed in the WIPP Experimental Area. Sealing experiments included expansive salt concrete, salt blocks, salt/bentonite blocks, and crushed salt backfill. All test configurations were pressurized by gas and/or brine. SSSPTs provided confidence to PA in the form of in-situ data on permeability and mechanical performance. The expansive salt concrete exhibited permeability to gas and brine in the range of 10^{-17} m² to 10^{-23} m². The flow path decreased within one year of emplacement and the emplacement itself was carried out using commercial equipment. By the late 1980s, it became evident that concrete–called Salado Mass Concrete–would play a central role at WIPP to construct components in the shaft sealing system. In the shaft-seal design concept for WIPP, concrete components provide redundancy as one element in a suite of seal materials (salt, clay, asphalt) in the overall design. Possibilities for further field-scale testing of seals in bedded salt is recommended with the concept of a potential HLW salt repository in mind.

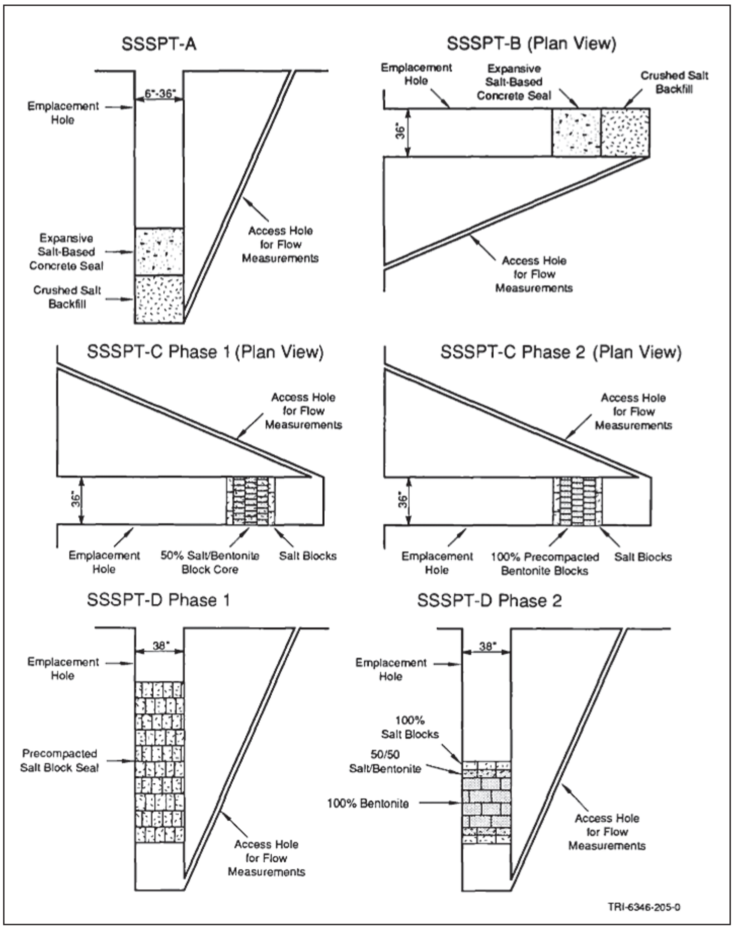


Figure 3.2: Configurations of the small-scale seal performance tests (Finley & Tillerson 1991; Knowles & Howard 1995).

In the Morsleben Repository, a brine-pressurized full-scale in-situ test is being performed to verify the constructability and performance of a salt concrete seal. An extensive measuring and investigation program, as well as accompanying numerical calculations are included in the in-situ test. The measuring and investigation program originates from concrete technology. Temperatures, stresses, displacements, strains, shrinkage, and pore pressure are continuously measured to learn more about the performance of the seal and to obtain a data basis for numerical calculations in order to improve and validate the numerical models. Especially the bonding of the salt concrete to the surrounding rock salt as well as the injectability of the contact zone is of interest. Many results were already presented at the 4th US-German workshop. A recent result of the hydraulic test is the decreasing integral permeability down to $1.4 \cdot 10^{-19}$ m^2, which is well below the target value of 10^{-18} m^2. Thus, it can be concluded that an integral permeability of less than 10^{-18} m^2 is achievable. Currently, additional investigations are being performed on core samples and in boreholes due to the cracks that evolved forming local pathways that were observed even though the in-situ test plan (due to salt concrete technology) has been fulfilled. Consequently, nondestructive (ultrasonic) investigations for crack detection were executed using the Large Aperture Ultrasonic System (LAUS). Originally, LAUS was developed to test thick concrete structures from the working face. As technical measures are available to reduce the risk of cracks, a review by external experts is planned. Furthermore, the aspect of corrosion has to be investigated in more detail.

LAUS measurements were also carried out to examine placement of the MgO-shotcrete pilot seal GV2 in Teutschenthal, which was mentioned at the US/German Workshop 2016. The LAUS measurements also penetrated several meters of the seal. It is expected that the LAUS method is suitable to demonstrate the integrity of a seal made of MgO-shotcrete.

Regarding cast-in-place MgO-concrete, more than a decade of experience in the planning and construction of flow barriers has now been gained at the Asse mine. The MgO-concrete is handled on an industrial scale, which means that it is transported hydraulically over distances of several hundred meters. The pilot constructions started in 2003; since 2007, the flow barriers have been routinely constructed in routine operation. The first horizontal flow barrier (SB-775-3) was installed at the beginning of 2007. By now, about 48,100 m^3 of Sorel concrete have been used for flow barriers and abutments.

The main steps of the planning and construction process of flow barriers are described below.

Planning

(01) Derivation of hydraulic requirements for every individual flow barrier by model calculations in terms of minimum hydraulic resistance

(02) Detailed geological description of flow barrier location and its investigation by geotechnical measurements

(03) Preliminary design of flow barrier taking into account the geotechnical situation and specification for drift recutting

(04) Detailed design of flow barrier and engineering verification of the ability for meeting the hydraulic requirement

(05) Compilation of the location-specific Quality Assurance (QA) documentation plan and the location-specific construction schedule

Construction

(01) Preparation of location, including recutting

(02) Inspection of preparatory work, third-party verification that preparatory work is adequate

(03) Completion of flow barrier

(04) Assessment of the overall documentation to determine if the engineering verification (step 4 of planning) holds in practice

(05) If all verification criteria are met or necessary additional measures have been carried out to meet them, the functionality of the flow barrier is explicitly documented

So far, 32 flow barriers have been installed in the Asse mine. For 16 barriers, it has been demonstrated that they have been constructed according to the requirements. Further demonstrations are in preparation. According to the current plan, 21 flow barriers still need to be installed.

3.4 Summary

Salt repository performance requires effective closure and sealing measures to preserve the natural dry environment of a salt repository and avoid radionuclide release. During the last decade, progress has been made in understanding the interaction of the salt barrier (EDZ) with backfilling and sealing measures.

Regarding crushed salt backfill, a reduction of the initial porosity to increase initial hydraulic resistance and initial stiffness, and corresponding accelerated pressure build-up in the EDZ, is decisive. Cut salt brick stonework is a concept to minimize the initial porosity and maximize initial stiffness of pure salt backfilling/sealing.

To cover the time period until the salt barrier is reestablished, additional seals are required. Progress was made in testing pilot seals at full scale and to establish a routine procedure to construct seals. Although some effects have still to be investigated in more detail, it can be concluded that technically tight seals can be realized.

4 Bedded, Pillow and Domal Salt Repositories

4.1 Introduction

Reinitiation of US/German Workshops on salt repository research, development and operation embraced an ideal that collaborative research would involve close relationships of Principal Investigators. Contemporary issues would be discussed openly and examined in terms of relevance. In preparation for the workshop held in September 2018, workshop coordinators asked that we collectively take time to reexamine similarities and differences among flat bedded, pillow and domal salt formations for disposal of heat-generating nuclear waste. A breakout session was organized to address this contemporary issue facing repository programs in both the USA and Germany. As a group, we have explored facets of this comparison previously; however, the repository decision-making process continues, and disposal in salt rocks remains a viable alternative. Witness the following Chapter, which delves more deeply into design options developed in the KOSINA project.

Technical matters investigated and discussed here benefit from expert international input, including nations of Poland, The Netherlands, and England. As a group, we initiated discussion on this wide-reaching topic a few years ago, culminating in a status report (Hansen et al. 2016). Material from that report (op. cit.) provided general questions to be discussed in a workshop exchange. Several presentations in the 2018 US/German Workshop concerned repositories in various salt formations. Many participants in the breakout session had some degree of salt expertise and positive attributes for permanent isolation of nuclear waste in salt are well known and documented. The primary obstacle to initiating disposal in salt rocks is identification of a site, which is a governmental matter.

Differences and similarities of salt formations include physical, mechanical, chemical, lithological, hydrological, and thermal properties or behavior, which become dominant at different scales (macroscopic to microscopic) when applied to nuclear waste disposal. Developing a large model for basin-scale hydrology seems relatively less complicated for flat-lying formations than folded piercement structures. Crosssections shown in Figure 4.1 (extracted from a presentation by Till Popp and included in the appendix of this document) provide a sense of structural differences. Elements of flat domains, such as stratigraphy, geological structure, boundary conditions, and flow paths, would likely exhibit areal continuity and reduce uncertainty in modeling parameters. Hydrogeologic properties would require quantification for each site-specific case, providing a challenge in either basin model.

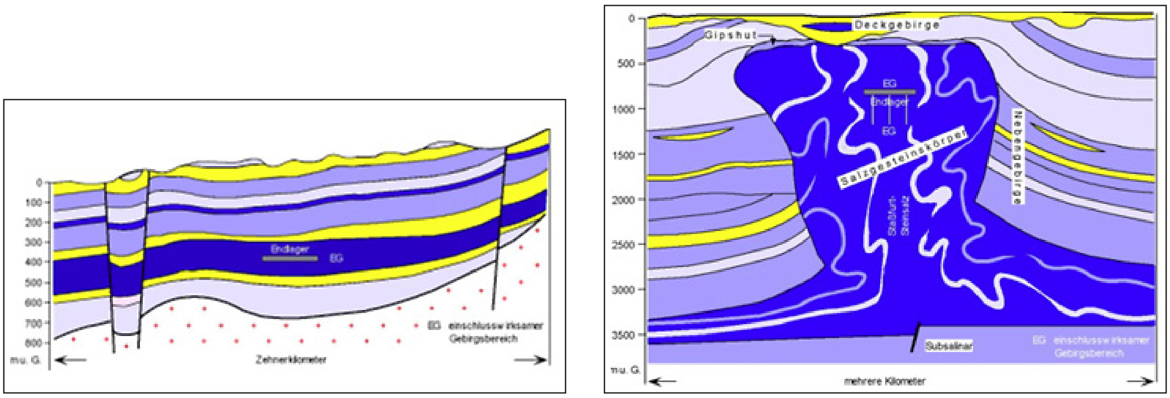


Figure 4.1: Cross sections of flat-bedded and domal salt structures.

The concept of disposal operations would naturally be influenced by available geology. A flat horizon offers large lateral dimensions, while a dome structure usually has substantial vertical dimensions. A pillow-salt structure could provide significant dimensions laterally and vertically. Seal systems for salt repositories have been widely studied and demonstrated, allowing sealing strategies and performance determination to be optimized for the geologic setting. A proposal to review seal systems was presented by Simon and Matteo. Near-field interactions at the room-scale would be governed by fluid accessibility, a function of lithology and stratigraphic position, interlaminations, evolution of the excavation damage zone (EDZ) and other factors unique to the selected site.

Comparison of various salt structures for nuclear waste disposal can expand in many directions. As collaborations continue, focused consideration will be given to selected domains of interest. The salt repository community continues to advance the technical basis for disposal in salt rocks. In this break-out session, we emphasized two main areas: anisotropy and modeling. Discussions help shape the frontier of research as well as guide evaluation of proposed studies.

4.2 Anisotropy

Mechanical properties of salt, as determined by laboratory testing (triaxial, shear and tensile strength), are usually characterized as isotropic, especially under conditions encountered in domes. Investigations on bedded salt have demonstrated that textural effects due to intercalated impurities (e.g., clay, sulfate layers) may have a significant influence on roof stability and development of the EDZ. Influence of inhomogeneities are manifested at WIPP, as shown in Figure 4.2. Inhomogeneous layering can be seen in the hanging roof beam. The stratigraphy at WIPP contains many laminations, some of which are thin. The WIPP disposal horizon was selected, in part, to accommodate shear along a clay seam coincident with the top of the pillars. The idea was the clay seam would allow the pillars to expand laterally without buckling the roof beam.

IfG recently performed a systematic experimental study to quantify the impact of textural salt features on its mechanical properties. Triaxial, shear and tensile strength tests were performed investigating three texturally distinct different salt rocks (weakly to strongly layered) applying different loading directions related to the bedding, as shown in Figure 4.3. For example, depending on the rock type, the local tensile strength can vary between nearly zero and around 2 MPa. However, the experimental outcome also showed that not every macroscopically recognizable anhydrite/clay layer within the salt host rock is also a weakening plane. Due to the challenge of an appropriate geomechanical description, it follows that for each site (i.e., bedded, pillow, or domal salt), an individual case-specific examination (with in-situ and laboratory investigations) must be carried out to provide the necessary database for subsequent rock-mechanical modeling to demonstrate room stability (in the near field) and barrier integrity (in the far field). An additional study of shear behavior of intercalations for the WIPP site is part of the WEIMOS collaboration.

Figure 4.2: Roof fall in Panel 3 access drift at WIPP.

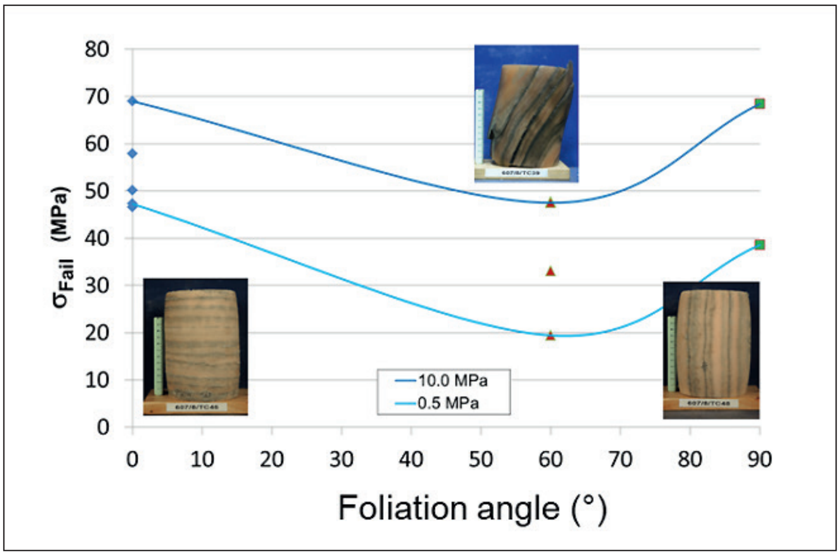


Figure 4.3: Triaxial strength of bedded salt related to the bedding.

Like mechanical planes of weakness, lithological intercalations may provide preferred pathways for fluid migration. These features are mostly horizontal in bedded formations, while steeply inclined in random parts of a dome setting. Intercalated layering in salt formations can also create positive, natural sealing. Under certain site-specific geologic backgrounds, thicker clay layers (up to 20 m) in flat bedded, pillow and domal salt structures may provide an impermeable lithological seal. Such intercalations are typical constituents of the stratigraphic rock column in the European Zechstein basin. They may act as additional geological (clay-based) barriers with possible advantages regarding the safety concept (“geological multi-barrier system”). At the moment, we know too little about the composition, lithology, distribution and properties of these clay-based barriers.

Another topic that was discussed in the KOSINA project is the role of different water contents in domal and bedded salt. Reliable data about the initial water content of salt rock are needed, because it is relevant for salt creep and for the compaction behavior of crushed salt if excess water from the host rock salt has access to the mine workings. The water content in domal salt is very low (lower than 0.05 wt.-%): in flat-bedded salt rocks, the water content is higher, reaching locally more than 1-2 wt.-%. The current database is insufficient and could be improved with additional information from various locations.

4.3 Comments on Modeling

The breakout session pondered the question: Which formation is more variable? In early repository deliberations in the US, salt formations were identified as the most promising geologic setting. From the 1970s onward, until political compromises gave rise to the Nuclear Waste Policy Act of 1982 (amended in 1987), salt studies were the focus of disposal programs. Early mechanical testing of salt from domes in Louisiana, Mississippi, and Texas suggested the salt was “sculpture-quality”: clean, uniform, and relatively dry. By comparison, bedded salt was wetter and included nonsalt layering, introducing inhomogeneities. The breakout session explored some of these general concepts. Sobolik pointed out from his long-term involvement in the US’ Strategic Petroleum Reserve Program that diapiric salt domes can have complex internal structure because of extraordinary deformation. This is mostly the case for isometric salt domes: the internal structure of elongated salt domes is less complex. Calibration of storage caverns to subsidence and workover response has proven to be highly variable and has fewer control points than field experiments in underground research facilities.

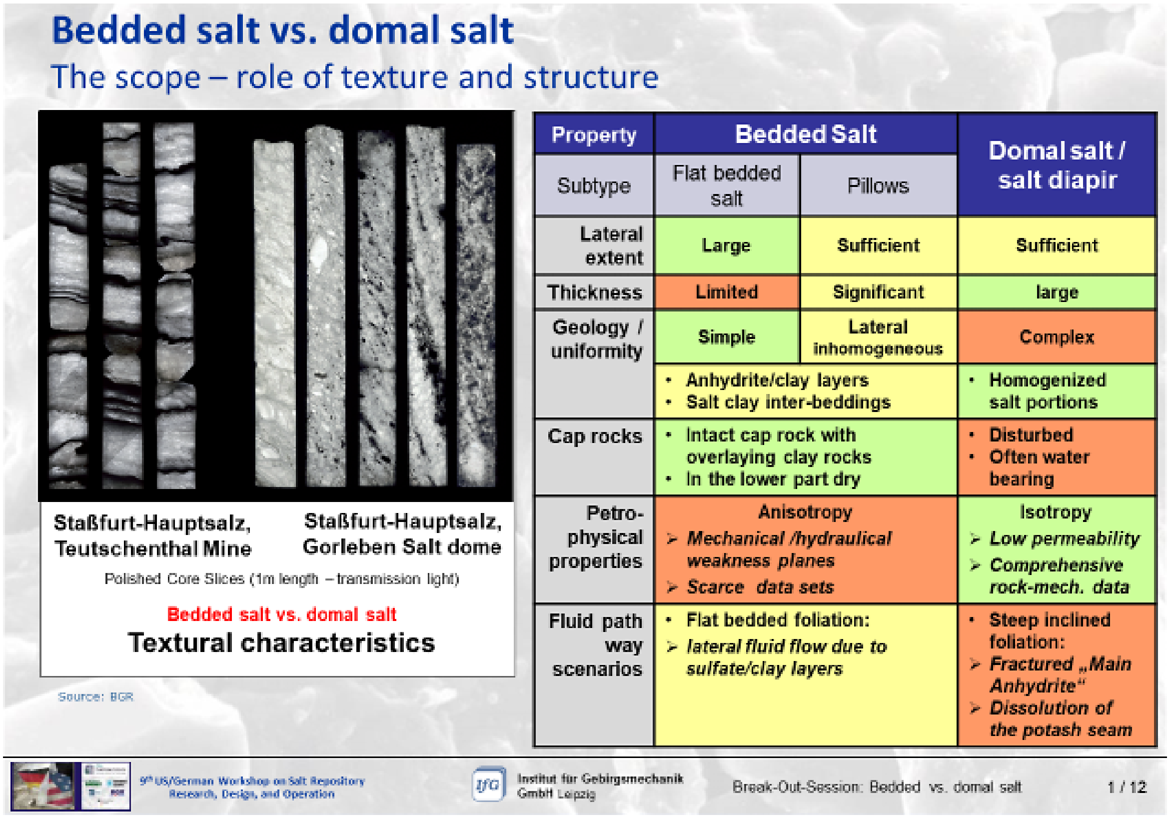
US/German Workshops have focused effort on developing thorough understanding of salt repository design, analysis, operation, and long-term prediction. A necessary component of these efforts is credible modeling of structural response. As noted in the WEIMOS summary (Chapter 2), matching or simulating experimental results can be challenging. Salt mechanical models and properties such as creep, strength, and dilatancy envelopes are based on laboratory tests. As noted by Sobolik, inevitable discrepancies exist between model results and observed behavior. Applied modeling illustrates that work remains to be done. Modeling is imperfect, even when exceptional detail is available.

4.4 Concluding Remarks

The technical basis for a salt repository has been well established in many areas and we continue to research facets that can be improved. In part, the US/German Workshop identifies areas of special interest each year. We tend to follow the empirical evidence, acknowledging that each site will offer unique characteristics. Constitutive models, for example, account for many driving mechanisms of deformation but will necessarily be calibrated for a selected salt site. Salt deformational behavior exhibits classic similarities, while discontinuities may complicate structural response of flat-lying formations. In turn, lithological intercalations influence development of the EDZ, availability of formation brine, and design of seal systems.

A one-page summary table of this breakout session was presented by Till Popp and is reproduced in Figure 4.4. Salt domes provide impressive areal expressions combined with great vertical dimensions often comprising relatively pure salt compared to bedded formations. Multiple-level construction and disposal concepts might be more readily achievable in a dome. Disposal in a borehole drilled into the floor of a drift would be more predictable in a dome than a similar strategy in bedded salt because of its intercalations of clay and anhydrite. The enormous areal dimensions of bedded or pillow salt formations would prove to be advantageous if a modular, design-build-operate-and-close concept is adopted.

Protocol for licensing a salt repository involves assessment of features, events and processes (FEPS). In detail, some differences between salt formations might be significant enough to render alternative treatment in the FEPs analysis. However, the FEP interaction must be quantifiable and therefore measurable.



Property	Bedded Salt		Domal salt / salt diapir
Subtype	Flat bedded salt	Pillows	
Lateral extent	Large	Sufficient	Sufficient
Thickness	Limited	Significant	large
Geology / uniformity	Simple	Lateral inhomogeneous	Complex
	• Anhydrite/clay layers • Salt clay inter-beddings		• Homogenized salt portions
Cap rocks	• Intact cap rock with overlaying clay rocks • In the lower part dry		• Disturbed • Often water bearing
Petro-physical properties	Anisotropy ➢ *Mechanical /hydraulical weakness planes* ➢ *Scarce data sets*		Isotropy ➢ *Low permeability* ➢ *Comprehensive rock-mech. data*
Fluid path way scenarios	• Flat bedded foliation: ➢ *lateral fluid flow due to sulfate/clay layers*		• Steep inclined foliation: ➢ *Fractured „Main Anhydrite“* ➢ *Dissolution of the potash seam*

Figure 4.4: Comparison of texture and structure.

5 Design Aspects

Throughout the life-cycle of a repository, designs of varying levels of detail and for advancing purposes are required. Designs increase in detail from initial generic levels, to conceptual designs for siting, to more-detailed technical levels for licensing and construction, and ultimately a design for closure. Such designs consist of preliminary concepts in the context of feasibility studies and early safety analyses as well as of detailed designs for the repository mine layout and demonstration of the integrity of geological and geotechnical barriers prior to submitting license applications. Beyond that, there is a necessity to consider the impact of retrievability requirements on the repository design, at least in Germany. Accordingly, case studies, research activities, project results, and discussions relevant to repositories in bedded and domal salt were presented in this session and are summarized in this chapter.

First, a case study was presented dealing with the characteristics of clay-salt complexes in salt diapirs. Mr. Burliga from the University of Wroclaw, Poland, introduced the geological map of Poland and highlighted particular areas with clay-salt rock formations, which are considered suitable host rocks for a repository in Poland. In the context of a case study, the detailed internal structures and the deformation of clay-rock complexes in a salt diapir were investigated, the results of which were explained in detail. The benefit of a combination of two important host-rock features for radionuclide isolation, namely the heat and pressure dependent convergence of rocksalt and the retardation capacity of clay materials were highlighted. Repository concepts have not yet been developed in detail.

Design considerations also included the final results from the KOSINA project, which has been presented and discussed in preceding workshops (for example, see Chapter 5 of the Proceedings of the 9th US/German Workshop on Salt Repository Research, Design, and Operation, 2018). KOSINA stands for Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept. The KOSINA project is a joint undertaking of the BGR, GRS, IfG and BGE TECHNOLOGY funded by the BMWi. The detailed results were presented by two young engineers/scientists from BGE TECHNOLOGY and IfG, both starting their professional career with this R&D project. They showed detailed results and summarized the following main points:

- An appropriate Safety and Demonstration Concept has been developed
- Two generic geological models for flat-bedded and salt pillow formation have been developed representing typical geological environments in Germany
- Design and planning of four different disposal concepts in bedded salt formations have been realized, adjusted to the geological environment, and comprise these key features:
  - Thermal design of HLW repository in compliance with the temperature criterion
  - Conception of the repository mine layout
  - Design and planning of transport and emplacement technology
  - Design of geotechnical barriers

- A new idea for an emplacement technology for a horizontal borehole disposal concept
- Numerical modeling calculations were performed for the safety analysis, including evaluation of the integrity of the geological barriers and analyses of radiological consequences. In this context, numerical simulations on barrier integrity were performed for two disposal concepts in two generic geological models. These included different model dimensions, constitutive models, and modeling methods (BGR +IfG). The results showed:
    - Uplift-induced temporary violation of the fluid pressure criterion in a limited area at the top of the salt
    - Penetration depth and duration of violation depends on disposal concept and geological model
    - Barrier integrity preserved in all cases, at least 300 m of undisturbed rock salt remains above the repository mine
- The analyses of radiological consequences, performed by GRS, for the four repository concepts showed no exceedance of Radiologischer Geringfügigkeits-Index (index of marginal radiological impact (RGI)) within the demonstration period of one million years and longer.

In conclusion, it was stated that the KOSINA project has shown the technical feasibility of constructing an HLW repository in bedded salt formations in Germany and that the required safety and integrity requirements will be met throughout a one-million-year demonstration period.

Retrievability requirements for disposing of heat generating waste and spent nuclear fuel have existed in Germany since October 2010. These regulations state that measures taken to secure the option of recovering or retrieval must not impair the passive safety barriers and thus the long-term safety. The results of R&D projects investigating the impacts of this requirement on the repository design have been presented in previous workshops. At this workshop a comparison was shown between ex-ante and ex-post planning of waste retrieval in salt repositories. Examples for ex-ante planning were given first, showing that the retrievability requirement does not impair long-term safety but might have an impact on the design provisions. In the case of disposing of self-shielding POLLUX® casks on the floor of emplacement drifts in a salt mine, the main impact is on the technical equipment for dismantling backfilled drifts and on the device for picking up a disposed waste package. However, the necessary design can be made in advance and approved by demonstration tests. The same is true for the concept of disposing of waste canisters into vertical boreholes. In this case, the main impact is that a liner is required and a redesign of the canister is needed to strengthen the canister for the retrieval process out of the lined borehole. Again, the necessary design can be done prior to submitting a license application. A different situation was presented as well showing the planning and the activities already undertaken to test the retrieval of low-level waste out of the Asse mine. In this case, ex-post planning is required, which shows a completely different approach. All necessary planning steps must be adjusted to the real situation at the site, at the specific emplacement rooms. This requires detailed investigations of the geomechancial conditions at the appropriate location in the mine. The data achieved may allow an assessment of the geomechanical changes when opening the emplacement rooms and removing the backfill material first. The radiological situation must be measured continuously; prior to any removal action and afterwards following the next steps of backfill and waste recovery. It was stated very clearly that technical solutions can be developed even for such a situation, but the advantage of ex-ante planning of course are obvious.

The status at WIPP continues to be of utmost interest, because it illustrates dynamic design choices under difficult conditions. As in the last workshops, an update on the situation at the WIPP was given by SNL/DOE highlighting the progress in remediation of the mine after the 2014 accidents and the restart of the waste shipment and emplacement in spring 2017. WIPP is continuing to be challenged with its mission due to the low ventilation rate, which is impacting mining, maintenance, and emplacement. It was mentioned that construction projects are underway to address low ventilation rates and enable

WIPP to resume full operations. However, it will take another 2 years until the new ventilation system will be constructed and in full operation. To achieve this goal, a significant amount of regulatory work is anticipated. With regard to future work, a preview of a concept to dilute and dispose surplus plutonium was introduced. WIPP would dispose of transuranic waste similar to waste streams that have previously been accepted and emplaced from several DOE sites. The US National Academy of Sciences is reviewing this approach. In case of acceptance, the approach will require enlargement of the repository. The evolving WIPP story remains of high interest to these workshops.

6 Concluding Remarks and Outlook

These Proceedings include summarizing chapters that document the activities, results,and advances at the 9th US/German Workshop on Salt Repository Research, Design, and Operation. In addition, the workshop's technical agenda, presentations, and abstracts (as provided) are included in the appendices of the document. In this way, the labor of ongoing partnerships on well-established investigations as well as emerging research topics are not only well documented but also made available to a larger community.

The US/German workshops serve as a platform for identifying a research horizon comprising achievable objectives of common interest. Collaborators discuss constructive near-term issues and agree to pursue mutually advantageous topics; these decisions help shape the agenda for the next workshop to be held at the South Dakota School of Mines & Technology in Rapid City, South Dakota, USA, May 28-29, 2019.

The agenda itself remains fluid and at the discretion of the organizing committee, but several main thrust areas were agreed upon. The technical salt community can expect to continue review of geomechanical modeling and testing via the highly successful WEIMOS project, which includes several partners. A similar session concerned with hydromechanical modeling was also suggested. A session on engineered barrier systems including sealing systems, backfill, and engineered barriers was favored by several participants. Near the conclusion of the 2018 Hanover workshop, two specific breakout sessions were identified: Natural Closure of Salt Openings, and Laboratory Test Sample Conditioning. Both topics are contemporary and applied among several partners. Breakout sessions also capture a "workshop" spirit, which is one of the founding tenets of these ongoing collaborations.

7 References

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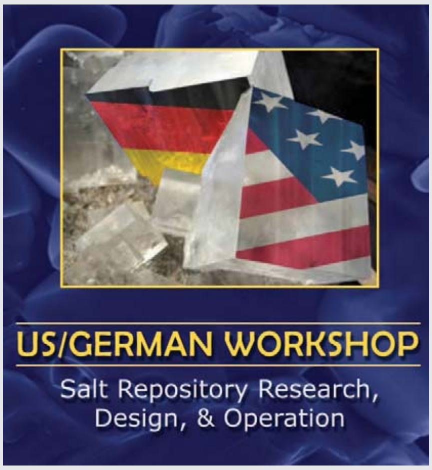
APPENDIX A: AGENDA

Final Technical Agenda

9th US/German Workshop on Salt Repository Research, Design, and Operation



September 10th and 11th, 2018

Venue: BGR (Federal Institute for Geosciences and Natural Resources)
Stilleweg 2, 30655 Hannover, Germany
Großer Sitzungssaal

September 10 – Monday

Day 1	08:30-09:15	**Registration**	
	09:15-09:30	**Kick off** and organizational details	W. Bollingerfehr, BGE TECHNOLOGY GmbH M. Bühler, KIT-PTKA S. Dunagan, SNL
	09:30-09:45	Welcome BGR	G. Enste, BGR
	09:45-10:00	Welcome BMWi	U. Borak, BMWi
	10:00-10:15	Welcome BGE	W. Hund, BGE
	10:15-10:45	Welcome DOE and Summary of US WM status	T. Gunter, DOE
	10:45-11:15	**Coffee Break** and **Group Photo**	
	11:15-11:30	Short Report on NEA Salt Club Meeting	J. Mönig, GRS
	11:30-12:00	IAEA presentation: International Issues in Salt Repository Development	A. Orrell, IAEA
	12:00-12:30	EPA presentation: Regulator's perspective	T. Peake, EPA

Final Technical Agenda

9th US/German Workshop on Salt Repository Research, Design, and Operation

12:30-13:30	**Lunch**	
	Joint Project WEIMOS (chair: M. Bühler, KIT-PTKA)	
13:30-14:00	Current Status of Research in Joint Project WEIMOS	A. Hampel, Hampel Consulting
14:00-14:20	Salt testing: bedding planes	S. Buchholz, RESPEC S. Sobolik, SNL
14:20-14:40	Micromechanical investigations	M. Mills, SNL
14:40-15:00	Simulations of Canister Compaction at WIPP	B. Reedlunn, SNL
15:00 15:30	**Coffee Break**	
	Key aspect session (chair: S. Dunagan, SNL) ***Engineered Barrier Systems (Concepts, materials, and demonstration)***	
15:30-16:00	R&D Project ELSA II - Compaction of crushed salt-clay-mixtures with high compaction energy	J. Aurich, TU BA Freiberg
16:00-16:30	Seals and Sealing Materials for a Salt Repository	E. Matteo, SNL
16:30-17:00	Description of a large scale pilot plant designed to analyze sealing systems of cut salt bricks	U. Düsterloh, TU Clausthal
17:00-17:30	Drift Seal Systems at the Morsleben Repository - Status of Investigations and Further Procedure	J. Wollrath, BGE
17:30-18:00	Industrial Planning and construction of drift seals in the Asse mine	N. Müller-Hoeppe, BGE TECHNOLOGY GmbH
19:00	**Workshop Dinner** (Altes Rathaus Karmarschstraße 42, 30159 Hannover)	

Final Technical Agenda

9th US/German Workshop on Salt Repository Research, Design, and Operation

September 11 – Tuesday

Day 2			
	Special Topics (chair: K. Kuhlman, SNL)		
	09:00-09:30	Operational Safety at WIPP	S. Dunagan, SNL
	09:30-10:30	Geochemistry in support of potential emergency measures for Schachtanlage Asse II	
		1. Introduction	M. Altmaier, KIT-INE
		2. Conceptualization of Radionuclide Source Term	J. Mönig, GRS
		3. Modeling the Geochemical Evolution and Gas Formation in Emplacement Chambers of the ASSE II	L. Wissmeier, CSD
		4. Radionuclide source terms, solubility and retention processes	M. Altmaier, KIT-INE
	10:30-11:00	**Coffee Break**	
	Repositories in bedded and domal salt (chair: W. Bollingerfehr, BGE TECHNOLOGY GmbH)		
	11:00-11:30	Internal structure and deformation of clay-salt rock complexes in salt diapirs: a case study from the Polish Zechstein Basin area.	S. Burliga, University of Wrocław
	11:30-12:00	WIPP: Status and future works	S. Dunagan, SNL
	12:00-12:30	Ex ante vs. ex post planning of radio-active waste retrieval in salt repositories	J. Mönig, GRS
	12:30-13:30	**Lunch**	
	Repositories in bedded and domal salt cont'd (chair: W. Bollingerfehr, BGE TECHNOLOGY GmbH)		
	13:30-14:00	KOSINA project results: Generic geological modelling, design parameters and repository concepts	E. Simo, BGE TECHNOLOGY GmbH
	14:00-14:30	KOSINA project results: Safety concept / safety assessment and geomechanical integrity analyses	M. Knauth, IfG GmbH

Final Technical Agenda

9th US/German Workshop on Salt Repository Research, Design, and Operation

14:30-15:00	**Coffee Break**	
Repositories in bedded and domal salt cont'd (chair: F. Hansen, Professional Associate RESPEC Inc.)		
15:00-16:30	Break-Out Session: Comparison of bedded and domal salt	With the opportunity for some short presentations (invited by the chair) to open the discussion.
16:30-16:45	Wrap up and outlook	W. Bollingerfehr, BGE TECHNOLOGY GmbH M. Bühler, KIT-PTKA S. Dunagan, SNL
16:45	*Adjourn for the day –* *no scheduled group activity*	

Organized by:	Project Management Agency Karlsruhe (PTKA) Karlsruhe Institute of Technology (KIT)
Information/ Registration:	http://www.ptka.kit.edu/veranstaltungen-2120.html (For late registration please contact michael.buehler@kit.edu)
Costs:	100,- € (payment with registration) for the catering during the two workshop days (all food and beverages)
Venue:	Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Großer Sitzungssaal (with friendly assistance by BGR)
Program committee:	W. Bollingerfehr (BGE TECHNOLOGY GmbH), S. Dunagan (SNL); M. Bühler (KIT-PTKA)
Contact:	Michael Bühler Project Management Agency Karlsruhe (PTKA) Karlsruhe Institute of Technology (KIT) Hermann-von-Helmholtz-Platz 1 76344 Eggenstein-Leopoldshafen, Germany email: michael.buehler@kit.edu phone: +49 721 608-24844, mobile: +49 160 7470666

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

APPENDIX B: WELCOME ADRESSES

Gerhard Enste

Federal Institute for Geosciences and Natural Resources (BGR)

Dear Ladies and Gentlemen,

it is my great pleasure to warmly welcome you here at the Federal Institute for Geosciences and Natural Resources – BGR – in Hannover to the 9th US/German Workshop on Salt Repository Research, Design, and Operation. I would like to thank the Project Management Agency Karlsruhe (PTKA), Karlsruhe Institute of Technology (KIT) very much for organizing this workshop as well as the Programm committee Wilhelm Bollingerfehr from BGE Tec, Sean Dunagan from Sandia National Laboratories, and Michael Bühler from the Project Management Agency Karlsruhe (PTKA), Karlsruhe Institute of Technology (KIT).

BGR is the central geoscientific authority in Germany and acts as the German geological survey and is subordinate to the Federal Ministry for Economic Affairs and Energy (BMWi). It advises federal ministries and European institutions in all geo-relevant questions and acts as a partner to the scientific community. Cooperation with international partners has always been an integral component of BGR's work in the various fields of our activities. Activities with a strong international orientation include: sustainable use of mineral resources, groundwater management, and technical cooperation with developing countries. As one of BGR's main topics, the field of radioactive waste disposal has always included the exchange of ideas within the international scientific community. BGR's task in this field is to provide the German Government with independent advice on all geoscientific issues concerning nuclear repository projects.

In Germany, the search and selection of a site for a repository for heat-generating radioactive waste is regulated by the "Act governing the search and selection of a site for a repository for high-level radioactive waste" (Site Selection Act – StandAG). In a new multi-phased comparative process, the site with the best-possible safety for one million years is to be determined, and then defined by an act of parliament. One of the new aspects here is increased public involvement right from the start of the process. Every step of the procedure must be transparent and comprehensible. The potentially suitable host rocks salt, claystone, and crystalline for a repository for radioactive waste in Germany will be taken into consideration as part of this process. A new task of the BGR is to support the BGE, the federal company for radioactive waste disposal. Since the 25th April of 2017 BGE is entrusted with the task of implementing the site selection procedure for a final repository in Germany, particularly for heat-generating radioactive waste. As part of an agreement on collaboration, it is planned that the BGR will investigate specific issues on behalf of the BGE and thereby support the BGE in finding a site with the best possible safety for a repository for high-level radioactive waste. Furthermore, BGR will carry out research and development work on behalf of the BGE.

BGR therefore participates in numerous international research projects, cooperation activities, and the technical-scientific exchange of experience with international experts to enlarge its understanding of geoscientific and geotechnical technologies with respect to criteria and methods for the investigation of all potentially suitable host rocks in Germany, and to underpin its research findings. BGR presents its expertise on salt, claystone, and crystalline on international conferences and organizes international conferences itself, like the PEBS-conference (the international Conference on the Performance of Engineered Barriers) and the SaltMech.

The agenda for this US/German Workshop is focused on engineered barrier systems and repositories in bedded and domal salt. As new results from research and rock engineering projects have been accumulated in the last year we look forward to an informative workshop with lively discussions and breakout sessions. I wish you a very pleasant stay at the BGR and in Hannover, and for the most of you also a successful participation in the SaltMech IX conference following this workshop here at BGR .

Thanks for coming.

U. Borak

Federal Ministry for Economic Affairs and Energy (BMWi)

Ladies and Gentlemen,

On behalf of the Federal Ministry for Economic Affairs and Energy, I would like to welcome you to our ninth U.S.-German Workshop on “Salt Repository Research, Design, and Operation”. This workshop has been jointly organised by Sandia National Laboratories, BGE TECHNOLOGY, and Project Management Agency Karlsruhe, with the support of the Federal Institute for Geosciences and Natural Resources – the BGR – which is hosting the workshop this year.

I am delighted that around 60 participants from Germany and from abroad have made their way to Hanover, the capital of Lower Saxony.

The chosen venue in the North German basin is of geological interest as we are surrounded here by salt structures underground. And it is also of special interest for us to spend the next two days at Germany’s geological service, the BGR. I would like to sincerely thank our host for all of its work in preparing this workshop.

As you probably know, there is a whole week of events in international salt research taking place. After our U.S.-German workshop, over 150 international participants will gather for the SALTMECH conference here at the BGR. And last Friday, the OECD NEA Salt Club also held its meeting here in Hanover.

The fact that so many colleagues are attending this workshop, not just from Germany but especially from abroad – from the United States, the Netherlands, Poland, and Switzerland, as well as from the International Atomic Energy Agency – shows the high level of international interest in salt research. It also underlines the particular importance of sharing knowledge and experience with one another in this area.

This is already our 9th workshop! – The currentness of the findings presented here and the continuity of our scientific exchange demonstrate the added value that we derive from our collaboration.

Ladies and Gentlemen,

I am particularly pleased that Mr Tim Gunter from the U.S. Department of Energy’s Office of Nuclear Energy has made the long journey to Hanover to attend this year’s workshop. This shows that both the U.S. DOE and the German Federal Ministry for Economic Affairs and Energy value this cooperation, which has been in place since 2011.

Our cooperation has been characterised by excellent scientific and technical relations, but also by the close personal contacts that have existed for many years now and the trust that has grown out of these. I would therefore like to express a special welcome to the “fathers” of the U.S.-German cooperation: Frank Hansen and Walter Steininger, and to thank them for all their hard work. Their efforts have enabled the cooperation between our two countries to grow and reach the outstanding level of science which we exchange upon today.

At the last workshop in Middelburg, these two colleagues passed on the baton to the next generation – to Sean Dunagan from Sandia National Laboratories and Michael Bühler from

Project Management Agency Karlsruhe. I wish the new leaders on both the U.S. and the German sides, together with Wilhelm Bollingerfehr from BGE TECHNOLOGY, every success in their future work in coordinating the U.S.-German cooperation.

The fruitful scientific exchange between our two countries will continue to be highly important, not least in the tasks of nuclear waste disposal that lie ahead of us.

Ladies and Gentlemen,

What are the current and future tasks of nuclear waste disposal facing us in Germany? During the last parliamentary term, we succeeded in taking major steps forward in defining the legal and organisational framework for the disposal of radioactive waste. This included modifying the site selection procedure for identifying a suitable final repository for highly radioactive waste and restructuring the funding for storage and disposal.

The Act “Reorganising Responsibility for Nuclear Waste Management” was drawn up under the leadership of the Economic Affairs Ministry. It has fundamentally answered key questions around the financing, decommissioning, and dismantling of nuclear power plants, as well as interim storage and final disposal, and sets out an organisational structure. The Act entered into force on 16 June 2017. It will prevent any situation whereby costs would be shifted towards society, whilst also avoiding any undue economic burden being placed on operators.

The Environmental Ministry was in charge of further developing the Site Selection Act, which stipulates the site selection procedure and related organisational issues. This Act entered into force on 16 May 2017. Details on the site selection procedure and the organisational structure have already been presented during the last meetings.

Reorganising responsibilities and ensuring the independence of the regulatory authority are further key issues. This included setting up the Federal Office for the Safety of Nuclear Waste Management in 2014, which commenced its work as regulatory authority in 2016. It also involved the amalgamation of Asse GmbH, the DBE, and parts of the Federal Office for Radiation Protection to create the state-owned repository operator, the Federal Company for Radioactive Waste Disposal – or BGE – in 2016. The responsibilities for operating interim storage facilities have also been reassigned. What used to be a task for the nuclear power plant operators themselves is now taken care of by the Federal Company for Interim Storage – the BGZ, which was founded as a spin-off of the Nuclear Service Company in 2017.

These institutions are currently being established and will report to the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety.

Following a restructuring process, the research institution DBE TECHNOLOGY was renamed BGE TECHNOLOGY on 21 June this year. Its leadership has also undergone a generational hand-over. The technical management has been passed on from Jürgen Krone to Thilo von Berlepsch. I would like to offer my congratulations on this.

Ladies and Gentlemen,

As the authority that is independent of the site selection process and of regulatory matters, the Federal Ministry for Economic Affairs and Energy is also responsible for basic and methodological research regarding the disposal of radioactive waste. In this way, the Economic Affairs Ministry ensures comprehensive and broad scientific and methodological support for the disposal of highly radioactive waste. This work is strengthened through international networks and experience which will be continued and driven forward in the future.

More than ever, research into disposal is focused on creating a scientific and technical basis for building a final repository. This means that we need to continue to do ground-breaking work in these fields, to build new skills, and to train the next generation of researchers. The Economic Affairs Ministry's research into disposal seeks to achieve these objectives.

The amended regulation governing Germany's site selection procedure for particularly highly radioactive waste provides for different host rock options to be given equal consideration. This means that the disposal of radioactive waste in salt as a host rock must continue to be regarded as a future option for the final disposal of radioactive waste. The need for further research in this area is also reflected by the tasks included in the Federal Ministry for Economic Affairs and Energy's current research programme.

We are convinced that the U.S.-German collaboration makes a considerable contribution to both research into rock salt, as well as further issues of common interest. The United States thus continue to be an important partner for Germany in the field of research, and the most important partner in the field of research into salt as a host rock. The scientific agenda for the 9th workshop particularly includes the joint WEIMOS project for developing and testing rock mechanical modelling for repositories in rock salt, engineered barrier systems such as concepts, materials, and demonstration on shaft or drift sealing, and repositories in bedded and domal rock salt, including a break-out session to compare bedded and domal salt.

Our international cooperation allows all partners to benefit from synergies that will help them in their own programmes. We can all benefit from the findings, both in scientific and economic terms, and continue our work based on what we have already achieved.

An example here is a recently approved, joint project entitled KOMPASS, which will investigate the compaction of crushed salt used as backfill material in a repository in rock salt and is being conducted by GRS, BGE TECHNOLOGY, IfG Leipzig, and Clausthal University of Technology – together with the associated partners BGR and Sandia National Laboratories.

The outcomes of joint scientific discussions provide an important stimulus for both new and current issues. This will continue to be the common added value of our cooperation.

Ladies and Gentlemen,

To finish, I would like to sincerely thank the leaders – Sean Dunagan, Michael Bühler, and Wilhelm Bollingerfehr – for their outstanding preparation of this workshop, and also the host – the Federal Institute for Geosciences and Natural Resources.

I wish you all a successful workshop, lively discussions, and a nice stay in Hanover.

Dr. Wilhelm Hund

Federal Company for Radioactive Waste Disposal (BGE)

Dear ladies and gentlemen, dear colleagues!

It is a great honour to me to welcome you on behalf of the Federal Company for Radioactive Waste Disposal and especially on behalf of our management board to the 9th US/German Workshop on Salt Repository Research, Design and Operation.

I want to thank the organization board for giving us the opportunity for this welcome address.

The numerous attendees from BGE indicate our strong intention to enhance the scientific exchange not only on the issue of the host rock salt but for all potential host rock systems.

To my person: My name is Wilhelm Hund. I'm geologist, for nearly thirty years working in the field of disposal of radioactive waste and actually designated head of division for Research, Development and Knowledge Management at the BGE.

Let me give a short insight in the BGE: At present the BGE, the Bundesgesellschaft für Endlagerung is amid of a comprehensive transforming process to accomplish the integration of three precedent institutions, the Department for Nuclear Safety of the Federal Office for Radiation Protection, the former implementer and operator, the German Company for the Construction and Operation of Repositories, and the Company for Operating the Asse Mine.

As you know, we restarted and reorganized the task of managing radioactive waste in Germany.

The Federal Government decided in 2011 to develop a new site selection procedure to identify a site for a geological repository for mainly heat-generating radioactive waste. With hindsight of the long lasting political and societal conflicts about the Gorleben project this new approach should be based on a great national consensus and was indeed supported by all political parties represented in the German Bundestag. Prerequisites for this national consensus were the phasing out of the commercial production of electricity from nuclear energy and the termination of the exploration of the Gorleben salt dome.

This new approach has been evaluated by the Endlagerkommission, a commission of experts, politicians, and representatives of diverse societal groups set up by the German Bundestag. The outcome of this evaluation process is the amendment of the site selection act in the year 2016 and a comprehensive restructuration of the organisation of radioactive waste management in Germany. The tasks of the implementer and of the operator should no longer be performed by a federal office but by a company in the ownership of the Federal Government. And all operator activities should be bundled by this new formed company with the aim to increase efficiency in fulfillment the tasks of the safe disposal of radioactive waste.

The BGE is one of the outcomes of this reorganisation process and was established in 2016. The only shareholder of the BGE is the Federal Government of Germany, represented by the BMU, the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety.

BGE commenced its work in April 2017 with about 180 employees from the former Department for Nuclear Safety of the Federal Office for Radiation Protection. At the end of 2017 the DBE and the Asse with at all 1.700 employees were integrated. The outstanding challenges for the BGE and for the about 1.900 employees at eight sites in Germany are the complexity of the merging process because of the very different structures in the preceding institutions and the constraint not to affect adversely the ongoing main tasks and projects (for example the transformation of the Konrad mine in to a repository).

The number of 1.700 employees sounds enormous great, but there is included the staff for operating four mines: Asse, Gorleben, Konrad and Morsleben. Remembering the German dictum: „Bergbau ist nicht eines Mannes Sache!“ (Mining is not the issue of a single man!) we have to deal with very complex and diverse structures and organizations for the operation of these mines. There are really many parallel structures and processes we have to bring together and to homogenize.

By the 15th of September – that is the end of this week – a first but still preliminary organization structure will be brought into force. Our next move will be the elaboration and implementation of substructures including the adaption of the needed processes and workflows. We work on finalizing the new organizational structure by the end of the year 2018.

To come eventually to R&D: The Endlagerkommission recommended both the implementer and operator as well as the regulator and licensing authority to establish independent promotion and funding of research activities to meet their specific R&D-demands. In following these recommendations the BGE supplements its organization with the new division “Research & Development and Knowledge Management”.

The BGE research activities in the field of the disposal of radioactive waste shall primarily serve to fill existing skill shortages and should enable BGE as the responsible implementer and operator to meet the scientific and technological challenges of the different repository projects and the site selection procedure. The research activities of the BGE don’t primarily aim to foster the state of the art in science and technology. These more fundamental scientific research tasks lay furthermore in the responsibility of the Federal Ministry of Education and Research and the Federal Ministry for Economic Affairs.

The Endlagerkommission stipulated for the new site selection procedure to be transparent, open, self-critical, and self-scrutinizing as well as learning. These principles are indispensable for the organisation and the work of the BGE as the implementer and operator as well as for the R&D-activities of the BGE.

In order to meet all these challenges we will enhance and broaden the cooperation with the BGR, the GRS and the research institutes in the domains of the Federal Ministry of Education and Research and of the Federal Ministry for Economic Affairs. We strive to enhance the cooperation with universities in Germany and with our partners abroad, namely for example the Andra, the Nagra and the SKB.

With our subsidiary company BGE-Technology, we have at hand a research and consulting institute with long-standing experience in diverse research programmes in the domain of waste management and mining. The BGE-Technology is embedded in our R&D-activities; and we will promote the cooperation with the BGE-Technology and its partners.

Germany will conclude the peaceful use of nuclear energy within the next four years, but we will have to deal with its legacy still for many decades in order to ensure a safe confinement of the radioactive wastes in an appropriate underground repository in deep geological formations.

This long-lasting, manifold and interdisciplinary task requires employees with different specialist skills and knowledge in natural sciences, engineering sciences, and also in social sciences. And there we are in a slight dilemma, for in Germany we are not only phasing out in the domain of nuclear engineering but also in the domain of mining engineering and have therefore to face the challenge to preserve the needed expertise and skills in these domains.

In modification of the cited dictum “The safe disposal of radioactive waste is not an issue of a single generation!” let me conclude: Besides the challenge of generating and providing the needed scientific knowledge and the needed technical findings we have to promote young scientists in order to have at hand skilled staff to apply the scientific knowledge and findings in due time.

I wish us a successful workshop with an open knowledge exchange and interesting perhaps even captivating discussions that might help us in our work and in promoting our projects.

Thank You and Glückauf!

APPENDIX C: LIST OF PARTICIPANTS AND OBSERVERS FROM 9th WORKSHOP

Surname	First Name	Affiliation	Email
Altmaier	Marcus	Karlsruhe Institute of Technology, Institute for Nuclear Waste Disposal Germany	marcus.altmaier@kit.edu
Aurich	Jan	TU Bergakademie Freiberg Germany	jan.aurich@mabb.tu-freiberg.de
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Bödecker	Stephan	State Authority for Mining, Energy, and Geology (Lower Saxony) Germany	stephan.boedecker@ lbeg.niedersachsen.de
Bollingerfehr	Wilhelm	BGE TECHNOLOGY GmbH Germany	wilhelm.bollingerfehr@bge.de
Borak	Ursula	Federal Ministry for Economic Affairs, and Energy Germany	
Buchholz	Stuart	RESPEC USA	stuart.buchholz@respec.com
Bühler	Michael	Karlsruhe Institute of Technology, Project Management Agency Karlsruhe Germany	michael.buehler@kit.edu
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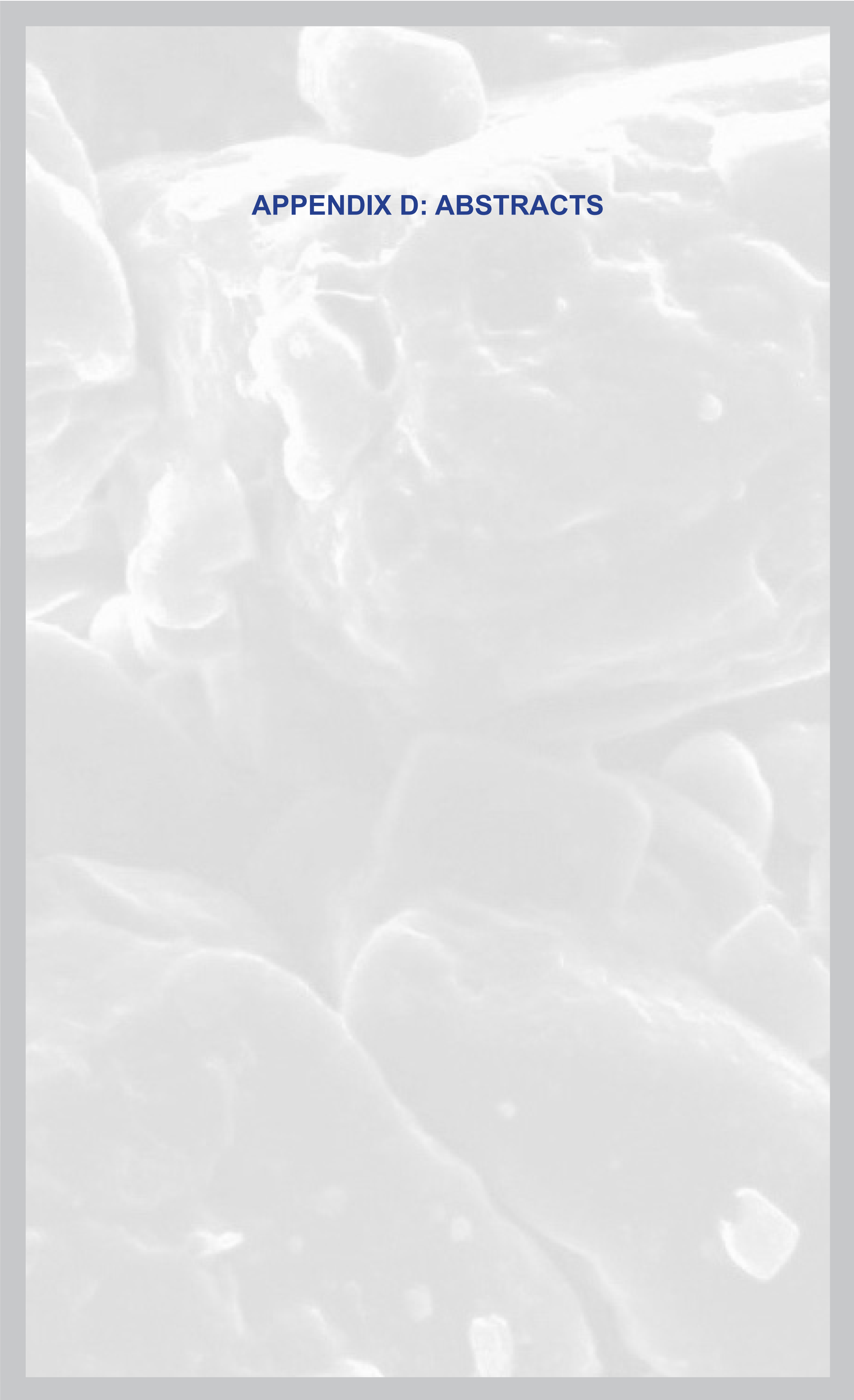

APPENDIX D: ABSTRACTS

Some Safety Case Related Regulatory Challenges at the Waste Isolation Pilot Plant

R. Thomas Peake, Ingrid Rosencrantz, Daniel Schultheisz,
Eugenio-Felipe Santillan, Jonathan Walsh

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Abstract

The US Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) is a deep geologic repository in southeastern New Mexico developed for the disposal of atomic defense waste contaminated with transuranic radionuclides, with plutonium-239 being the primary long-term (after 3,000 years) radionuclide. The U.S. Environmental Protection (EPA) provides oversight of DOE's WIPP activities that affect compliance with EPA's radioactive waste regulations for the long-term performance of deep geologic repositories. EPA first certified (i.e., licensed) WIPP in 1998 after a review of the performance assessment and documentation submitted by DOE that together comprise the safety case. EPA did require DOE to do additional calculations to address questions about the modeling. This process has been followed with each five-year recertification application that the WIPP Land Withdrawal Act requires DOE to submit. EPA has now recertified DOE three times, most recently in July 2017.

DOE has demonstrated that the WIPP complies with EPA's regulations; however, DOE must also update data to continue to show compliance and maintain confidence in the disposal system. One regulatory challenge for EPA involves identifying whether DOE appropriately updates data used in performance assessment. Chemistry is a topic for which this is an issue.

A February 2014 incident at WIPP released minor amounts of radioactivity to the surface and contaminated the underground. DOE staff could not access the underground for six months to do ground control maintenance on the salt, which creeps. Some contaminated parts of the repository posed worker safety and roof stability issues, causing DOE to abandon parts of the repository. DOE will need a new design and will have to consider new initial conditions for the modeling as the panel closures won't be emplaced as planned and more open areas will exist than has been modeled. EPA will review DOE's modeling of the new conditions at WIPP to make sure they are appropriately considered.

Micromechanical investigations

M. Mills

Sandia National Laboratories (SNL)

Abstract

A creep mechanism between intermediate and low equivalent stresses have been observed in salt, but only theories as to what the mechanism is. Knowledge of this dominating mechanism is important for understanding the micro-mechanics of creep and will allow constitutive models to intelligently account for creep at low deviatoric stresses. Due to low strains, a mechanism is difficult to identify and could be overlapped by relictic microstructures. Low deviatoric tested WIPP core samples from the WEIMOS project were supplied to perform microstructural investigations by optical and scanning electron microscopy. A current status of the ongoing research will be presented.

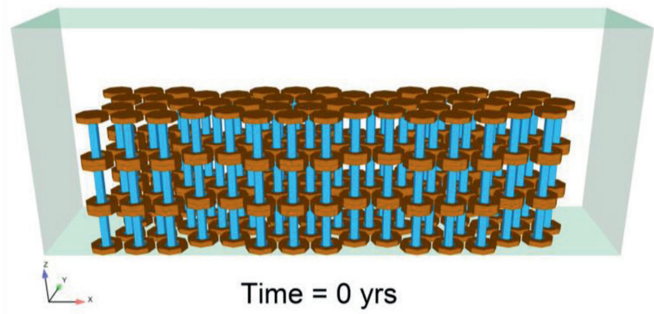
Simulations of Canister Compaction at the Waste Isolation Pilot Plant (WIPP)

Ben Reedlunn

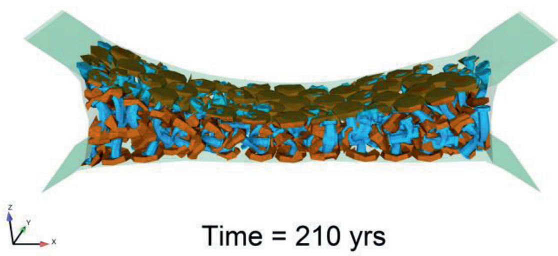
Sandia National Laboratories (SNL)

Abstract

Once canisters are placed underground in a WIPP disposal room, the surrounding rock salt compresses the canisters over several centuries, thereby isolating the waste from the biosphere. Although the collection of canisters within a room have been traditionally modeled as a homogeneous solid material, a new canister design under consideration consists of a thin-walled, 17 cm diameter, stainless steel pipe and plywood within a 55-gallon drum. These new canisters are structurally anisotropic and susceptible to buckling during compaction, which prompted the need to discretely model the individual canisters, including the pipe and plywood within each drum (see Fig. 1a). Sierra/Solid Mechanics's explicit dynamics capability is well suited to modeling the pervasive contact and severe plastic deformation as the canisters compress, but the timestep is typically about a microsecond. To avoid this limitation, the rock salt viscoplasticity was sped up by several orders of magnitude (while verifying that the kinetic energy was negligible), thereby squeezing hundreds of years into seconds. Short duration geomechanical events such as rock falls were not considered in these calculations. An example compaction prediction is shown in Fig. 1b, where the canisters clearly deformed in a non-uniform and highly complex manner. These high-fidelity simulations will help SNL assess the nuclear waste isolation process and evaluate whether the risks of an adverse event are acceptably low.



a) Undeformed canisters



b) Deformed canisters

Figure 1: Several rows of canisters with stainless steel pipes in blue and plywood in brown. (The surrounding rock salt and 55-gallon drums are not shown for visualization purposes.)

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Compaction of crushed salt-clay-mixtures with high compaction energy

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Abstract

This report is part of the R & D project ELSA Phase II – *Concept development for shaft seals and testing of sealing elements for HAW repositories*. The topic of discussion is the compaction of crushed salt-clay-mixtures with high energies.

The installation of sealing elements in salt rock requires a mechanical support system, which is chemical compatible with the host rock. In future HAW-repositories parts of the shafts could be backfilled with an almost congeneric material, such as crushed salt-clay-mixtures.

The hydrological properties of consolidated salt-clay-mixtures based on the initial density and porosity of the material after emplacement. A highly compacted material with low porosity will lead to low permeability. The dynamic compaction technology and an optimized material composition offers gross densities of about 2.115 g/cm³ and total porosities down to 7.28 % in laboratory.

The prerequisite for the implementation of such a technology in a repository is the knowledge about the behavior of the material during assembling and a manageable compaction equipment under mining conditions.

The handling of high compaction energies in a half scale shaft has been test in 2015. Some equipment modifications such as a changed foot impactor geometry improved the compaction process and reduced surface bulking in a second field test in 2017. With an in-situ porosity of 9.6 % in average after dynamic compaction the general capability of this technology under realistic conditions has been shown. An ultra-sonic measurement during the second field test made it possible to review the necessary specific energy input. With a specific energy input of 15 MJ/m³ the maximum of compaction was achieved.

Seals and Seal Materials for a Generic Salt Repository in the US

E. Matteo

Sandia National Laboratories (SNL)

Abstract

This presentation will offer a historical perspective on seal designs, field tests, and seal materials for a Salt host media from the US Nuclear Waste Repository Programs. Case studies from the WIPP Borehole Plugging Program, the Small Scale Seal Performance Tests at WIPP, and the Studies of Grouts and Concretes for WIPP offer perspective on approaches to seals and seal testing that can be utilized in future seal testing projects in bedded salt. Additional topics will include discussion of the design bases for seal systems, as well as a brief overview of plans for an underground field test of seal materials at the WIPP. This talk aims to highlight the opportunities to formulate research to address key unresolved issues relevant to cementitious seal systems in bedded salt, and will hopefully generate some workshop discussion of potential collaborative synergies amongst the workshop partners.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525, SAND2018-9686A.

Description of a large scale pilot plant designed to analyze sealing systems of cut salt bricks

U. Düsterloh

TU Clausthal

Abstract

In different to backfilling a shaft with crushed salt the initial porosity of a sealing element composed of salt bricks and gaps with crushed salt filling can be reduced from some 40% to a range of one percent to five percent depending on the size of individual salt bricks and thickness of individual gaps. To analyze weather or not the integration of a several deca meter to hundred meter thick layer of salt bricks into a shaft sealing system is able to guarantee long term static stability and tightness, the thermomechanical-hydraulically coupled behaviour of such a sealing system is demanded to be investigated experimentally. To ensure appropriate ratios between individual salt bricks, salt crystal size, gaps, and flow paths a pilot plant able to investigate cylindrical sealing systems of 1,5 m in height and 0.75 m in diameter has been constructed and bring into operation. A first main part of the presentation deals with a description of main components, process of construction and performance data of the pilot plant.

A second emphasis of the presentation is given by investigations into preparation of salt bricks to build up a sealing element composed of salt bricks and gaps with crushed salt filling on the one hand and numerical investigations into the load bearing behaviour of the system on the other hand.

Preparation of rock salt bricks has been done by using a milling machine. Raw material of rock salt to create rock salt bricks was taken from large cores of 20 cm in diameter and rock salt blocks of 0,4 m x 0,4 m in cross section. Theoretical investigations to create appropriate geometrical configurations of rock salt bricks, taken into account a various thickness of gaps as well as the demand to avoid continuous gaps in direction of flow path led to the evaluation of a software code. The software enables to determine individual 3D size of rock salt bricks as well as their positioning in space. Based on the software a cylindrical sealing system characterized by a height of h = 1,5 m, a diameter of d = 0,75 m, and a total number of 375 individual rock salt bricks has been realized.

Regarding the amount of rock salt needed to create a cylindrical sealing system of 1,5 m in height and 0,75 m in diameter it has been learned from research work, that some 4 m^3 of rock salt and 1 year of preparation time are required to create the aforesaid sealing system. Both, the time as well as the amount of raw material are significantly higher than estimated prior starting the project.

To check the performance of the current available numerical instrumentation regarding a retrospective as well as a prognostic analysis of the mechanical load bearing behaviour of sealing systems composed of rock salt bricks with gaps of crushed salt on the one hand and sealing systems made of crushed salt on the other hand numerical sensitivity studies have been conducted. As a result of numerical investigations it could be stated, that the numerical instrumentation current available in general is able and verified to image the load bearing behaviour of shaft sealing systems made of rock salt bricks and crushed salt. Further investigations needed to qualify and improve the instrumentation are particularly concerning:

- further qualification of the constitutive model C-WIPP used to image the compaction and creep behaviour of crushed salt,
- integration of appropriate calculation algorithms to image sealing systems made of rock salt bricks without any gap filling,
- validation of coupled mechanical-hydraulically processes.

Drift Seal Systems at the Morsleben Repository – Status of Investigations and Further Procedure

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Abstract

The Morsleben repository is located in a former salt mine in Northern Germany and contains low-and intermediate-leve lnuclear waste. It has a total excavated volume of 8.9 Mio m^3.The total radionuclide inventory is small (37,000 m^3, 2.6×10^{14} Bq by the end of 2014) and dominated by short-lived radionuclides. The closure concept includes sealing of the two shafts, Bartensleben and Marie, and backfilling of large volumes with salt concrete in order to stabilize the mine building. Furthermore, the disposal areas containing the main part of the longer-lived radioactive inventory will be sealed. The seals are located in horizontal drifts mainly surrounded by rock salt. The previous sealing concept foresees salt concrete as construction material.

A drift seal was erected in 2010 in the Morsleben repository to demonstrate the technical feasibility of constructing such a seal. Furthermore, its functional efficiency (integral permeability of ≤ 10^{-18} m² as target value) should be representationally demonstrated. The presentation deals with the results and lessons learned of this in-situ test.

So far, the main results are the following:

- The technical feasibility of constructing such a seal has been demonstrated.
- The permeability goes below the target value of ≤ 10^{-18} m² since November 2015; the actual value is 1.4×10^{-19} m² (still slightly deceasing flow rate of currently 3.4 ml/d).
- A horizontal crack developed at the air face of the seal contrary to the expectation. Especially there is currently no clear proof of crack limitation available. In the case that cracks will be created, corrosive solutions could penetrate the sealing structure in the long term and the permeability of the seal might increase.

According to these results further investigations are planned:

- The extension of the horizontal crack will be further investigated by drilling boreholes and innovative nondestructive measurements (e.g. LAUS-measurements).
- The pressure test will continue as long as the testing device is functioning. Among other things, the probably unaffected middle segment of the seal will be examined with ultrasonic measurements in boreholes in the next year.
- To limit the potential corrosion of the sealing body a new working program was initiated to evaluate the chemistry of the solutions near the sealing location as accurate as possible (especially in terms of Mg-content).
- To account for the chemistry of solutions near the seals three sealing materials were selected as main candidates for sealing systems (salt-concrete and MgO-concrete systems also as shotcrete to limit the high setting temperature). There are positive experiences with these materials in other projects of BGE and R&D-projects (e.g. MgO-SEAL).

It is planned to perform additional in-situ demonstrations with this other materials. Based on the results of these in-situ demonstrations a re-run of the post-closure safety assessments incl. detailed planning (with the real reachable hydraulic and geochemical properties of the drift seals) will be necessary.

Industrial Planning and Construction of Drift Seals in the Asse Mine

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BGE TECHNOLOGY GmbH

Abstract

More than a decade of experience in the planning and construction of flow barriers has now been gained by BGE and BGETEC at the Asse mine. The flow barriers have been constructed in the mine workings since 2003, first as pilot constructions /1/2/3/, since 2007 in routine operation.

The construction had to consider the site specific conditions of the Asse mine. As the original goal was to exploit the mine for its minerals, the Asse mine has a high excavation level. During mineral extraction, huge carnallitite areas were opened up. After more than 100 years of operations the rock is damaged in some areas. For more than 4 decades, radioactive waste has been disposed in the mine workings. Since 1988 a brine inflow characterizes the Asse mine. Although it is quite constant in its volume (approx. 12 m³/d), it can change at any time and grow to amounts that exceed the mine capacity.

Since 2013, there has been a legal mandate to close and decommission the Asse mine – the radioactive waste has to be retrieved. Thus, the preparation of an emergency plan to minimize the probability of brine inflow and to minimize the consequences of excessive brine inflow (i.e. exceeding the capacity of the mine) was essential. This emergency plan includes precautionary measures to stabilize the mine workings and to protect the emplacement chambers. Essential measures are the installation of flow barriers, which are made of magnesium oxychloride concrete in order to guarantee chemical long-term stability against $MgCl_2$ solutions as well as the compatibility with the host rock. Because these constructions are to impede flow, the construction material has to have a low permeability. In order to achieve quick rock pressure build-up, the material has to have sufficient mechanical strength and stiffness. Furthermore, it has to be at least constant in volume, i.e. it is not to shrink, and – ideally – the material has swelling capability. Last but not least, the material has to be handled on an industrial scale, which means that it has to be transportable hydraulically over distances of some 100 meters.

The first horizontal flow barrier (SB-775-3) was installed at the beginning of 2007. By now, about 48,100 m³ of sorel concrete have been used for flow barriers and abutments, which is about 14% of 342,000 m³ of sorel concrete that have been placed in total.

So far, 32 flow barriers have been installed in the Asse mine. For 16 barriers, it has been demonstrated that they have been constructed according to the requirements. Further demonstrations are in preparation. According to the current plan, 21 flow barriers still need to be installed.

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/2/ Kamlot, P., Weise, D.; Gärtner, G.; Teichmann, L.: Drift sealing elements in the Asse II mine as a component of the emergency concept – assessment of hydro-mechanical functionality, Proc. 7th Conf. Mech. Beh. Salt VII, Paris, France, 16-19 April 2012

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Geochemistry in support of potential emergency measures for Schachtanlage Asse II

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Abstract

Current studies performed by GRS, CSD, and KIT-INE in support of potential emergency measures for the Asse II mine were presented. In the Asse II mine, emplacement of low and intermediate level waste took place from 1967-78. Inflow of saline solution from the overburden occurs since 1988. Due to the inflow of saline solution and stability problems, the mine has to be closed. However, the proof of long-term safety is not possible at the current state of knowledge. Accordingly, the retrieval of the radioactive waste (i.e. implementation of "Lex-Asse" (§ 57 b AtG)), and emergency preparedness according to mining law & nuclear law in the case of disposition of radioactive waste in the Asse II mine (e.g. in the case of an Auslegungsüberschreitendes Ereignis) are ongoing. The latter activities are aiming to provide measures to reduce the probability of occurrence and measures to minimize the consequences of an uncontrollable inflow of saline solution.

The contribution "Geochemistry in support of potential emergency measures for Schachtanlage Asse II" was divided into four strongly related talks:

- Introduction (KIT-INE, M. Altmaier)
- Conceptualization of Radionuclide Source Term (GRS, J. Mönig)
- Modeling the Geochemical Evolution and Gas Formation in Disposal Chambers of the ASSE II (CSD, L. Wissmeier)
- Radionuclide source terms, solubility and retention processes (KIT-INE, M. Altmaier).

The related talks provide a short overview of the work performed in this context and highlight the complementary approaches used by GRS, CSD, and KIT-INE to derive geochemically based tools to support potential emergency measures by BGE. Special focus was given to the geochemical modeling of the chemical evolution and gas formation in the disposal chambers, the studies on radionuclide behavior and solubility in the disposal chambers aiming at deriving radionuclide source terms, and the consecutive conceptualization of the total radionuclide source terms for larger emplacement areas.

Acknowledgement: The work leading to the following presentations by GRS, CSD, and KIT-INE were performed under contract to BGE.

Internal structure and deformation of clay-salt complexes in salt diapirs: a case study from the Polish Basin area

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[2] Polish Geological Institute – National Research Institute, Wrocław, Poland

Abstract

Clay-rich salt formations are considered as suitable sites for repository location because of sorption properties of clays. Investigations on Zechstein (Upper Permian) clayey salt rocks in Poland showed that their strength and rheological properties are lower while sorption properties stronger than those of rock salt. The major difficulty in laboratory tests is that they provide results for small-size samples, which are not representative for bulk rock-mass. Studies carried out in the Klodawa Salt Structure (KSS) showed that Permian clayey salt successions are lithologically heterogeneous and consist of layers differing in clay/halite content, displaying variegated sedimentary structures and textures as well as tectonic deformation. Clayey salt complexes are internally folded and mostly occur in large scale synclinoria. Layers rich in clays are cut with systems of veins, indicative of several episodes of fluid circulation and fracture sealing, whereas halite-rich layers show only recrystallization of halite. Detailed petrographic studies evidenced common preservation of primary sedimentary structures, implying that despite diapirism, long-term deformation and fluid migration clayey salt complexes represent relatively stable portions of the KSS. This is probably due to strain partitioning, resulting primarily from the difference in bulk rheology of clayey salt and rock salt domains, however, establishing the key rheological parameters for clayey salts is really challenging. An important note in terms of repository location in clayey salts is that clay cap rock develops above these rocks, isolating the salt structure interior from groundwater.

KOSINA Project Results: Geological Modeling and Technical Repository Concepts in Bedded Salt Formation

Eric Simo[1], Wilhelm Bollingerfehr[1] (Coordinator), Niklas Bertrams[1], Dieter Buhmann[2], Ralf Eickemeier[3], Sandra Fahland[3], Wolfgang Filbert[1], Jörg Hammer[3], Jonathan Kindlein[2], Markus Knauth[4], Tatjana Kühnlenz[3], Wenting Liu[3], Wolfgang Minkley[4], Jörg Mönig[2], Till Popp[4], Sabine Prignitz[1], Klaus Reinhold[3], Eike Völkner[3], Jens Wolf[2]

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Abstract

According to the German Site Selection Act for a repository for heat-generating radioactive waste and spent nuclear fuel [StandAG 2017] the repository site shall be identified that best ensures the repository safety for a demonstration period of one million years. Owing to the geological situation in Germany, several potential host rocks (salt, claystone, and crystalline rocks) are to be considered in a science-based comparative procedure. As a prerequisite it is necessary to develop at least generic repository concepts as well as suitable safety and demonstration concepts for a repository in all potential host rocks (salt, claystone, and crystalline rocks).

A reference repository design in salt domes was developed in the early 1980s and comparable investigations for a generic repository in claystone or crystalline host rock formations were launched in the early 2000s. Bedded salt formations, however, were not considered as host rock for the disposal of radioactive materials so far. For this reason, the R&D project KOSINA was launched and funded by BMWi, represented by the Project Management Agency Karlsruhe, in summer 2015. KOSINA is a German acronym for “Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept”. Thus, the KOSINA project serves to investigate the technical feasibility and the long-term safety of a generic repository in bedded salt formations.

The work programme includes a compilation of basic data and design requirements, the development of generic geological models and compilation of adequate material parameters and the conception of repository designs for four different disposal options necessary for the demonstration of integrity of geological barriers, the analysis of radiological consequences, and the investigation of operational safety.

Prior to the start of repository design work representative 3D geological models for both flat bedded salt formations and salt pillows were developed. This requires definitions of the geological conditions for the potential host rock and the repository site. The statutory criteria defined in the Site Selection Act (StandAG 2017) were not foreseeable when the KOSINA project began in 2015. Consequently geological criteria were used that were up for discussion at that time for the site selection (see AkEnd 2002, Krull et al. 2004, Hammer et al. 2009). For flat-bedded salt formations an approx. 8.8 km long generic geological cross-section was elaborated based on the available knowledge on flat-bedded evaporitic horizons in Germany. A geological model representing a characteristic geological situation in regions with flat-bedded rock salt successions of Zechstein age in Germany has been developed. The thicknesses compiled in the standard profile are used for most evaporitic model layers. The thickness of the rock salt succession in the Staßfurt Formation selected as the emplacement horizon varies in the “flat-bedded” model area between 160 m in the western part of the model area and 290 m in the eastern part. For the “salt pillow” type an approx. 12.5 km long reference profile was derived which shows a characteristic salt pillow structure of the Zechstein rock salt succession in Germany. The geological model units are identical with the reference profile for the “flat-bedded” model type. The thickness of the Staßfurt Formation rock salt succession selected as the emplacement horizon is up to 600 m in the centre of the salt pillow.

On basis of detailed information about the types and amounts of radioactive waste (interim report), on basis of the two generic geological models “flat bedded salt” and “salt pillow” as well as on basis of the safety and demonstration concept repository designs were developed for four considered disposal options (two different disposal options for each of the two geological models). Another design fundamental were national regulations, ordinances, and safety requirements, and in particular that all repository designs had to meet the retrievability requirement of waste packages at any time during the operational period of the repository. The repository mine layouts were developed on basis of the aforementioned fundamental data and on the results of thermal calculations providing the geometric data for waste package, borehole, and drift spacing. Transport and emplacement technology was adjusted to the appropriate disposal option and eventual backfilling and sealing measures designed to meet the goals of the safety concept. While knowledge for the disposal options “drift disposal of POLLUX® casks” and “vertical borehole disposal “ are quite advanced it became obvious that there still is a need for further R&D for the disposal options “horizontal borehole disposal” and “direct disposal of transport and storage casks”. In particular the “horizontal borehole disposal option” needs detailed planning of safety relevant technical components and processes. Regarding operational safety all in all, it could be concluded that the level of knowledge for the individual analyses of operational disturbances varies. This is mainly due to the fact that demonstration tests were carried out for the “drift disposal of POLLUX® casks” and the “vertical borehole disposal“ only, but rough concepts are available for the other two disposal options. However, it could be shown that operational disturbances can be safely managed at all situations of repository operation.

Reflecting the achievements of the KOSINA project, finally unresolved issues and identified needs for additional R&D were compiled. It was distinguished between R&D needs linked to a more detailed understanding of bedded salt formations and the improvement of conceptual repository designs in particular for the disposal option emplacement in horizontal boreholes.

KOSINA Project Results: Safety Concept / Safety Assessment and Geomechanical Integrity Analyses of Generic Repositories in Bedded Salt Formation

Markus Knauth[4], Wilhelm Bollingerfehr[1] (Coordinator), Niklas Bertrams[1], Dieter Buhmann[2], Ralf Eickemeier[3], Sandra Fahland[3], Wolfgang Filbert[1], Jörg Hammer[3], Jonathan Kindlein[2], Tatjana Kühnlenz[3], Wenting Liu[3], Wolfgang Minkley[4], Jörg Mönig[2], Till Popp[4], Sabine Prignitz[1], Klaus Reinhold[3], Eric Simo[1], Eike Völkner[3], Jens Wolf[2]

[1] BGE TECHNOLOGY GmbH, Peine, [2] GRS mbH, Braunschweig, [3] BGR, Hannover, [4] IfG GmbH, Leipzig

Abstract

According to the German Site Selection Act for a repository for heat-generating radioactive waste and spent nuclear fuel [StandAG 2017] the repository site shall be identified that best ensures the repository safety for a demonstration period of one million years. Owing to the geological situation in Germany, several potential host rocks (salt, claystone, and crystalline rocks) are to be considered in a science-based comparative procedure. As a prerequisite it is necessary to develop at least generic repository concepts as well as suitable safety and demonstration concepts for a repository in all potential host rocks (salt, claystone, and crystalline rocks).

A reference repository design in salt domes was developed in the early 1980s and comparable investigations for a generic repository in claystone or crystalline host rock formations were launched in the early 2000s. Bedded salt formations, however, were not considered as host rock for the disposal of radioactive materials so far. For this reason, the R&D project KOSINA was launched and funded by BMWi, represented by the Project Management Agency Karlsruhe, in summer 2015. KOSINA is a German acronym for "Concept development for a generic repository for heat-generating waste in bedded salt formations in Germany as well as development and testing of a safety and demonstration concept". Thus, the KOSINA project serves to investigate the technical feasibility and the long-term safety of a generic repository in bedded salt formations.

The safety and demonstration concept for the project KOSINA is based on concepts developed and refined in the projects ISIBEL and VSG. Based on the safety principles set out in the Safety Requirements and on existing knowledge concerning the processes that could impair the safety of the repository, and the site properties, the following guiding principles have been derived:

- the radioactive waste must be contained as widely as possible in the CRZ,
- the containment shall be effective immediately post-closure and it must be provided by the repository system permanently and maintenance-free, and
- the immediate and permanent containment shall be accomplished by preventing or limiting intrusion of brine to the waste forms.

Thus, the decisive elements of the safety and demonstration concept are demonstration of integrity of the geological barrier, demonstration of integrity of the geotechnical barriers, scenario analysis, and evaluation of release scenarios.

The impact of the heat generating radioactive waste on the long-term barrier integrity of the bedded salt was analysed numerically for all four disposal options. The results of the THM-coupled 2D modeling by IfG using the DEM codes UDEC & 3DEC and the TM-coupled 3D modeling by BGR using the FEM code JIFE are in good agreement. Both in the modeling of the flat-bedded salt and the salt pillow, the results of the numerical calculations show the effect of thermal expansion of the salt

rock. As a result of the deformation, the horizontal stresses at the top of the salt barrier were reduced and the fluid pressure criterion was locally violated in an up to 60 meter thick zone. According to the reduction of horizontal stress, the pressure-driven fluid percolation in the THM-coupled modeling acts in a vertically aligned direction with a penetration depth similar to the violation depth of the minimum principle stress criterion analysed in continuum mechanical analyses. However, the violation of the integrity criteria is only associated with the thermal pulse occurring in the first 2000 years after emplacement of the radioactive waste. It is crucial that the integrity of a large part of the salt barrier (at least 300 meters thick) is not affected during the simulated observation period of 10,000 years after which the thermal pulse of the emplaced heat generating radioactive waste will have passed off. At any time there are no continuous migration paths between the top of the salt barrier and the emplacement areas. In general, the integrity analysis of the geological barrier by different numerical approaches, model dimensions, and constitutive models has yielded comparable results, which substantiates their predictive capabilities.

The results of the numerical investigations of radiological consequences for the four disposal options demonstrate that radionuclides remain securely contained within the containment-providing rock zone during the demonstration period and beyond. Geotechnical barriers along with the long-term sealing effect of compacted crushed salt backfill will reduce radionuclide release from the containment-providing rock zone to negligible values. The potential radionuclide releases from the repository, that is from the CRZ, are mainly controlled by diffusion and only occur at very late times beyond the demonstration period. Reduced convergence rates may increase radionuclide releases or add an advective portion but only to a very limited extent. With the aid of preliminary test cases it was shown that optimization of the repository design based on numerical analysis of the consequences is possible and beneficial. Computational case studies with parameter variations as well as the examination of What-If cases are useful and necessary for process analysis as well as for identifying sensitive model parameters. Probabilistic calculations are useful and necessary tools for the investigation of parameter und model uncertainties, mainly in the reference case. Using current state of the art in science and technology, the safety and the demonstration concept have been successfully applied to the geological situation represented by typical bedded salt formations that can be found in Germany. The results provide evidence that a safe HLW repository in a bedded salt formation with a suitable geological structure is feasible and that its long-term safety can be demonstrated according to the state of the art in science and technology. This statement depends, however, on several generic assumptions which will have to be confirmed by comprehensive site-specific investigations. However, a bedded rock salt formation offers only minor restrictions on the horizontal expansion of a repository. Thus, a large distance between the emplaced waste and the shafts offers advantages for long-term safety, namely in the form of a delay in both solution access to the waste and solution migration from the waste to the surface.

Reflecting the achievements of the KOSINA project, finally unresolved issues and identified needs for additional R&D were compiled. It was distinguished between R&D needs linked to improvements of models and tools, to a reduction of uncertainties and to a better understanding of proof of integrity of geotechnical barriers.

Bedded salt vs. domal salt – Role of texture and structure

Till Popp

IfG Institut für Gebirgsmechanik GmbH

Abstract

A comparison of bedded and domal is a subject of great interest because both salt formations provide prime candidates for disposal of heat-generating nuclear waste. This statement evolves from extensive salt repository experience obtained by both the US and Germany in their respective R&D programs. Both countries have advanced salt repository science and engineering over several decades for the specific purpose of developing a safety case for salt disposal of radioactive waste. Largely, nuclear waste disposal in the US has concentrated on geologic bedded salt at WIPP while similar efforts in Germany emphasized geologic salt domes at Gorleben, Asse, and Morsleben. The knowledge demonstrates that differences and similarities exist for bedded and domal salt at different scales when applied to nuclear waste disposal. Therefore, characteristics of the similarities or differences become relevant on the basis of scale from the large-scale (basin or geologic formation), to the mesoscale (meters), and down to the microscopic scale.

At the formation scale structural geology, formation characteristics (i.e., layering, stratigraphy, petrography), flow paths, access ways, and therefore seal systems, concept of operations, and performance assessment numerical modeling (with required parameters and boundary conditions) come into play. Relevant topics of the actual discussion are e.g.

- Mining safety – room stability

  Operational performance of the underground facility is strongly related to room and roof stability not only during excavation of the underground workings, but especially during the long-lasting emplacement of heat-generating waste under consideration of backfill timing and its characteristics. Thus, consideration of the individual site conditions is an important aspect of the entire repository layout, independently from the salt type. A discussion is presented to the actual rock-mechanical understanding, of roof instabilities related to field and lab testing, respectively numerical modelling.

- Mechanical / hydraulical anisotropy

  Bedded salt is mechanical /hydraulical anisotropic due to existing intercalated lithological weakness planes of different composition and thickness. E.g. intact sulfate/clay intercalations are canalizing fluid flow, acting as impervious layers. Despite its relevancy for near- and far-field phenomena, only scarce data sets about salt anisotropy are available.

A special topic of bedded salt formations, especially in Germany are intercalated massive clay beds (up to >10 m thickness) created during the various sedimentary cycles of salt precipitation. In addition, several sites are characterized by intact cap rocks in the overburden consisting of clay formations. As a unique advantage, these geological characteristics of a bedded salt repository provides a natural multiple barrier system in the near- and far-field to prevent the release of radionuclides to the biosphere respectively inflow of water from the overburden.

Design and Performance Guidelines of Geotechnical Barrier Systems in Salt Formations

Eric Simo[1] and Edward N. Matteo[2]

[1] BGE TECHNOLOGY GmbH, Peine, [2] Sandia National Laboratories, USA

Abstract

The isolation of radioactive waste in salt formations is provided by a multi-barrier system based on a combination of engineered and natural barriers. The natural barrier is provided by salt itself whereas the engineered barrier is made of geotechnical sealing components installed at specific locations in the excavated repository. For the long-term safety of a repository in salt formations, the integrity of the natural barrier has to be proven for a time period of 1 million years. In Germany, the geotechnical barrier system of a HLW repository has to maintain is structural and functional integrity up to the ice age [1], [2]. This corresponds to a function time of 50000 years. The design and construction of the geotechnical barrier system presents formidable challenges, owing to the long-time scales needed for the repository safety case, as well as due to the sensitivity of the performance assessment to long-term evolution of the geotechnical seal system.

Geotechnical barriers for a repository in salt formations have already been the subject of numerous research projects. As part of the preliminary safety analysis for the Gorleben site (VSG), a verification method for the integrity of sealing elements in a HLW repository in do-mal salt formation was developed [1], [2]. This made it possible to carry out a more detailed verification for a shaft closure as a whole. In the ELSA project, the design of shaft closures for HLW repositories was carried out [3]. Further research projects such as [4] and [5] investigated different aspects of geotechnical closure systems. First recommendations for the planning and execution of geotechnical barriers were formulated in [6] by the working group salt mechanics of the DGGT (German Geotechnical Society).

On the practical side, BGE and BGE TECHNOLOGY have been developing and building drift seals in the Asse repository for more than ten years. 32 drift seals have been built already in routine operation. A real scale prototype sealing structure was built by the BGE in the Morsleben repository mine and is currently being scientifically investigated. BGE and BGE TECH-NOLOGY dis-pose therefore of a well-founded know-how in the field of geotechnical barriers.

Sandia National Laboratories has a long history in the design and testing of shaft and drift seals in bedded salt, including the design of geotechnical barriers at the Waste Isolation Pilot Plant (WIPP), as well as for barriers and seals in a generic HLW repository in a bedded salt host media [7, 8, 9, 10].

Despite extensive knowledge and experience about geotechnical barriers in salt formations, there is no guideline for the design and verification of such structures for a HLW repository. BGE TEC and SANDIA propose to develop jointly a *Design and Integrity Guideline for Engineered Barrier Systems for a HLW Repository in Salt* in the framework of a joint project between Germany and USA with the acronym *RANGERS*.

This guideline to develop in the scope of the proposed RANGERS-Project will incorporate the existing knowledge and experience about geotechnical barriers in Germany and in the United States. Recommendations for the design and verification of geotechnical barriers based on the state of the art in science and technology will be formulated and an overview of new concepts, building materials, and technologies that will shape the state of the art of tomorrow will be given. Four sub-goals are formulated for this purpose:

1. Compilation of existing knowledge and experience for the design and construction of geotechnical barriers

2. Development of a guideline based on the state of the art in science and technology for the design and verification of geotechnical barriers

3. Prototypical design and verification of the geotechnical barrier system for selected repository concepts in Germany and in the United States based on the developed guideline.

4. Compilation of new concepts and technologies on the subject of geotechnical barriers

This collaboration will bring together the institutional expertise from the nuclear waste programs in both Germany and the US, and will also integrate the next generation of researchers into this important subject area.

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[2] Müller-Hoeppe, N. et al.: VSG AP 9.2 Teil 2 – Geotechnische Barrieren: vertiefte Nachweisführung, GRS-Bericht GRS-288, Köln 2012

[3] Kudla W. et al. : Schachtverschlüsse für Endlager für hochradioaktive Abfälle – ELSA Teil 1, FK 02E10921 / 02E10931, Freiberg, Peine 2013

[4] Kudla W. et al.: Diversitäre und redundante Dichtelemente für langzeitstabile Verschlussbauwerke, FK 02C1124, Freiberg 2009

[5] DGGT – Empfehlungen des Arbeitskreises Salzmechanik AK 3.1: Empfehlungen zur Planung und Ausführung geotechnischer Barrieren für Untertagedeponien im Salinargebirge, 2017, nicht veröff.

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[7] Christensen, C. L. Test Plan Bell Canyon Test WIPP Experimental Program Borehole Plugging. SAND79-0739, Sandia National Laboratories, Albuquerque, NM, 1979.

[8] Stormont, J. C., Small-Scale Seal Performance Test Series "A" Thermal/Structural Data through the 180th Day, SAND87-0178, Sandia National Laboratories, Albuquerque, NM, 1987.

[9] Wakeley, L. D., P. T. Harrington, F. D. Hansen. Variability in Properties of Salado Mass Concrete. SAND94-1495, Sandia National Laboratories, Albuquerque, NM, 1994.

[10] Hansen, F.D. and M. K. Knowles. Design and Analysis of a Shaft Seal System for the Waste Isolation Pilot Plant, SAND99-0904J, Sandia National Laboratories, Albuquerque, NM, 1999.

Mechanical Behavior of Bedded Salt Interfaces and Clay Seams Subjected to Shear

Stuart Buchholz[1], Steven R. Sobolik and Benjamin Reedlunn[2]

[1] RESPEC, Rapid City, USA, [2] Sandia National Laboratories, USA

Abstract

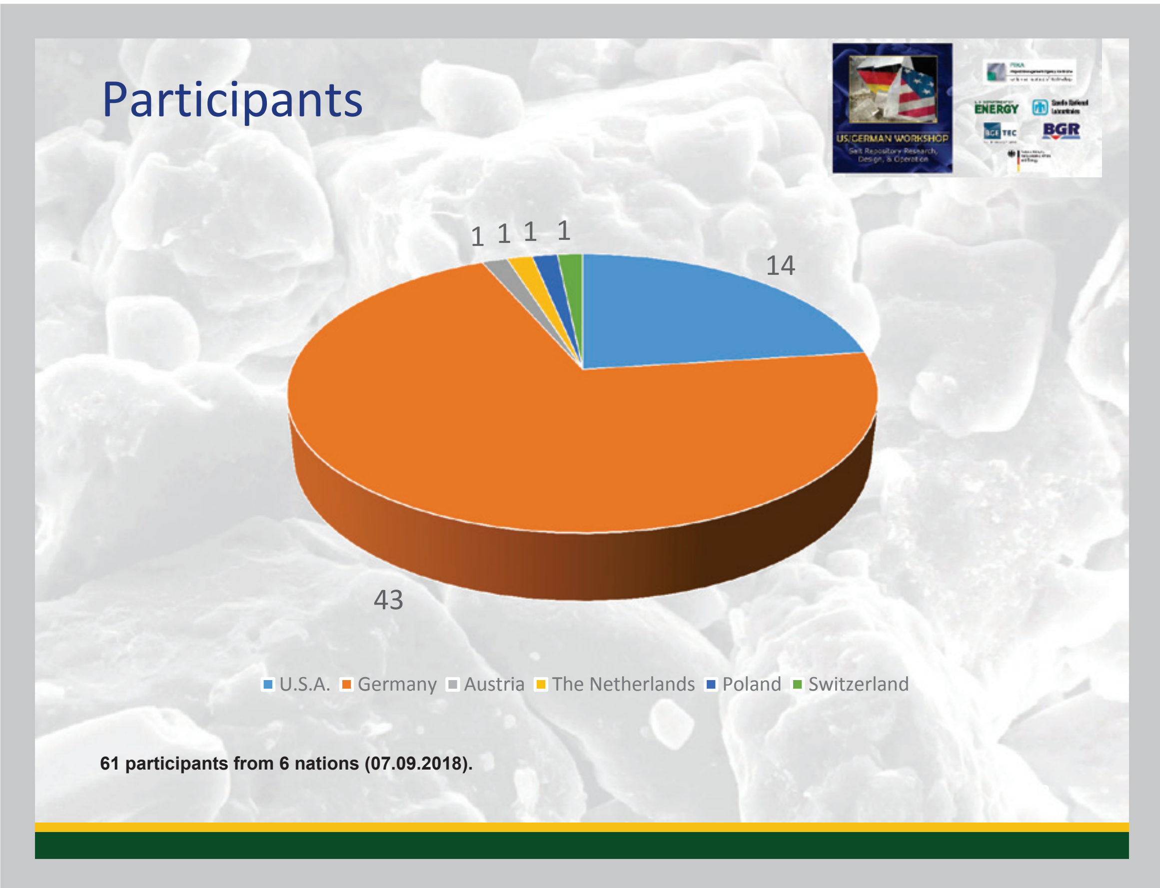
Extensive collaborations between United States and German salt repository researchers have identified four key research areas to better understand the behavior of salt for radioactive waste repositories. One subject area includes the influence of inhomogeneities, specifically interfaces between the host salt and other in situ materials such as clay seams within bedded salt, or different materials such as anhydrite or polyhalite in contact with the salt. The potential increases in creep rate, roof collapse, and permeability near and along these inhomogeneities are thought to be first-order effects. Despite their importance, characterizations of the peak shear strength, residual shear strength, and permeability of interfaces in salt are extremely rare in the published literature.

This paper presents preliminary results from laboratory experiments designed to measure the mechanical behavior of a bedding interface or clay seam as it is sheared. The series of laboratory direct shear tests reported in this paper were performed on several samples of materials typical of Waste Isolation Pilot Plant (WIPP) emplacement drifts. Some test samples were control samples – machined blocks of halite and other materials such as anhydrite, clay, or polyhalite. These tests were conducted at several normal and shear loads up to expected in situ pre-mining stress conditions, and at multiple shear velocities to scope for potential velocity-dependence of shear stress evolution. Additional tests were performed on samples with a clay seam, and other samples with a halite/anhydrite or halite/polyhalite. As part of the analysis of the data from these tests, a preliminary constitutive model for interface behavior as a function of stress and rate of strain has been developed; this model will continue to be developed as additional laboratory and in situ test data are gathered.

APPENDIX E: PRESENTATIONS

M. Bühler


9th US/German Workshop on Salt Repository Research, Design, and Operation
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
PTKA
ENERGY
Sandia National Laboratories
BGE TEC
BGR
Han(n)over, Germany
September 10-11, 2018


Participants
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
ENERGY
BGR
1 1 1 1
14
43
U.S.A.
Germany
Austria
The Netherlands
Poland
Switzerland
61 participants from 6 nations (07.09.2018).

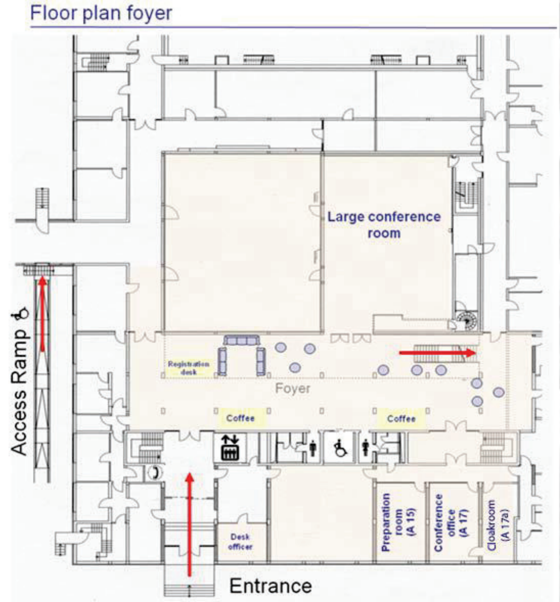
Practical Information

SALT CLUB; US/GERMAN WORKSHOP ON SALT; SALTMECH IX
SEPTEMBER 07 - 14, 2018 - HANNOVER, GERMANY
PRACTICAL INFORMATION

Practical Information

Practical Information

Floor plan foyer



Workshop Dinner

Invited Dinner

at

Altes Rathaus

Karmarschstraße 42, 30159 Hannover

Monday, September 10th, 19:00

At the Restaurant "Altes Rathaus" please use the main entrance (Karmarschstraße) and pass between the ATMs in the Sparkasse bank or use the side entrance (Schmiedestraße).

Agenda

Monday, September 10th, morning

08:30-09:15	**Registration**	
09:15-09:30	Kick off and organizational details	W. Bollingerfehr, BGE TECHNOLOGY GmbH M. Bühler, KIT-PTKA S. Dunagan, SNL
09:30-09:45	Welcome BGR	G. Enste, BGR
09:45-10:00	Welcome BMWi	U. Borak, BMWi
10:00-10:15	Welcome BGE	W. Hund, BGE
10:15-10:45	Welcome DOE and Summary of US WM status	T. Gunter, DOE
10:45-11:15	Coffee Break and Group Photo	
11:15-11:30	Short Report on NEA Salt Club Meeting	J. Mönig, GRS
11:30-12:00	IAEA presentation: International Issues in Salt Repository Development	A. Orrell, IAEA
12:00-12:30	EPA presentation: Regulator's perspective	T. Peake, EPA

Agenda

Monday, September 10th, afternoon

Joint Project WEIMOS (chair: M. Bühler, KIT-PTKA)		
13:30-14:00	Current Status of Research in Joint Project WEIMOS	A. Hampel, Hampel Consulting
14:00-14:20	Salt testing: bedding planes	S. Buchholz, RESPEC S. Sobolik, SNL
14:20-14:40	Micromechanical investigations	M. Mills, SNL
14:40-15:00	Simulations of Canister Compaction at WIPP	B. Reedlunn, SNL
15:00 15:30	Coffee Break	
Key aspect session (chair: S. Dunagan, SNL) Engineered Barrier Systems (Concepts, materials, and demonstration)		
15:30-16:00	R&D Project ELSA II - Compaction of crushed salt-clay-mixtures with high compaction energy	J. Aurich, TU BA Freiberg
16:00-16:30	Seals and Sealing Materials for a Salt Repository	E. Matteo, SNL
16:30-17:00	Description of a large scale pilot plant designed to analyze sealing systems of cut salt bricks	U. Düsterloh, TU Clausthal
17:00-17:30	Drift Seal Systems at the Morsleben Repository - Status of Investigations and Further Procedure	J. Wollrath, BGE
17:30-18:00	Industrial Planning and construction of drift seals in the Asse mine	N. Müller-Hoeppe, BGE TECHNOLOGY GmbH

Agenda

Tuesday, September 11th, morning

Special Topics (chair: K. Kuhlman, SNL)		
09:00-09:30	Operational Safety at WIPP	S. Dunagan, SNL
09:30-10:30	Geochemistry in support of potential emergency measures for Schachtanlage Asse II 1. Introduction 2. Conceptualization of Radionuclide Source Term 3. Modeling the Geochemical Evolution and Gas Formation in Emplacement Chambers of the ASSE II 4. Radionuclide source terms, solubility and retention processes	M. Altmaier, KIT-INE J. Mönig, GRS L. Wissmeier, CSD M. Altmaier, KIT-INE
10:30-11:00	Coffee Break	
Repositories in bedded and domal salt (chair: W. Bollingerfehr, BGE TECHNOLOGY GmbH)		
11:00-11:30	Internal structure and deformation of clay-salt rock complexes in salt diapirs: a case study from the Polish Zechstein Basin area.	S. Burliga, University of Wrocław
11:30-12:00	WIPP: Status and future works	S. Dunagan, SNL
12:00-12:30	Ex ante vs. ex post planning of radioactive waste retrieval in salt repositories	J. Mönig, GRS

Agenda

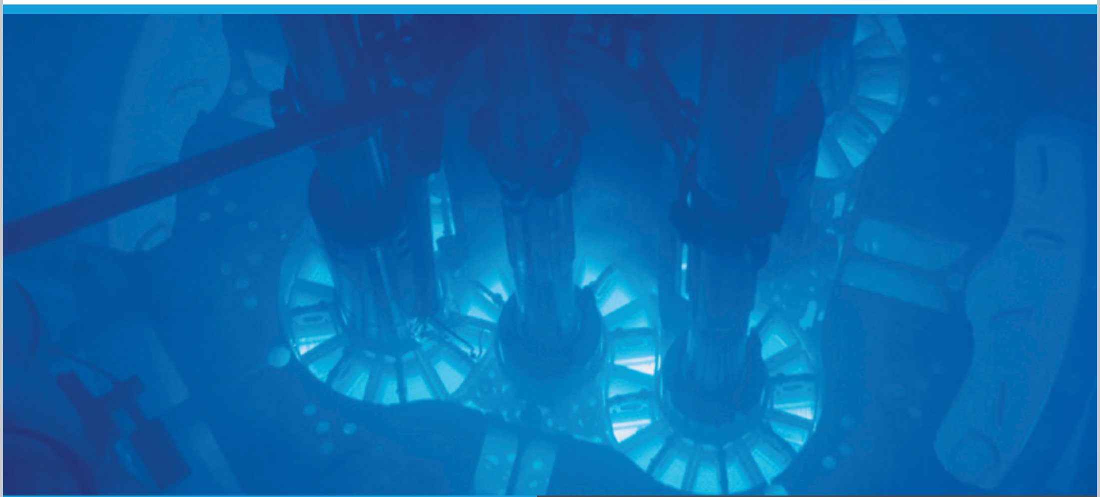
Tuesday, September 11th, afternoon

Repositories in bedded and domal salt cont'd (chair: W. Bollingerfehr, BGE TECHNOLOGY GmbH)		
13:30-14:00	KOSINA project results: Generic geological modelling, design parameters and repository concepts	E. Simo, BGE TECHNOLOGY GmbH
14:00-14:30	KOSINA project results: Safety concept / safety assessment and geomechanical integrity analyses	M. Knauth, IfG GmbH
14:30-15:00	**Coffee Break**	
Repositories in bedded and domal salt cont'd (chair: F. Hansen, Professional Associate RESPEC Inc.)		
15:00-16:30	Break-Out Session: Comparison of bedded and domal salt	With the opportunity for some short presentations (invited by the chair) to open the discussion.
16:30-16:45	Wrap up and outlook	W. Bollingerfehr, BGE TECHNOLOGY GmbH M. Bühler, KIT-PTKA S. Dunagan, SNL

T. C. Gunter

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.



Timothy C. Gunter

Federal Program Manager – Disposal R&D

Spent Fuel and Waste Science and Technology

9th US/German Workshop on Salt Repository Research, Design, and Operation

Hannover, Germany

10 September 2018

Presidential and Departmental Nuclear Energy Priorities

- President Trump ordered review of nuclear energy policy:

  "[W]e will begin to revive and expand our nuclear energy sector… which produces clean, renewable and emissions-free energy. A complete review of U.S. nuclear energy policy will help us find new ways to revitalize this crucial energy resource."
- Commercialization of advanced Small Modular Reactors crucial to future of US nuclear sector
- Executive Order Promoting Energy Independence and Economic Growth
- Nuclear energy role as clean baseload power is key to environmental challenges:

  "If you really care about this environment that we live in… then you need to be a supporter of this [nuclear energy] amazingly clean, resilient, safe, reliable source of energy." Secretary Rick Perry at Press conference, May 10th
- Make nuclear cool again and inform citizenry regarding nuclear energy's attributes

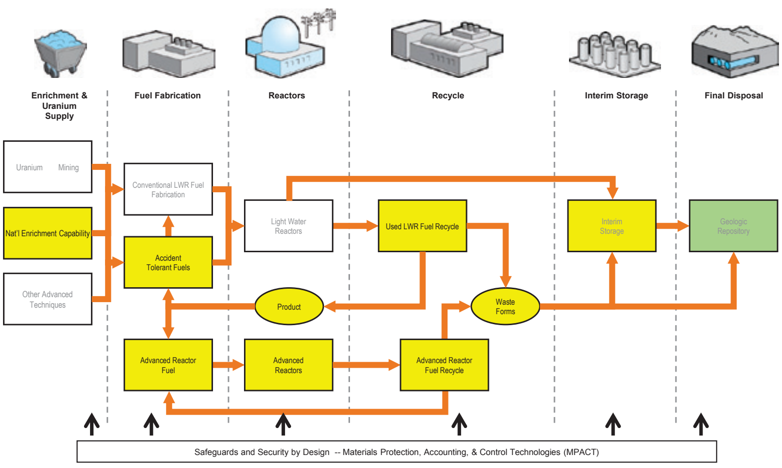
2

Mission Priorities

- **Existing Fleet**
- **Advanced Reactor Pipeline**
- **Fuel Cycle Infra-structure**

3

Focus Areas: Nuclear Technology Research and Development



4

Fuel Cycle R&D Program

Conduct early-stage applied research and development on advanced fuel cycle technologies that have the potential to enhance safety, improve resource utilization and energy generation, reduce waste generation, and limit proliferation risk

Focus Areas:

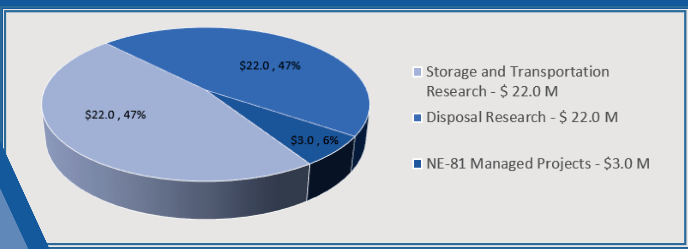
- Advanced Fuels activities focus on early-stage R&D supporting fuel concepts for advanced light water and non-light-water reactors. An area of major focus is accident tolerant fuels.
- Systems Analysis and Integration performs analyses of complete nuclear energy systems, from resource acquisition to waste disposal.
- Material Protection focuses on innovative approaches to monitor, control, and account for materials to ensure nuclear materials are not misused, diverted, or stolen.
- Material Recovery activities focus on early-stage R&D related to significant improvements to the current back end processes of the nuclear fuel cycle.

5

Spent Fuel and Waste Science and Technology

Mission is to identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles.

FY2018 →



FY2019 Funding yet to be determined

6

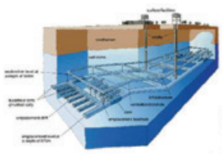
Storage and Transportation R&D

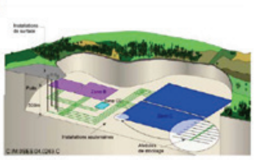
- Extended storage of spent nuclear fuel
  - Dry Canister Stress Corrosion Cracking R&D
  - EPRI/DOE High-Burnup Confirmatory Spent Fuel Data Project & Sister Rod Testing
- Fuel retrievability and transportation after extended storage
  - EPRI/DOE High-Burnup Confirmatory Spent Fuel Data Project & Sister Rod Testing
  - Thermal analysis of dry storage canisters
- Transportation of high-burnup spent nuclear fuel
  - Complete analysis of the multi-modal DOE-ENSA-ROK transportation test performed in FY17
  - Evaluation of options for 8-axle rail car
- Security assessment

7

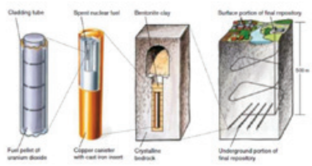
Disposal R&D

- Options for Dual Purpose Canisters (DPC)
  - Cost and risk evaluations of alternatives for DPC management
  - Continue analysis of potential for postclosure criticality
  - Conduct postclosure criticality consequence analysis
  - Analyses of DPC fillers for criticality control
  - Modeling of DPC postclosure performance including fillers
  - Design enhancement options for existing and future DPCs
  - Geotechnical considerations for postclosure performance





- Improved safety assessment modeling capabilities
  - High performance computing of system performance (PFLOTRAN)
  - Uncertainty Quantification and Sensitivity Analysis tools
  - Performance assessment inventory of DOE-managed wastes



- International collaborations and enhanced R&D to support disposal concepts in multiple geologic media
  - Heated borehole field test in salt at WIPP
  - Experimental and modeling activities in salt, argillite, and crystalline rock

8

NE's University Programs

Nuclear Energy University Program (NEUP), Integrated University Program (IUP), Research Reactor Infrastructure (RRI)

Nuclear Energy University Program (NEUP)

- NE designates up to 20 percent of the funds appropriated to its R&D programs to R&D and infrastructure projects awarded through an open solicitation process.

Integrated University Program (IUP)

- NE provides graduate-level student fellowship and undergraduate-level student scholarship grants through an open, competitive process to support nuclear science and engineering education.

Research Reactor Program

- NE supports the continued operation of U.S. university reactors by providing fuel services.

Traineeships

- NE awards grants to competitively selected universities to train graduate level students in specific disciplines aligned with Department of Energy workforce needs.

9

Bilateral, Multilateral and Commercial Cooperation

- **Bilateral Engagement**
  - R&D coordination and integration with advanced fuel cycle countries, e.g., bilateral action plans, International Nuclear Energy Research Initiatives (I-NERIs), and R&D agreements
  - Technical and policy support for civil nuclear energy working groups and bilateral MOUs
- **Multilateral Engagement**
  - Coordination and leadership for NE's engagement in multilateral organizations such as the International Atomic Energy Agency (IAEA), Generation IV International Forum (GIF), the International Framework for Nuclear Energy Cooperation (IFNEC), OECD's Nuclear Energy Agency (NEA), and the International Energy Agency (IEA)
- **International Commercial Engagement**
  - Promotion of U.S. civil nuclear energy policy and technical objectives through engagement on international commercial nuclear matters
  - Advancement of issues associated with developing commercial options for the safe and secure management of used fuel, including regional and international disposal, to support the growth of nuclear power

10

Summary

- The demand for domestically-generated, reliable, and clean sources of base-load electricity will continue to drive many countries toward nuclear energy as part of their "energy security" and national economic and environmental calculus.

- Profound opportunity for new nuclear growth:
  - Strong global market interest
  - Growing need for increased global access to electricity
  - Support energy security, economic and environmental goals
  - U.S. leadership to ensure safety & nonproliferation are as important as ever

- The Administration is committed to advancing nuclear energy in the United States and abroad.

"Nuclear energy is a critical component of America's energy future, and entrepreneurs are developing promising new technologies that could truly spur a renaissance in the United States and around the world."

11

Questions?

Clean. **Reliable. Nuclear.**

12 energy.gov/ne

J. Mönig

Short Report on 8th Annual NEA Salt Club Meeting

Jörg Mönig
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH

Hanover, Germany
September 10-11, 2018

US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2018-XXXX.

Salt Club Membership

- Salt Club membership has increased (now six member states)
  - UK and Romania have joined the NEA Salt Club in 2018
    - RWM, UK
    - Institutul de Cercetari Nucleare, Romania
- 8th Annual Meeting
  - 25 participants registered from 4 countries
    - United Kingdom & Poland could not attend
    - participants from WMOs, a regulator, authorities, TSO & research entities
  - Structure of Annual Meeting
    - Formal Aspects
    - NEA Update
    - Topical Session
    - Update of SC Activities

Steering Group

- Chair : Jörg Mönig (since 2013)
- Vice Chair : Sean Dunagan (since 2018)
- Members : Wilhelm Bollingerfehr (since 2012)
- Jacques Grupa (since 2012)
- Jeroen BARTOL (new)
- Andrzej Chwas (since 2012)
- Michael Bühler (since 2018)
- Alice Ionescu (new)
- Amy Shelton (new)
- Timothy C. Gunter (since 2016)

Topical Session (1)

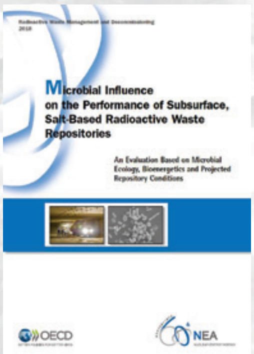
- Design Guidelines for a Repository in Rock Salt
  - Chair: Sean Dunagan
- 3 Presentations
  - Method of Repository Design in the KOSINA project
    - Niklas Bertrams (BGE Technology)
  - Design of a Repository for Heat Generating Waste and Spent Nuclear Fuel in Domal Salt Formations
    - Wilhelm Bollingerfehr (BGE Technology)
  - Engineering Solutions for Disposal of large stent-fuel package in Salt
    - Ernest Hardin, SNL

Topical Session (2)

- Important aspects of Presentations & Discussion
  - Technical & Regulatory Challenges with retrievability requirement in Germany, e.g.
    - Impact on canister design & loading and repository layout
    - Measure for requirement „retrievability must not impair long-term safety“
  - Feasibility of remote handling of large unshielded waste canisters
  - Choice of waste canister steers repository concept & layout
    - *What comes first: Hen or egg?*
  - Relevance of IAEA design requirements

Update of Salt Club Activities

- Geochemical Aspects and TDB topics
- Importance of Crushed Salt as Technical Barrier Element
  - Preparation of a NEA report planned
- FEP Catalogue, Database, and Salt Knowledge Archive
  - continues to be populated, 450 entries
  - Extensive references (SITED „included“)
  - www.saltfep.org
- (Work on Microbial Aspects)
  - NEA report published in May 2018
  - www.oecd-nea.org/rwm/pubs/2018/7387-salt-club.pdf



Outlook

- Application for renewal of mandate for 2019 – 2020 at IGSC meeting in Oct. 2018
  - Mandate and Programme of Work have been updated
- Next Annual Meeting
  - in combination with the next US/German Workshop on Salt Repository Research, Design & Operation
  - One-day meeting in the US, before the summer break
    - again with a Topical Session
  - Steering Group videoconference in early 2019

A. Orrell

9th US/German Workshop on Salt Repository Research, Design, and Operation

Andrew Orrell
IAEA

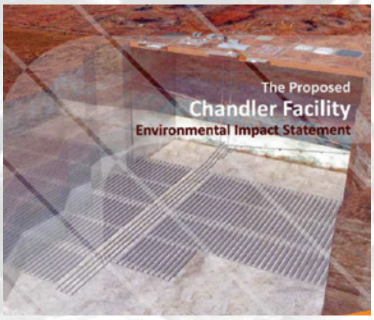
Hannover, Germany
September 10-11, 2018

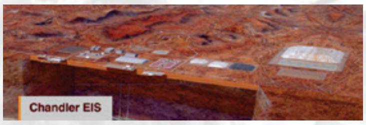
Outline

- Review and Key MS Updates from 2017
- Joint Convention Developments & URF Network
- Peer Reviews and the EC Waste Directive
- Other Considerations

Review and Update from 2017

- Finland / Sweden / France
- USA
  - More later this week
  - Pivot back toward Yucca Mountain: Trump administration has included a budget request to restart the repository program, stalled since 2010.
    - Shelving the DBFT and the Defense Repository projects.
  - WIPP Developments
    - Importance of recovery (second to accident prevention)
  - Surplus Pu Disposition
    - 34MT to WIPP in a 'dilute and dispose' approach
- Germany
- South Australia
  - Public acceptance challenge for HLW remains.
  - TELLUS
    - http://www.tellusholdings.com/project_chandler_environmental_impact_statement.html





Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

- Sixth Triennial Review Meeting of the Contracting Parties, May 21 - June 1, 2018
  - 78 Contracting Parties (69 attended, 75 provided National Reports)
- General areas where major progress has been made in:
  - (i) The development of geological disposal facilities in a number of Contracting Parties, with a licence issued for construction of one facility and two more projects in an advanced stage of development. Other Contracting Parties reported progress on site selection and implementing underground research laboratories.
  - (ii) The development of national policies, strategies and programmes for spent fuel and radioactive waste management;
  - (iii) Demonstration of efforts to enhance openness, transparency and public involvement;
  - (iv) Safety improvements in the regulatory control and funding of disused radioactive sealed source activities;
  - (v) Construction, and commissioning of new or expanded storage facilities for spent fuel
  - (vi) Construction and commissioning of near surface disposal facilities for low level waste;
  - (vii) Safety of spent fuel storage in light of the Fukushima Daiichi accident;
  - (viii) Research and development (R&D) activities for spent fuel and radioactive waste management;
  - (ix) The remediation of sites containing legacy waste from mining and minerals processing activities;
  - (x) Expanded use of international co-operation and published peer reviews;
  - (xi) Recruiting, training, maintaining and developing human resources to address emerging issues and expanding programmes (but some challenges);
  - (xii) Review of arrangements related to funding of decommissioning and waste management activities; and
  - (xiii) Minimization of radioactive waste volumes
- URF Network
  - The IAEA guidance encourages URFs, existing facilities provide a very rich set of data of value to others
  - Fostering knowledge sharing and multilateral use of underground research facilities
  - https://nucleus.iaea.org/sites/connect/URFpublic/Pages/default.aspx

International Peer Reviews

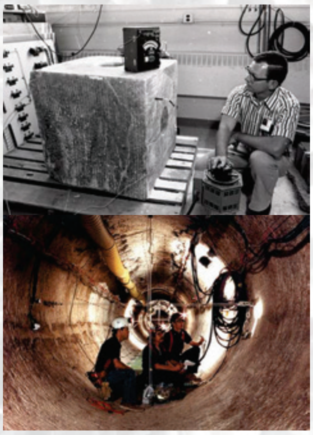
- ARTEMIS Peer reviews requested by MS on RWM
  - To improve programmes for Radioactive Waste and Spent Fuel Management, Decommissioning, and Remediation
- Obligations of the EU Radioactive Waste and Spent Fuel Management Directive
  - EU countries have a national policy for spent fuel and radioactive waste management
  - EU countries draw up and implement national programmes for the management of these materials, including the disposal, of all spent nuclear fuel and radioactive waste generated on their territory
  - EU countries should have in place a comprehensive and robust framework and competent and independent regulatory body, as well as financing mechanisms to ensure that adequate funds are available
  - Public information on radioactive waste and spent fuel and opportunities for public participation are available
  - EU countries carry out self-assessments and invite international peer reviews of their national framework, competent authorities and/or national programme at least every ten years (by August 2023)
- Several MS reviews completed and more are in planning and development

ARTEMIS

Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation

Other Considerations

- Nuclear newcomers embracing nuclear power defer the issue of disposal
  - There is not a requirement to have disposal capacity in place a-priori or coincident with power (or waste) production, only the expectation.
- IAEA
  - Can disposal be incentivized?
  - Can the barriers to disposal be lowered?
    - Multinational Repositories
    - Alternative disposal concepts
    - Capitalizing / leveraging existing solutions
    - Improving public acceptance
- Same as 2016, 2017: *Quantify* the Salt Potential!
  - How salt experience translates to other member states
  - Romania, Mexico, South Australia, etc.
  - Design experience,
  - Lab, Field, in-situ Testing and Data,
  - Safety Case, PA, FEP
    - Containment and isolation vs. dose standards




60 Years
IAEA
Atoms for Peace and Development
Thank you!

Some Safety Case Related Regulatory Challenges of the Safety Case at the Waste Isolation Pilot Plant

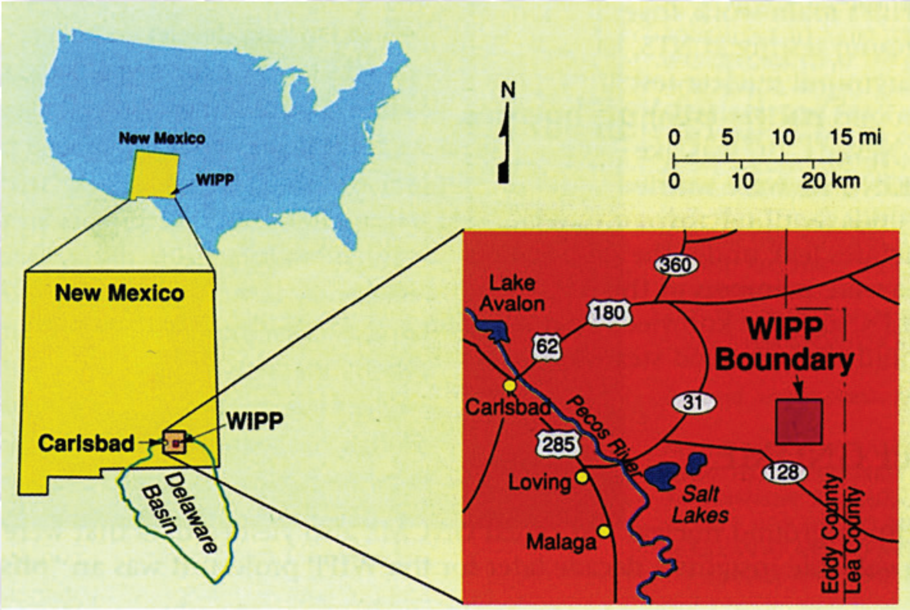
R. Thomas (Tom) Peake
US Environmental Protection Agency
Washington, DC USA

Hannover, Germany
September 10-11, 2018

Topics

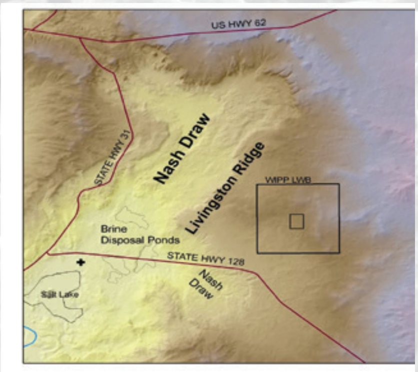
- WIPP background
- EPA's general review process
- Challenges
  - Updating Data
    - Chemistry
  - 2014 Incidents
    - Fire and Radiological Release
    - Abandoning Panel 9
  - Changes in Design
  - When to update data and calculations?
- Summary

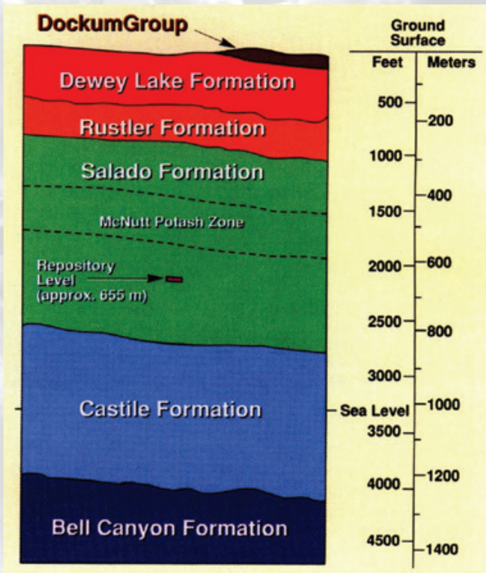
WIPP is in the New Mexico Delaware Basin



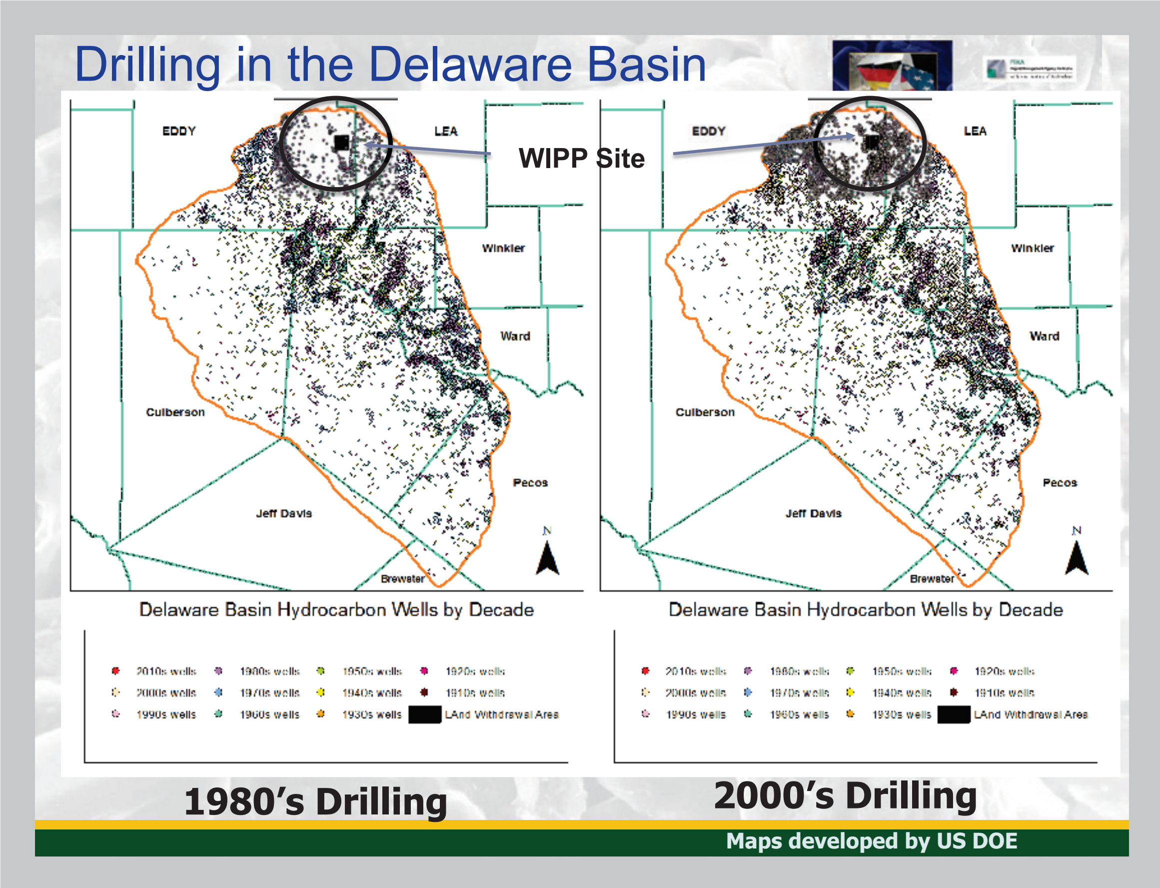
Graphics from DOE

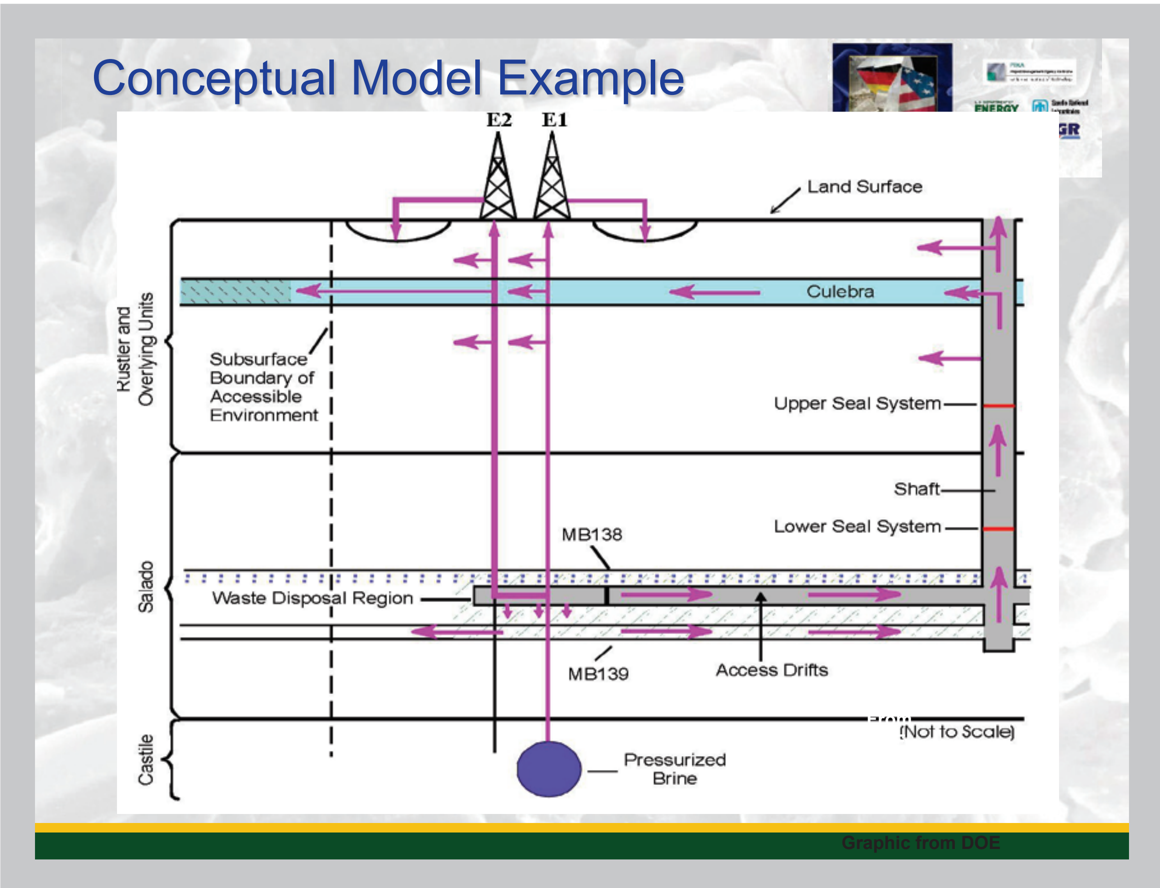
Various Views of WIPP





Graphics from DOE and EPA


Drilling in the Delaware Basin
EDDY
LEA
WIPP Site
Winkler
Ward
Culberson
Pecos
Jeff Davis
Brewster
N
Delaware Basin Hydrocarbon Wells by Decade
2010s wells
1980s wells
1950s wells
1920s wells
2000s wells
1970s wells
1940s wells
1910s wells
1990s wells
1960s wells
1930s wells
LAnd Withdrawal Area
1980's Drilling
2000's Drilling
Maps developed by US DOE


Conceptual Model Example
E2
E1
Land Surface
Culebra
Rustler and Overlying Units
Subsurface Boundary of Accessible Environment
Upper Seal System
Shaft
Lower Seal System
MB138
Salado
Waste Disposal Region
MB139
Access Drifts
(Not to Scale)
Castile
Pressurized Brine

WIPP Overview: What Does EPA Do?

- EPA to review WIPP Recertification every 5 years
  - DOE to provide new information or changes to facility, old information needs reevaluation
- Continuing Compliance
  - Waste Characterization (generator sites, general documentation)
  - Quality Assurance
  - Planned/unplanned changes at WIPP
    - Technical (i.e., PA-related; supercompacted waste, panel closures, future—surplus plutonium, design changes)
  - Inspections at WIPP
- Outreach
  - Supports all EPA WIPP activities (website, public meetings, etc)
  - After the 2014 radiological incident, the public and Congress looked to EPA to confirm WIPP remained safe

WIPP Technical Review Process

- Review DOE's documentation for scientific/technical adequacy in the context of EPA's radioactive waste disposal regulations applicable for 10,000 years
- Identify important technical items
- Document review & decisions completely in supporting documents and summary information

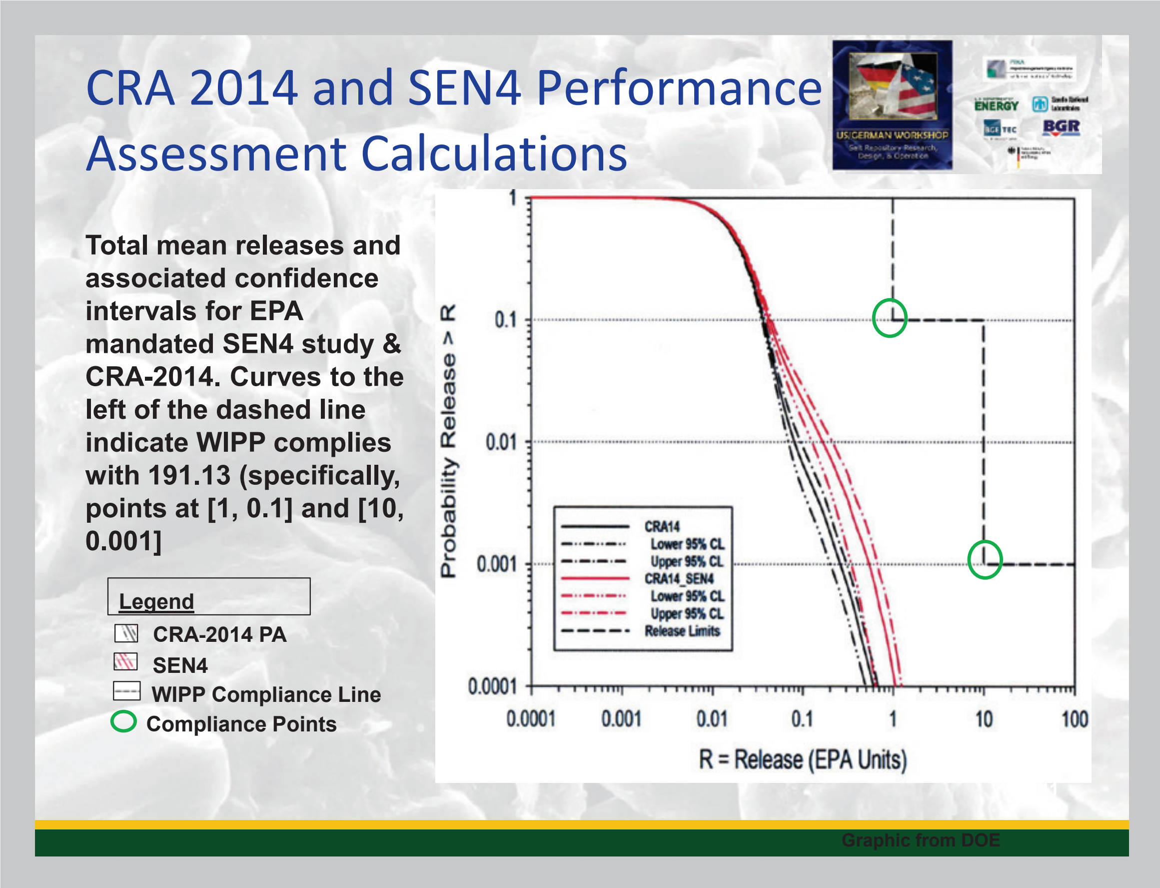
- For Re-certification
  - We focus on what has and should have changed
    - At WIPP (e.g., inventory, design/model changes)
    - Data/Science (e.g., actinide solubility)

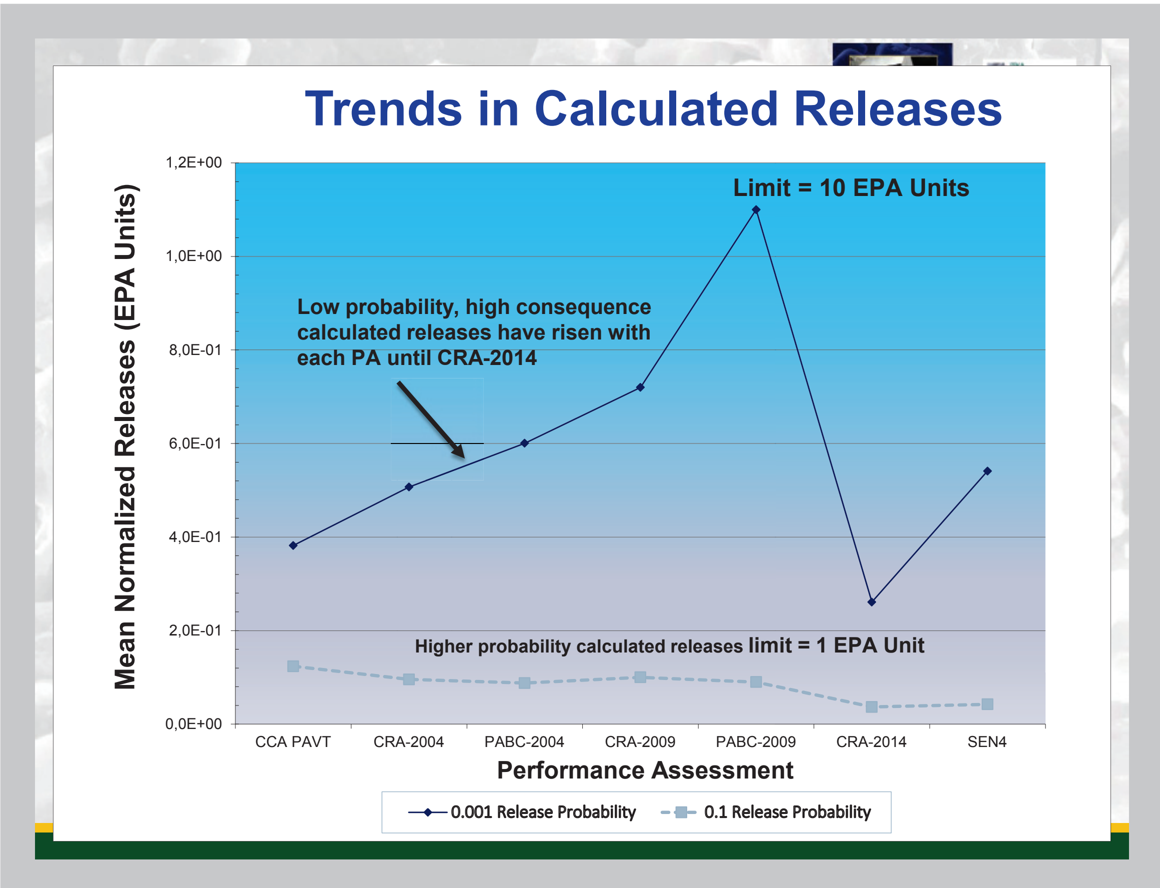
Release Mechanisms

- Undisturbed scenario: no releases are expected
- Disturbed scenario via drilling intrusion has four release mechanisms that are modelled
  - Cuttings and cavings occurs each time there is a drilling intrusion
  - Direct brine releases (DBR)—dissolved actinides to surface
  - Spallings—solid materials transported to surface
  - Long-term groundwater releases via Culebra Dolomite
- Most uncertainty surrounding direct brine releases

Performance Assessment: Technical Areas of EPA Focus

- Modeling direct brine releases
  - Need high enough pressure and liquid to force brine up a borehole to the surface
- Actinide solubility
  - Chemical database needs to be updated periodically to reflect new data
  - Colloidal actinide source term
  - Plutonium oxidation state data and modeling (e.g., Pu(III) vs Pu(IV))
- Chemical conditions in the repository
  - Gas generation, steel corrosion model, water balance, radiolysis
- Repository design and effects on performance
  - Assumptions
  - Scope of changes
  - Treatment of areas initially open at time of closure
  - Modeling capability


CRA 2014 and SEN4 Performance Assessment Calculations
Total mean releases and associated confidence intervals for EPA mandated SEN4 study & CRA-2014. Curves to the left of the dashed line indicate WIPP complies with 191.13 (specifically, points at [1, 0.1] and [10, 0.001]
Legend
CRA-2014 PA
SEN4
WIPP Compliance Line
Compliance Points
Probability Release > R
R = Release (EPA Units)
CRA14
Lower 95% CL
Upper 95% CL
CRA14_SEN4
Lower 95% CL
Upper 95% CL
Release Limits
Graphic from DOE


Trends in Calculated Releases
Mean Normalized Releases (EPA Units)
Limit = 10 EPA Units
Low probability, high consequence calculated releases have risen with each PA until CRA-2014
Higher probability calculated releases limit = 1 EPA Unit
CCA PAVT
CRA-2004
PABC-2004
CRA-2009
PABC-2009
CRA-2014
SEN4
Performance Assessment
0.001 Release Probability
0.1 Release Probability

Challenges

- Updating Data
  - Chemistry
- 2014 Incidents
  - Fire and Radiological Release
  - Abandoning Panel 9
- Changes in design
- When to update calculations?

Chemistry

- Updating the chemistry database using recent data
  - DOE did not use as recent data as they should have
- Radionuclide solubility uncertainty
  - Disagreement on studies that should be included in analysis
- Plutonium oxidation state and solubility
  - DOE has assumed Pu (III) and Pu (IV) will exist in equal proportions – reflected 1998 state of knowledge
  - EPA's review of the current data suggests that Pu (III) will dominate in the highly reducing conditions expected at WIPP – proportions uncertain at this time

Redox Ladder

- Plutonium oxidation states
  - Pu^{6+}, Pu^{5+}, Pu^{4+}, Pu^{3+}
  - Pu solubility
    - Pu(VI) > Pu(III) > Pu(V) > Pu(IV)
- Redox ladder
  - Oxidizing conditions: Pu(VI) & Pu(V)
  - Reducing conditions: Pu(IV) & Pu(III)
  - WIPP is modeled under sulfate-reducing conditions
  - Highly reducing conditions are expected at WIPP

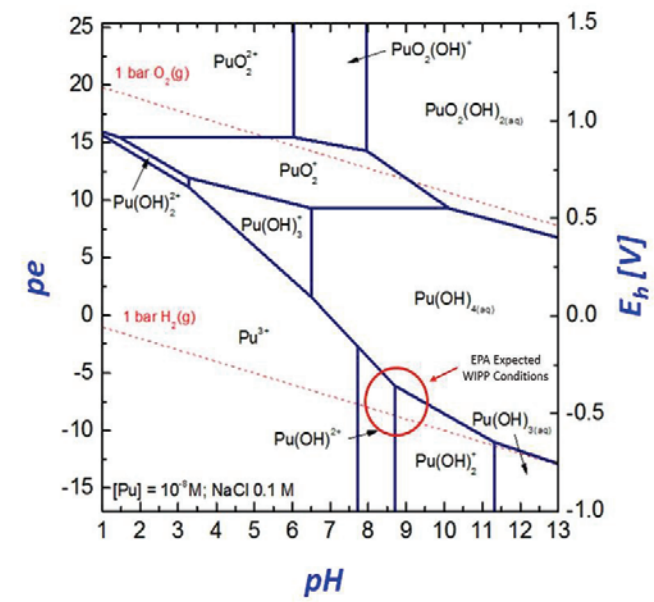
$Fe(s) + (x+2)H_2O(l) \rightarrow Fe(OH)_2 \cdot xH_2O(s) + H_2(g)$
$Fe(s) + H_2S(g) \rightarrow FeS(s) + H_2(g)$
$Fe(s) + 2H^+ \rightarrow Fe^{2+} + H_2(g)$

$2\ PuO_2(am) + 6\ H^+ + H_2(g) \rightarrow 2\ Pu^{3+} + 4H_2O$

Oxidizing Conditions ↑ / Reducing Conditions ↓

Electron Acceptor	Product
O_2	H_2O
NO_3	N_2
SeO_4	SeO_3
Mn(IV)	Mn(II)
Fe(III)	Fe(II)
U(VI)	U(IV)
SO_4	H_2S
CO_2	CH_4
H^+	H_2
Fe(II)	Fe(0)

Pu Oxidation State Phase Diagram

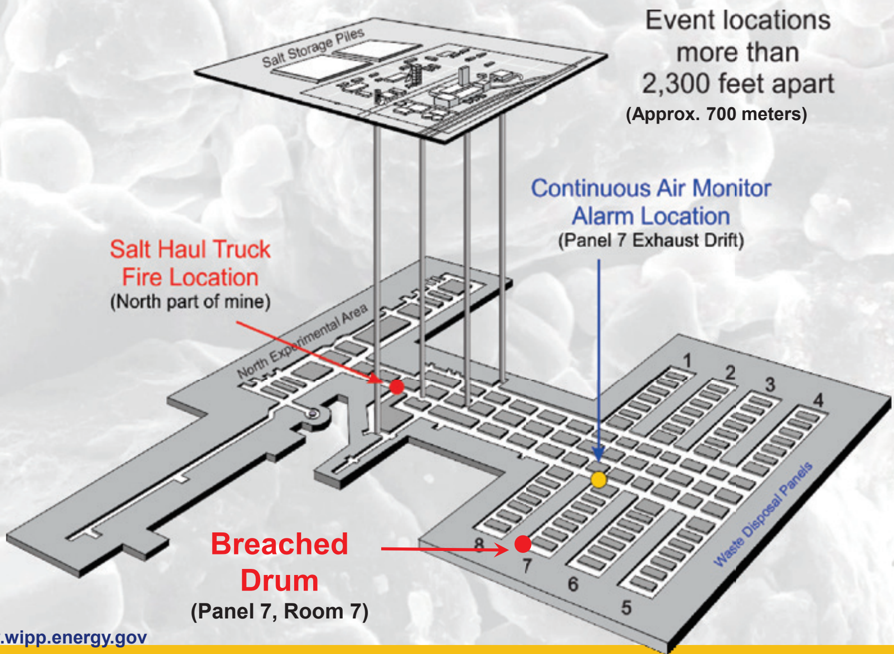


Adapted from Altmaier et al., 2017

Some Ramifications of 2014 Incidents

- 2 year shutdown of facility
- Change in processes, especially waste characterization
- Effect on underground operations/maintenance
- Forced to abandon one panel (Panel 9)
  - Unable to install panel closures as planned
  - Need to relocate Panel 9 to maintain worker safety
- DOE needs a new design that EPA needs to review
  - DOE needs to make changes, requests, in between EPA's recertification decision and the next CRA, which can be difficult

Event Locations Underground



www.wipp.energy.gov

Changes in Design

- New ventilation shaft to be constructed
- Loss of Panel 9 will change symmetry of repository
- New computer modeling system needed to deal with asymmetry
  - New panel layout will be different from original plan provided as part of the initial certification
- Assumptions of original repository configuration and initial conditions need to be re-examined
  - Panel closures won't be installed as planned
  - More open areas will exist than previously modeled

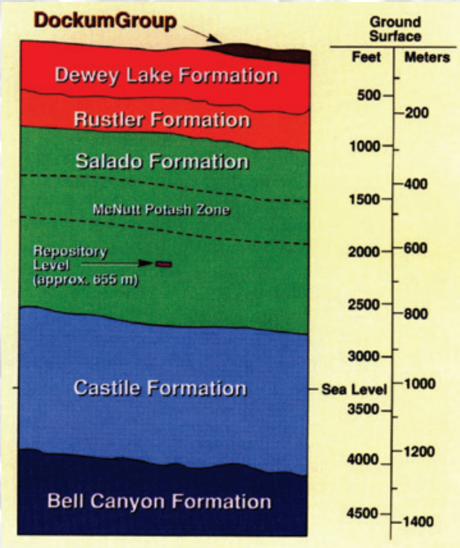
When Does Safety Case Data Need to be Updated?

- DOE submits Compliance Recertification Applications (CRAs) every 5 years per statute
- EPA's expectation is that DOE will include the most recent data in the CRA, but what is "ripe" for inclusion and when?
  - Cutting edge data?
  - Data that has been reproduced by multiple researchers?
  - Impact on results?
- Actinide chemistry for WIPP is an example:
  - Updates to chemistry database need to be included every CRA as there are incremental changes due to new experiments
  - Plutonium oxidation state assumptions and resulting solubility have stayed the same, but EPA has suggested the model needs updating
- The 2014 WIPP incidents are causing changes in the underground
  - More open areas are expected as fewer panel closures will be used
  - New panels may be beyond current scope of brine pocket remote sensing
  - How & when should EPA expect DOE to use new information in models?

Summary

- WIPP is a robust disposal system and WIPP complies with EPA's radioactive waste disposal standards
- EPA is especially interested in direct brine releases and the behavior of the repository that may affect direct brine releases
- General challenges at WIPP involve science and changes in design as a result of the 2014 incidents
  - Panel 9 relocation
  - General design changes involve different assumptions which require new modeling approach
  - Initial conditions and subsequent repository behavior
  - Incorporation of new science
  - Modeling within CRA application 5 year schedule

WIPP Geologic Column



Dewey Lake Red Beds Formation: sandstone, siltstone, silty claystone

Rustler Formation: halite, anhydrite, clastics, gypsum & carbonates; *Culebra dolomite* is a potential radionuclide transport pathway

Salado Formation: ~ 2,000 ft (600 m) thick; halite w/anhydrite interbeds & some potash

Castile Formation: anhydrite & halite w/ local pressurized brine pockets

Bell Canyon Formation: siltstone & sandstone; contains oil and gas

A. Hampel

9th US/German Workshop on Salt Repository Research, Design, and Operation

BGR Hannover
September 10-11, 2018

Current Status of Research in Joint Project WEIMOS

Andreas Hampel

WEIMOS

Verbundprojekt: **Wei**terentwicklung und Qualifikation der gebirgsmechanischen **Mo**dellierung für die HAW-Endlagerung im **S**teinsalz

Joint Project: Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

Supported by: Federal Ministry for Economic Affairs and Energy, on the basis of a decision by the German Bundestag

MANAGED BY PTKA Project Management Agency Karlsruhe, Karlsruhe Institute of Technology

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

Joint Project WEIMOS

Partners

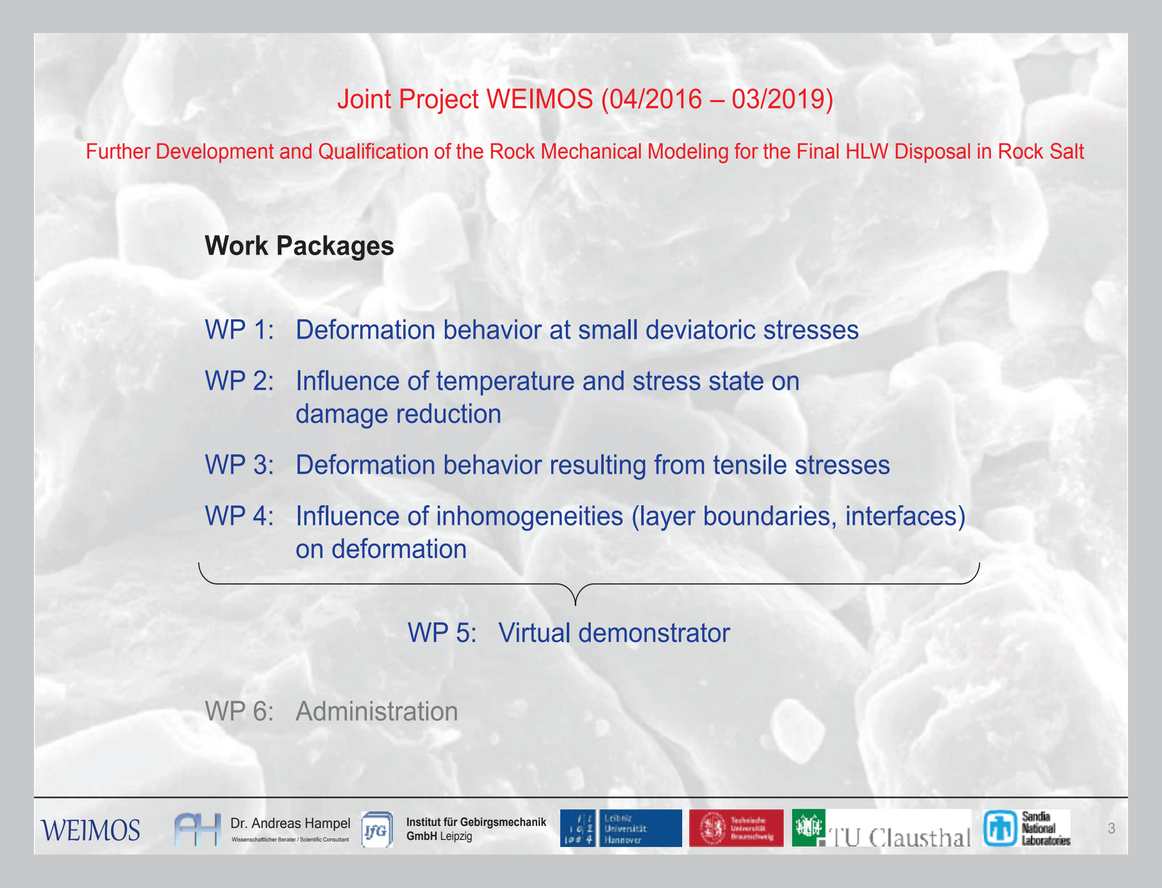
Germany:

- Dr. Andreas Hampel, Mainz (Coordinator of WEIMOS)
- Institut für Gebirgsmechanik GmbH (IfG), Leipzig
- Leibniz Universität Hannover (LUH)
- Technische Universität Braunschweig (TUBS)
- Technische Universität Clausthal (TUC)

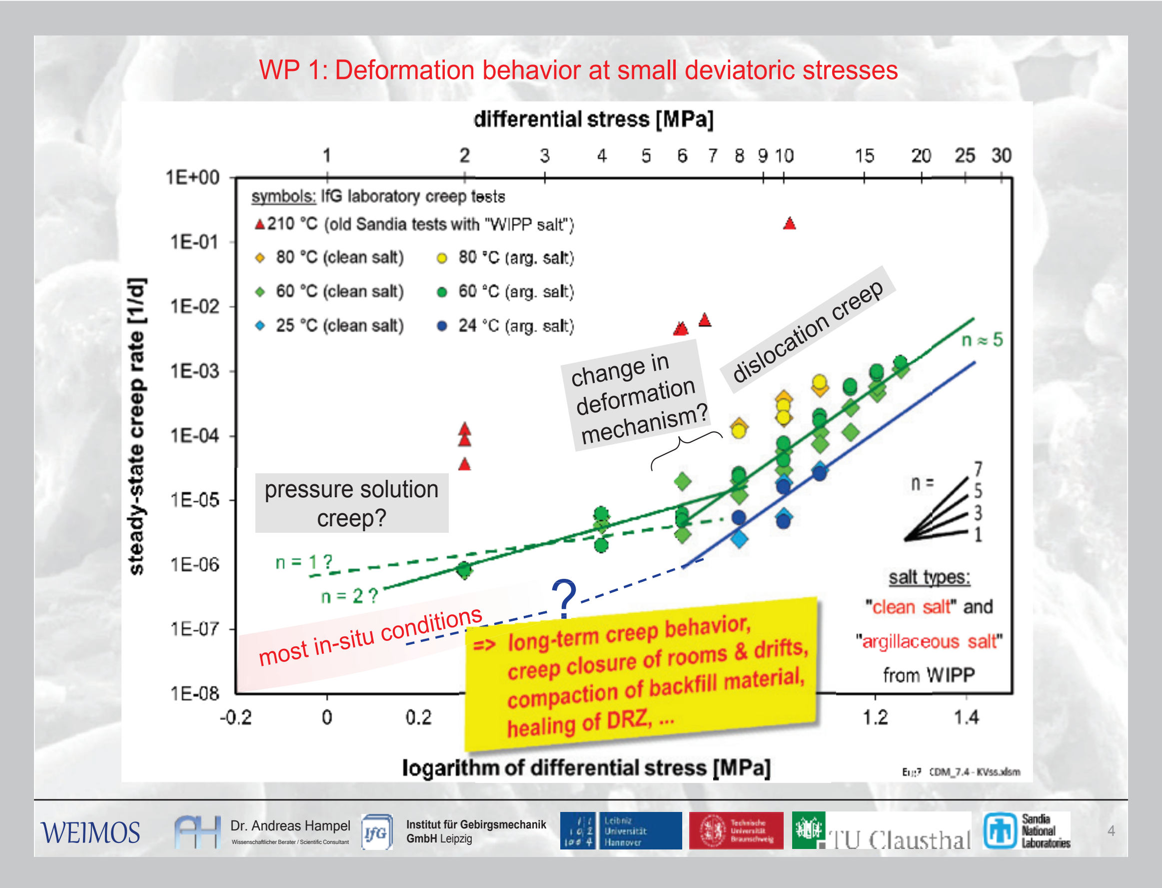
United States:

- Sandia National Laboratories, Albuquerque & Carlsbad

WEIMOS · Dr. Andreas Hampel · Institut für Gebirgsmechanik GmbH Leipzig · Leibniz Universität Hannover · Technische Universität Braunschweig · TU Clausthal · Sandia National Laboratories 2



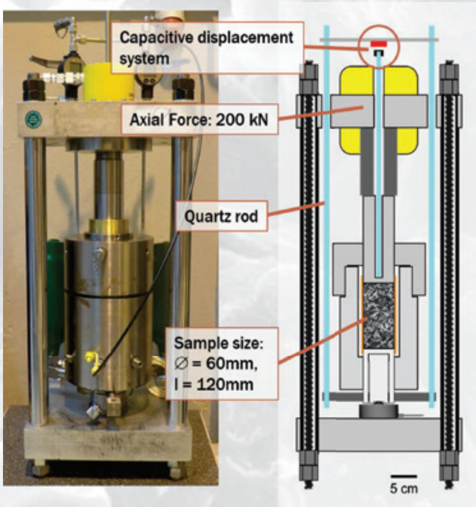
Joint Project WEIMOS (04/2016 – 03/2019)
Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt
Work Packages
WP 1: Deformation behavior at small deviatoric stresses
WP 2: Influence of temperature and stress state on damage reduction
WP 3: Deformation behavior resulting from tensile stresses
WP 4: Influence of inhomogeneities (layer boundaries, interfaces) on deformation
WP 5: Virtual demonstrator
WP 6: Administration
WEIMOS
Dr. Andreas Hampel
Institut für Gebirgsmechanik GmbH Leipzig
TU Clausthal
Sandia National Laboratories
3



WP 1: Deformation behavior at small deviatoric stresses
differential stress [MPa]
steady-state creep rate [1/d]
logarithm of differential stress [MPa]
symbols: IfG laboratory creep tests
210 °C (old Sandia tests with "WIPP salt")
80 °C (clean salt)
80 °C (arg. salt)
60 °C (clean salt)
60 °C (arg. salt)
25 °C (clean salt)
24 °C (arg. salt)
change in deformation mechanism?
dislocation creep
n ≈ 5
pressure solution creep?
n = 1 ?
n = 2 ?
most in-situ conditions
=> long-term creep behavior, creep closure of rooms & drifts, compaction of backfill material, healing of DRZ, ...
salt types:
"clean salt" and
"argillaceous salt"
from WIPP
WEIMOS
Dr. Andreas Hampel
Institut für Gebirgsmechanik GmbH Leipzig
TU Clausthal
Sandia National Laboratories
4

WP 1: Deformation behavior at small deviatoric stresses

IfG:
- ☺ 3 new creep test riggs constructed, built, calibration completed in 2018,
- ☺ climate-controlled chamber (ΔT = ± 0.2 °C) constructed and built,
- ☺ isolated from floor vibrations,
- ☺ remote readout and logging installed.



CSH02FL-CRm1,4	
Resolution	0.15 nm
Linearity	0,05 µm
Temperature sensitivity	-2.4 nm/°C

Measuring principle

The principle of capacitive displacement measurement using the capaNCDT (capacitive Non-Contact Displacement Transducer) system is based on how an ideal plate-type capacitor operates. The two plate electrodes are represented by the sensor and the opposing measurement object

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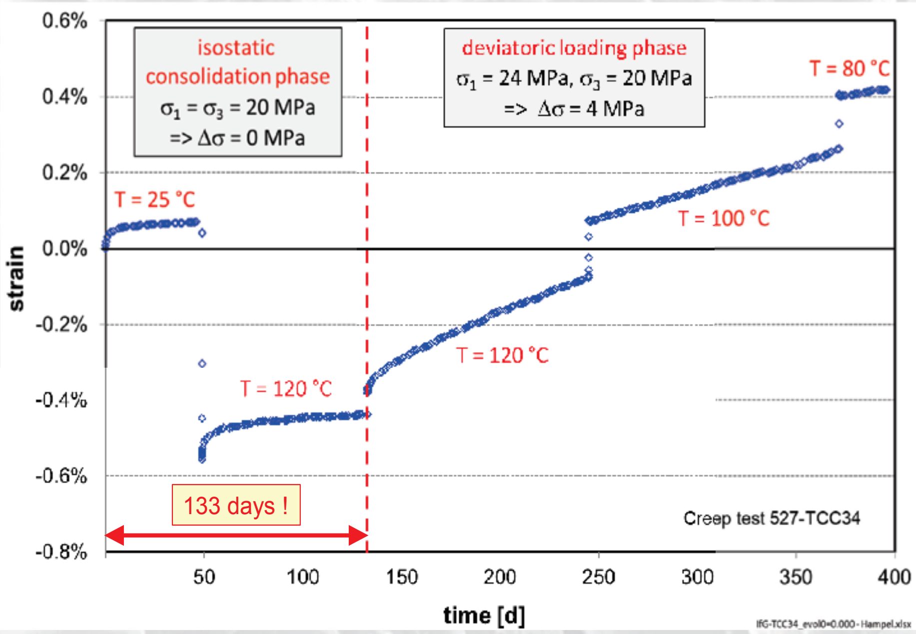
WP 1: Deformation behavior at small deviatoric stresses

IfG: Pre-test performed in an existing test rig



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WP 1: Deformation behavior at small deviatoric stresses

Planned triaxial creep tests with clean salt from WIPP in the 3 new test riggs:

Series 1:

a) **Consolidation for 100 days at T = 120 °C** with $\sigma_1 = \sigma_3$ = 20 MPa

b) Rig 1: $\Delta\sigma$ = 2 MPa, σ_3 = 20 MPa, T = 80 … 60 … 30 °C
Rig 2: $\Delta\sigma$ = 4 MPa, σ_3 = 20 MPa, T = 80 … 60 … 30 °C
Rig 3: $\Delta\sigma$ = 6 MPa, σ_3 = 20 MPa, T = 80 … 60 … 30 °C
(each temperature stage for 100 days)

Series 2:

a) **Consolidation for 100 days at T = 120 °C** with $\sigma_1 = \sigma_3$ = 20 MPa

b) Rig 1: $\Delta\sigma$ = 1 MPa, σ_3 = 20 MPa, T = 80 … 60 … 30 °C
Rig 2: $\Delta\sigma$ = 3 MPa, σ_3 = 20 MPa, T = 80 … 60 … 30 °C
Rig 3: $\Delta\sigma$ = 5 MPa, σ_3 = 20 MPa, T = 80 … 60 … 30 °C
(each temperature stage for 100 days)

Proposed extension of WEIMOS (2019 – 2021)

Accompanying microscopic investigations (Melissa Mills, Sandia)

=> Further development of the modeling of creep at small deviatoric stresses based on experimental results

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Joint Project WEIMOS (04/2016 – 03/2019)

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

Work Packages

WP 1: Deformation behavior at small deviatoric stresses

➡ WP 2: Influence of temperature and stress state on damage reduction

WP 3: Deformation behavior resulting from tensile stresses

WP 4: Influence of inhomogeneities (layer boundaries, interfaces) on deformation

WP 5: Virtual demonstrator

WP 6: Administration

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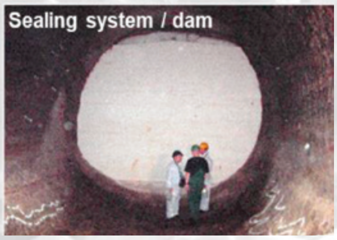
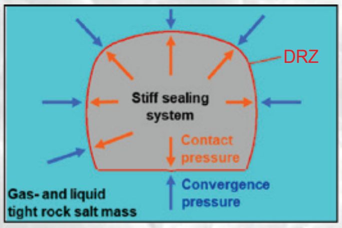
WP 2: Influence of temperature and stress state on damage reduction

Creep of surrounding rock salt against backfill material and a sealing system leads to closure of (micro-)cracks in the DRZ:
- ➢ reduction of secondary permeability
- ➢ restoration of properties of undisturbed salt: tightness and strength

damage reduction (“healing“)

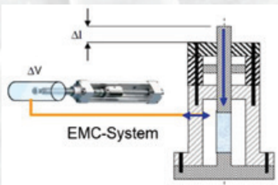


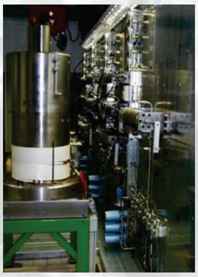


Knowledge of the damage reduction process is important for the repository safety case

WP 2: Influence of temperature and stress state on damage reduction

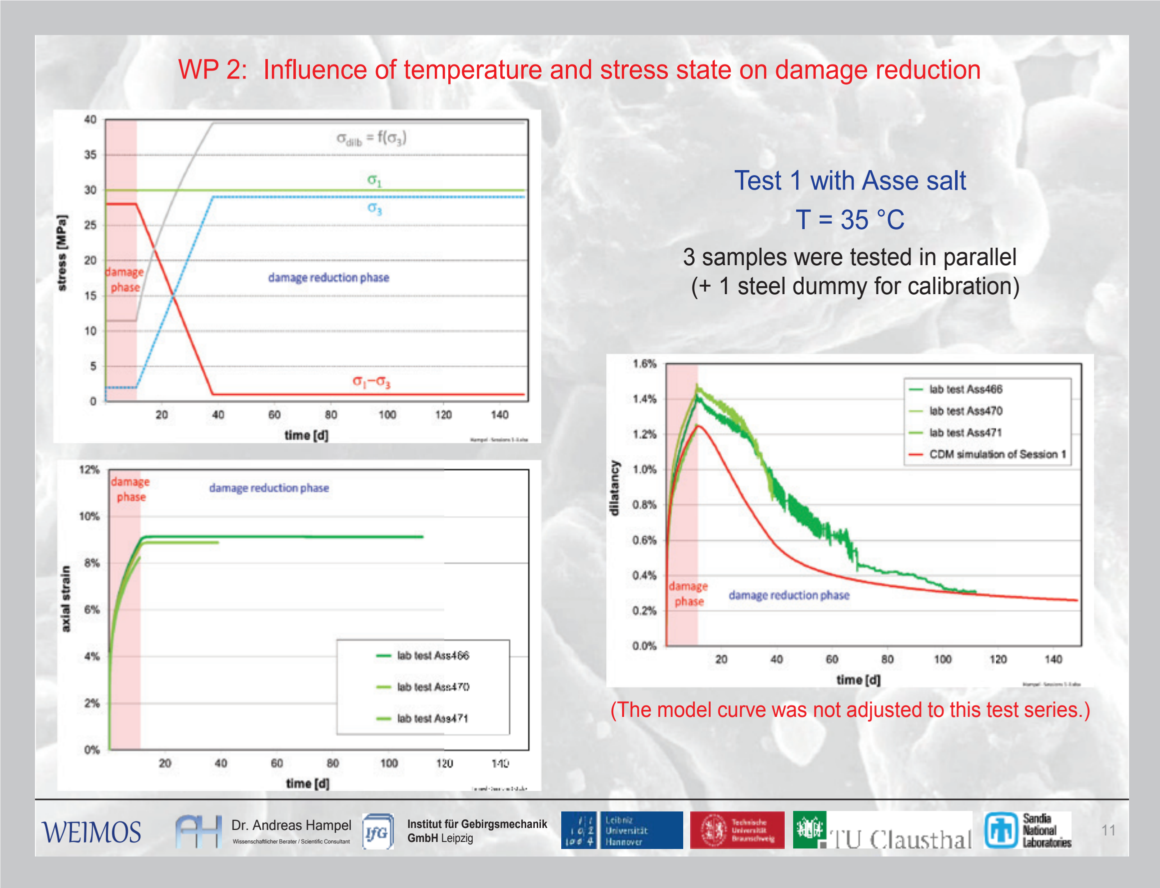
TUC: ☺ 4 new healing test riggs with high-resolution dilatancy measurement for testing of large cylindrical specimens (∅ 150 mm, l = 300 mm) in a climate-controlled chamber constructed, built, calibrated





Measured volume change (ΔV) depends on:
- piston movement
- temperature changes
- oil and rig compressibility
- ➢ dilatancy of salt sample (healing: slow and very small effect!)

TUC: ☺ further healing tests are performed in the main hall of the TUC lab


WP 2: Influence of temperature and stress state on damage reduction
Test 1 with Asse salt
T = 35 °C
3 samples were tested in parallel
(+ 1 steel dummy for calibration)
stress [MPa]
time [d]
damage phase
damage reduction phase
$\sigma_{dilb} = f(\sigma_3)$
σ_1
σ_3
$\sigma_1 - \sigma_3$
axial strain
lab test Ass466
lab test Ass470
lab test Ass471
dilatancy
CDM simulation of Session 1
(The model curve was not adjusted to this test series.)
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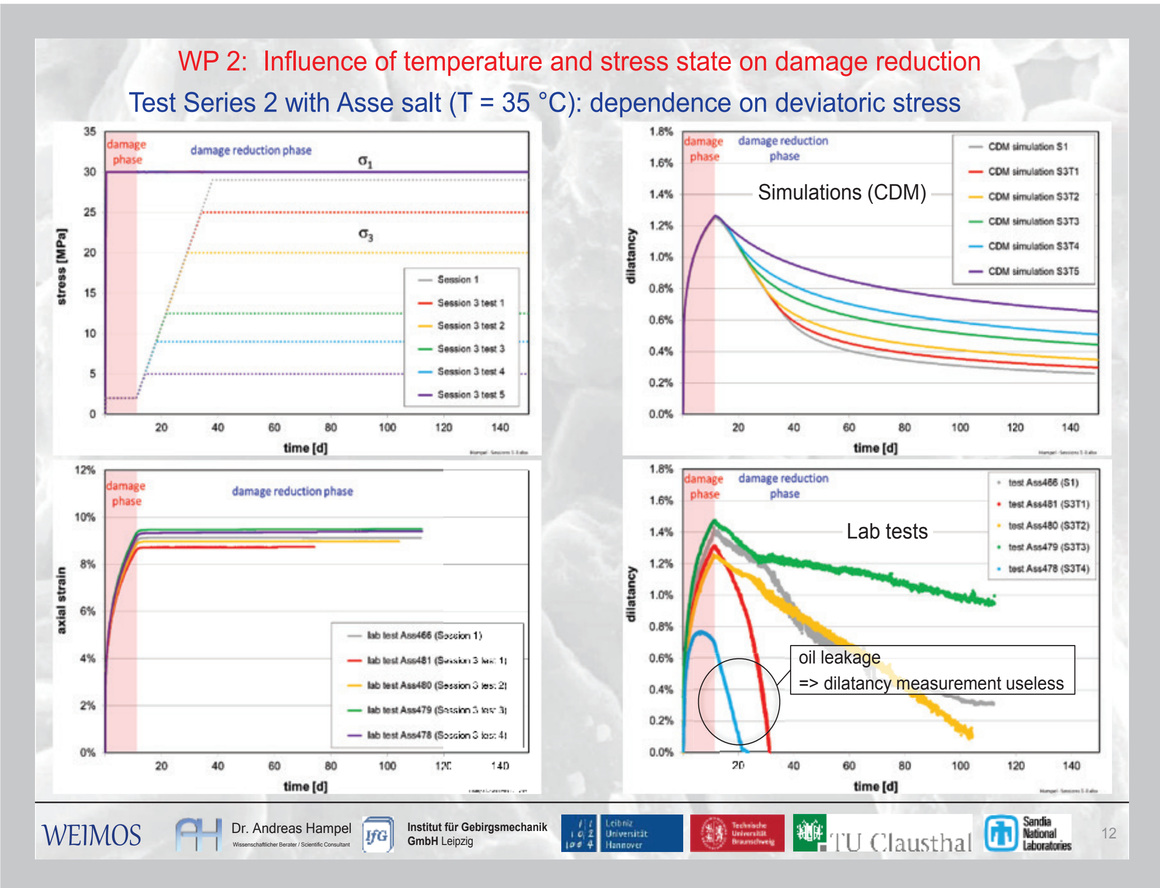
WP 2: Influence of temperature and stress state on damage reduction
Test Series 2 with Asse salt (T = 35 °C): dependence on deviatoric stress
stress [MPa]
time [d]
damage phase
damage reduction phase
σ_1
σ_3
Session 1
Session 3 test 1
Session 3 test 2
Session 3 test 3
Session 3 test 4
Session 3 test 5
dilatancy
Simulations (CDM)
CDM simulation S1
CDM simulation S3T1
CDM simulation S3T2
CDM simulation S3T3
CDM simulation S3T4
CDM simulation S3T5
axial strain
lab test Ass466 (Session 1)
Lab tests
test Ass466 (S1)
test Ass481 (S3T1)
test Ass480 (S3T2)
test Ass479 (S3T3)
test Ass478 (S3T4)
oil leakage
=> dilatancy measurement useless
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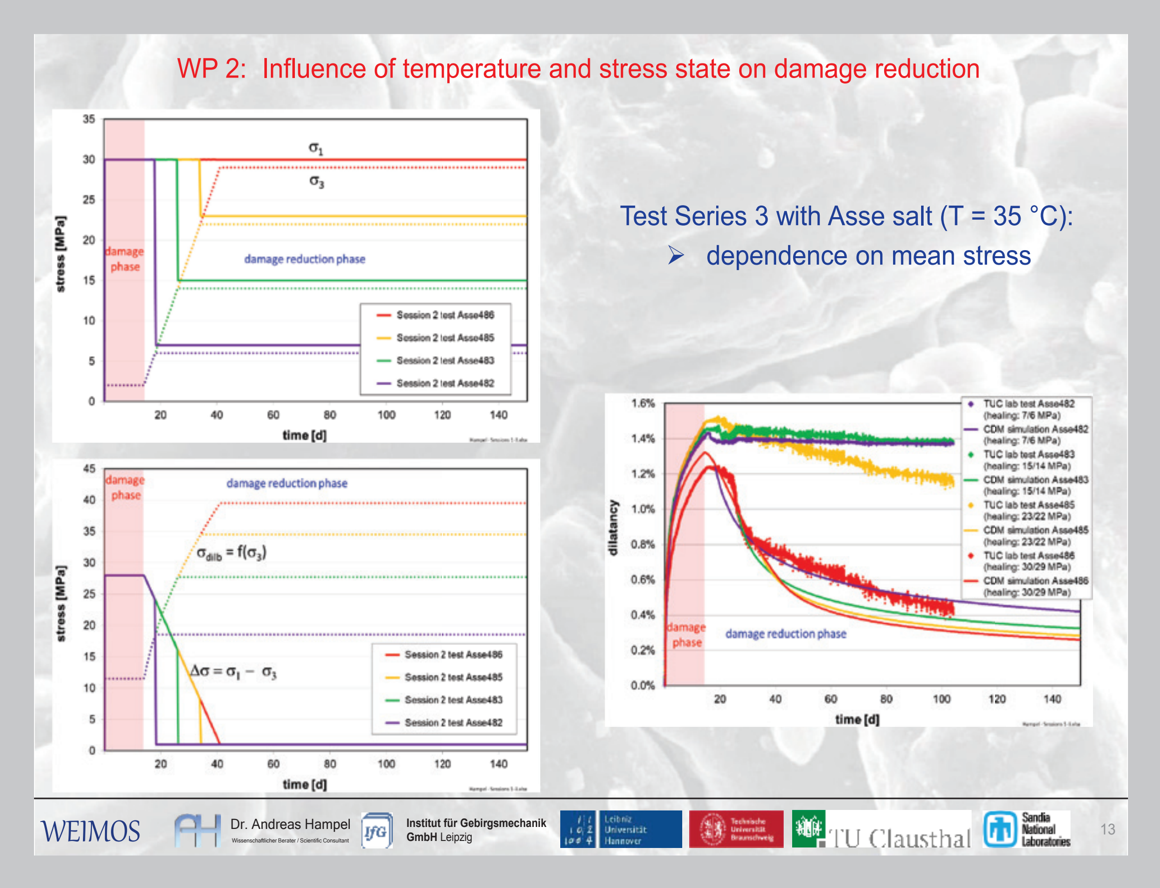

WP 2: Influence of temperature and stress state on damage reduction
Test Series 3 with Asse salt (T = 35 °C):
dependence on mean stress
stress [MPa]
time [d]
damage phase
damage reduction phase
σ1
σ3
Session 2 test Asse486
Session 2 test Asse485
Session 2 test Asse483
Session 2 test Asse482
σdilb = f(σ3)
Δσ = σ1 − σ3
dilatancy
TUC lab test Asse482 (healing: 7/6 MPa)
CDM simulation Asse482 (healing: 7/6 MPa)
TUC lab test Asse483 (healing: 15/14 MPa)
CDM simulation Asse483 (healing: 15/14 MPa)
TUC lab test Asse485 (healing: 23/22 MPa)
CDM simulation Asse485 (healing: 23/22 MPa)
TUC lab test Asse486 (healing: 30/29 MPa)
CDM simulation Asse486 (healing: 30/29 MPa)
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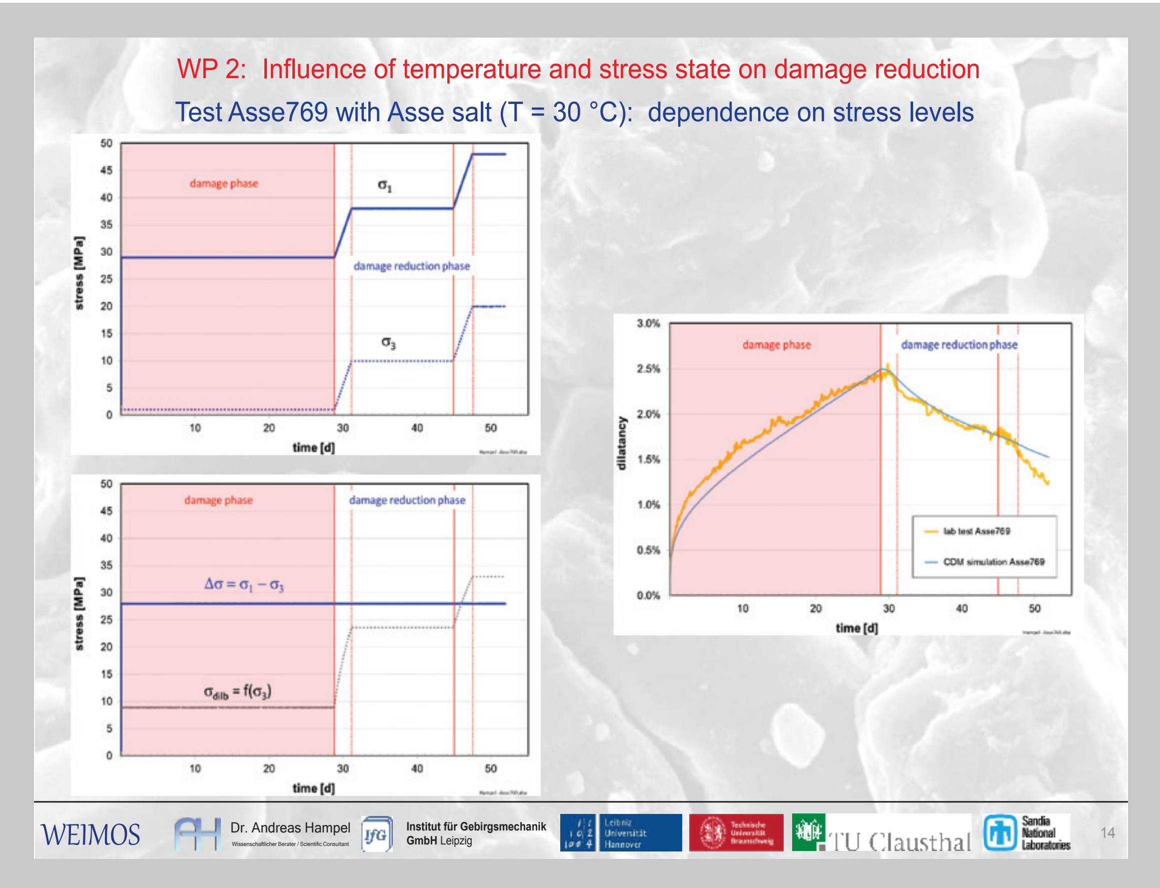

WP 2: Influence of temperature and stress state on damage reduction
Test Asse769 with Asse salt (T = 30 °C): dependence on stress levels
stress [MPa]
time [d]
damage phase
damage reduction phase
σ1
σ3
Δσ = σ1 − σ3
σdilb = f(σ3)
dilatancy
lab test Asse769
CDM simulation Asse769
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WP 2: Influence of temperature and stress state on damage reduction

Planned healing tests with Asse salt (TUC lab):

Series 1: 4 tests with defined initial damage, then healing at different isotropic stress levels (T = 35 °C)

Series 2: 4 tests with defined initial damage, then healing at different deviatoric stresses (T = 35 °C)

Series 3: same as Series 1, but T = 70 °C

Series 4: same as Series 2, but T = 70 °C

Series 5/1: test with constant $\Delta\sigma$, but changing σ_1 and σ_3 (T = 35 °C) (-> creep of damage-free creep, damaged-influenced creep, and healing in the same specimen)

Series 5/2: healing test with initial damage up to 2.5 % dilatancy, then healing at different stress levels (T = 35 °C)

Planned healing tests with clean salt from WIPP (TUC lab):

Series 6/1: 2 tests like Series 1 (T = 35 °C)

Series 6/2: 2 tests like Series 2 (T = 35 °C)

Series 7/1: 2 tests like Series 5/1 (T = 35 °C)

Series 7/1: 2 tests like Series 5/2 (T = 35 °C)

Proposed extension of WEIMOS (2019 – 2021)

Accompanying microscopic investigations (Sandia)

=> Further development of the modeling of damage reduction and healing based on experimental results

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Joint Project WEIMOS (04/2016 – 03/2019)

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

Work Packages

WP 1: Deformation behavior at small deviatoric stresses

WP 2: Influence of temperature and stress state on damage reduction

➡ WP 3: Deformation behavior resulting from tensile stresses

WP 4: Influence of inhomogeneities (layer boundaries, interfaces) on deformation

WP 5: Virtual demonstrator

WP 6: Administration

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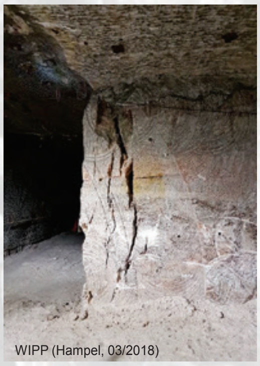
WP 3: Deformation behavior resulting from tensile stresses

Tensile damage processes and tensile strength play dominant roles for development of micro-cracks and progressive damage in the "Disturbed/Damaged Rock Zone" (DRZ).

Tensile stresses may also be generated by thermal effects
(e.g. heating/cooling after disposal of HLW)

=> Modeling of tensile damage and tensile strength is important for operational safety and integrity of geotechnical barrier systems.



WP 3: Deformation behavior resulting from tensile stresses

Simulations of different examples performed with the material models of the partners:

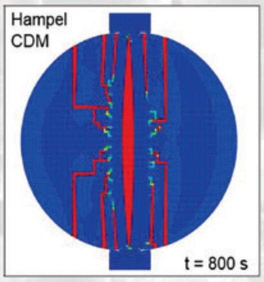
bending beam, Brazilian test, HFCP test, Room D at WIPP

- Comparison of calculated tensile damage, tensile strength, crack patterns

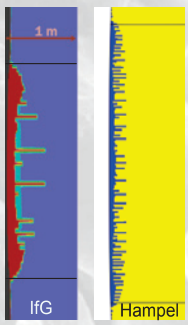
=> Plausible qualitative results.

For parameter determinations and quantitative results, and for a further development of the models, experimental investigations are needed.

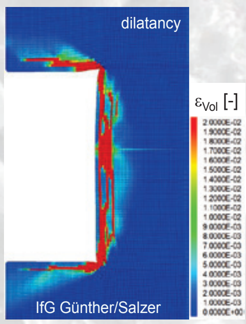
damage in a Brazilian test



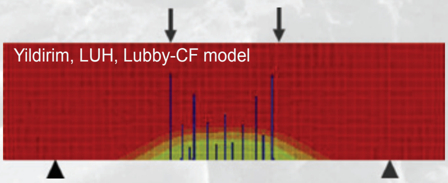
damage in a borehole wall section after cooling (HFCP)



damage around Room D at WIPP

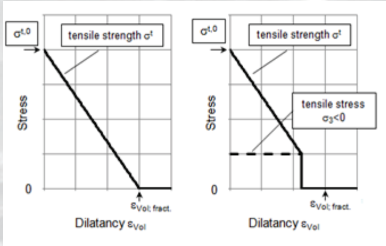


damage in a bending beam



WP 3: Deformation behavior resulting from tensile stresses

no tensile stress | with tensile stress



Current material models of the partners describe tensile strength in dependence of damage (dilatancy) (IfG, Günther et al. 2015):

$\sigma^{t,0}$: tensile strength of undamaged salt (≈ 0.5 ... 3 MPa)

$\varepsilon_{Vol,fract}$: dilatancy at peak strength (failure) (≈ 1 ... 3 %)

tensile stress reaches $\sigma^t(\varepsilon_{vol})$ curve => σ^t -> 0 (brittle fracture)

Planned tensile tests with clean salt from WIPP (IfG and TUC labs):

Series of 30 triaxial tests with different σ_3 = 0.2 ... 5 MPa:

a) initial damage in compression (ε_{vol} = 0.5 ... 3 %),

b) then direct tension tests with the pre-damaged specimens

measurements: tensile strength, ultrasonic wave velocities

Proposed extension of WEIMOS (2019 – 2021)

=> Further development of the modeling based on experimental results

Joint Project WEIMOS (04/2016 – 03/2019)

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

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➡ WP 4: Influence of inhomogeneities (layer boundaries, interfaces) on deformation

WP 5: Virtual demonstrator

WP 6: Administration

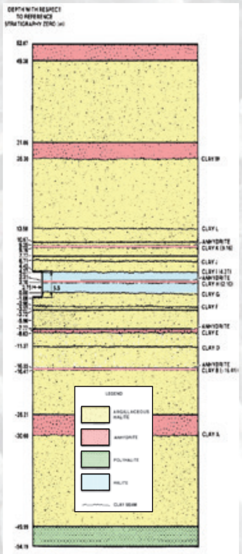
WEIMOS WP 4: Influence of inhomogeneities (layer boundaries, interfaces)

Research:
- Influence on convergence (e.g. sliding on clay seams at WIPP)
- Influence on damage and dilatancy in the DRZ
- Modeling of these phenomena

Objective:
- Study, develop further and improve the modeling

=> Reduce uncertainties of simulation results, increase confidence in the results

Stratigraphy at WIPP



after Munson et al. (1990): Sandia Report SAND89-2671

Experimental investigations
- RESPEC lab: shear tests on layered rock salt specimens
  -> Presentation of Stuart Buchholz (RESPEC) & Steve Sobolik (Sandia)
- Proposals of Sandia (1983, 2016): In-situ experiments

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Joint Project WEIMOS (04/2016 – 03/2019)

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

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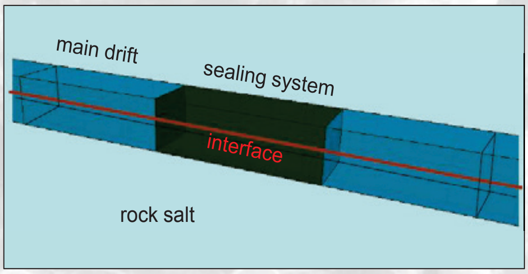
WEIMOS WP 5: Virtual demonstrator

Objective: Simulation of a complex model to demonstrate the improved modeling of the investigated phenomena:

- small deviatoric stresses
- damage reduction and healing
- influence tensile stresses (less)
- influence of interfaces/layer boundaries



Simulations:

step 1: open drift

step 2: installation of a (simplified) dam

step 3: post-operational phase & long-term behavior

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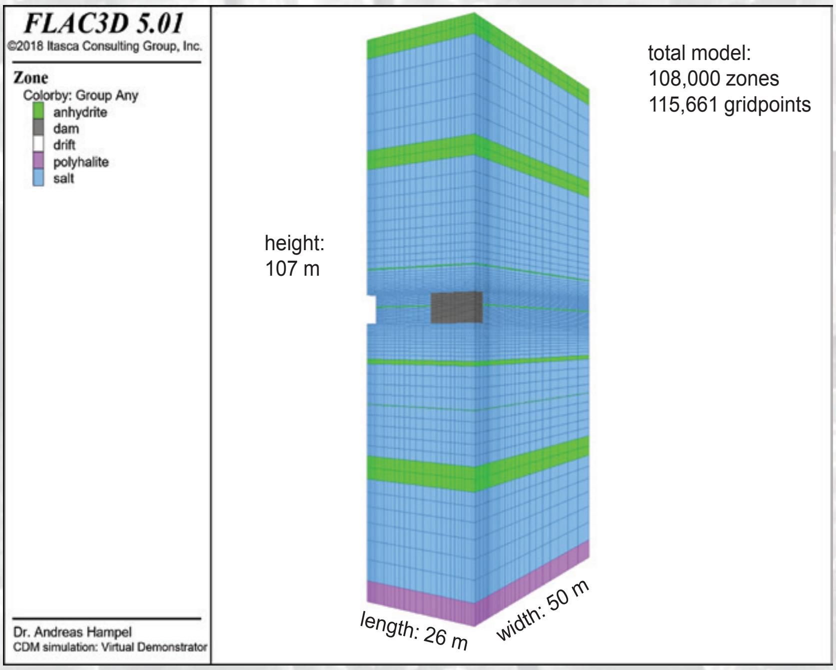
WEIMOS WP 5: Virtual demonstrator



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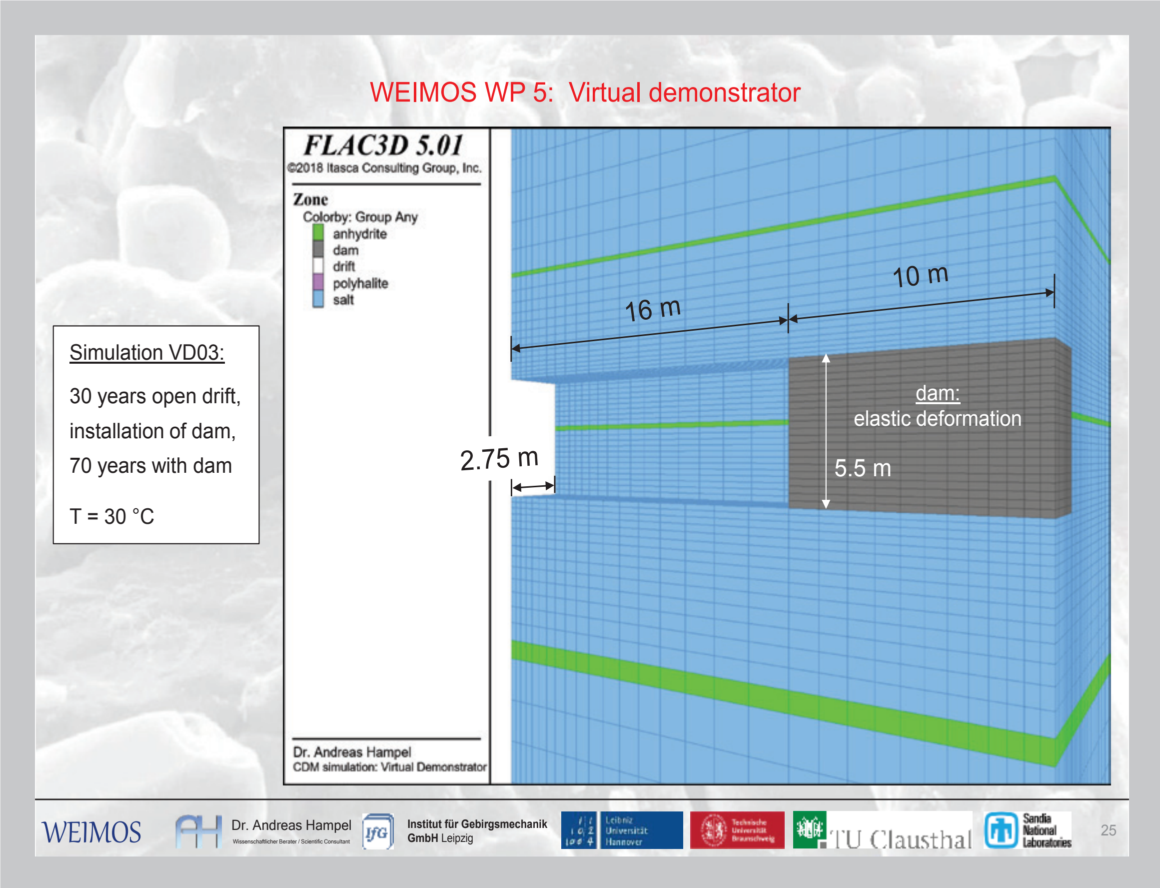
WEIMOS WP 5: Virtual demonstrator
FLAC3D 5.01
©2018 Itasca Consulting Group, Inc.
Zone
Colorby: Group Any
anhydrite
dam
drift
polyhalite
salt
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CDM simulation: Virtual Demonstrator
Simulation VD03:
30 years open drift,
installation of dam,
70 years with dam
T = 30 °C
16 m
10 m
2.75 m
dam:
elastic deformation
5.5 m
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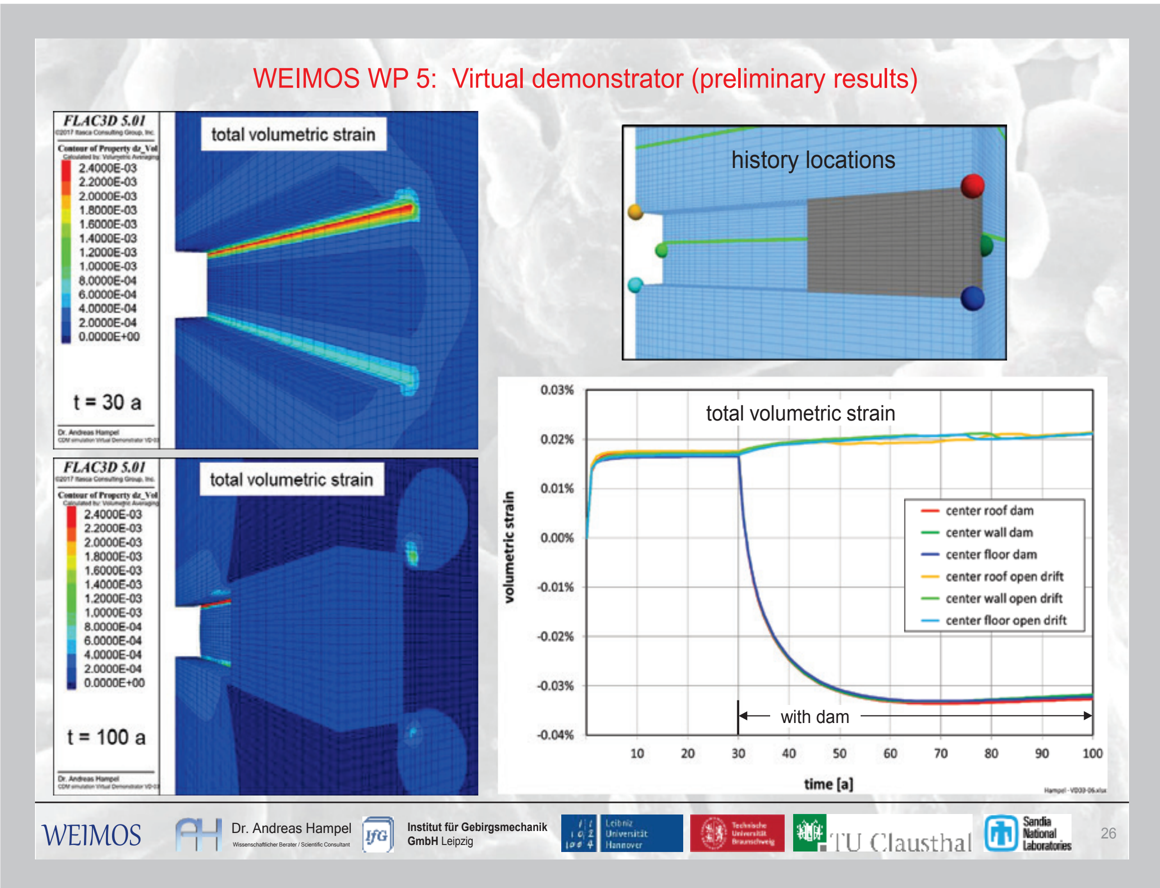
WEIMOS WP 5: Virtual demonstrator (preliminary results)
FLAC3D 5.01
total volumetric strain
2.4000E-03
2.2000E-03
2.0000E-03
1.8000E-03
1.6000E-03
1.4000E-03
1.2000E-03
1.0000E-03
8.0000E-04
6.0000E-04
4.0000E-04
2.0000E-04
0.0000E+00
t = 30 a
t = 100 a
history locations
total volumetric strain
volumetric strain
time [a]
center roof dam
center wall dam
center floor dam
center roof open drift
center wall open drift
center floor open drift
with dam
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WEIMOS WP 5: Virtual demonstrator

Future work:

I. Simulations of Virtual Demonstrator

a) with different temperatures and/or a temperature gradient

b) with interfaces / clay seams

II. Simulations of a second demonstration model focusing on tensile damage and slab separation

Proposed extension of WEIMOS (2019 – 2021)

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Joint Project WEIMOS (Phase 1): 2016 – 2019
Proposed extension (Phase 2): 2019 – 2021

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

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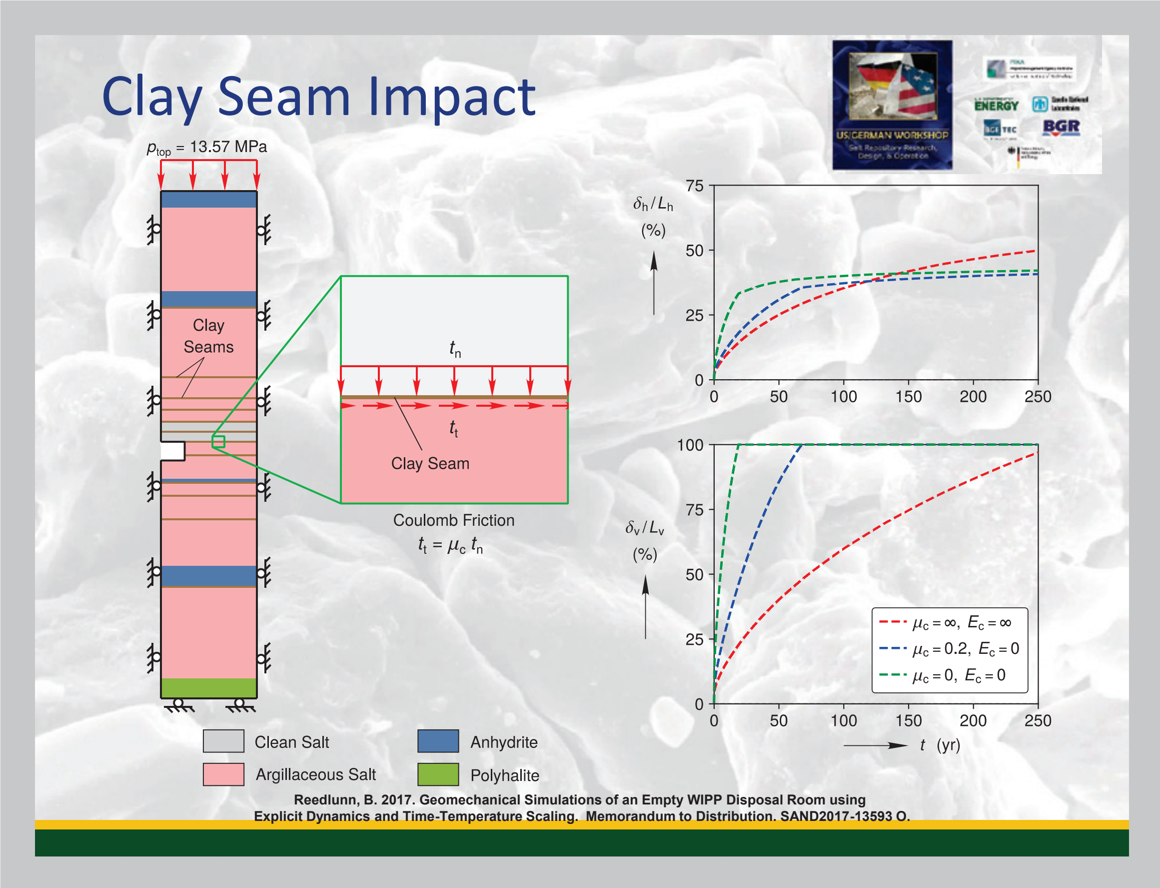
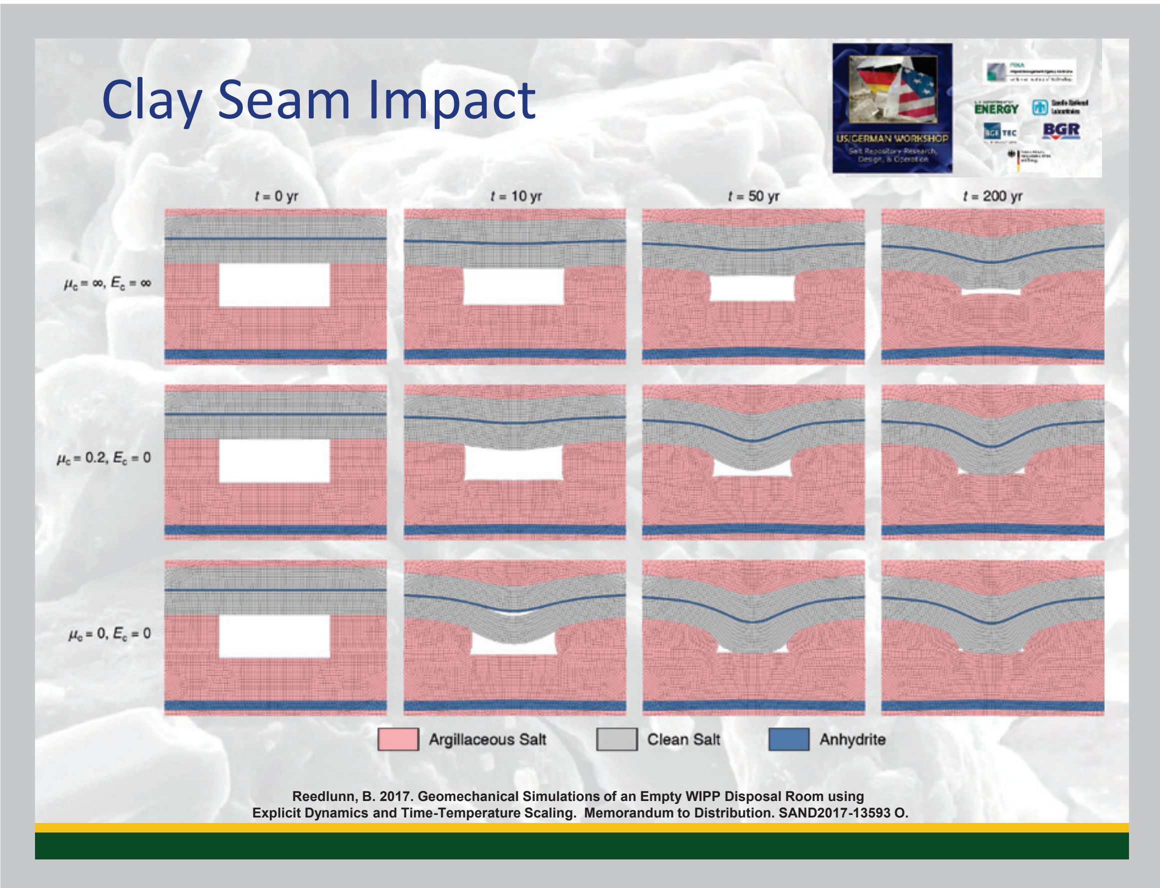
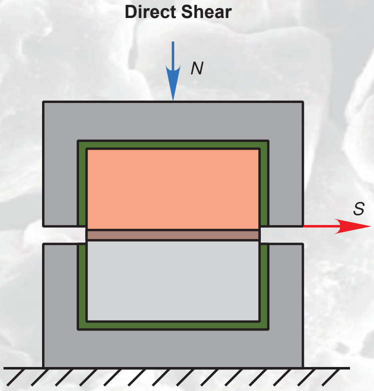
S. R. Sobolik & B. Reedlunn, S. Buchholz, E. Keffeler, S. Borglum


Clay Seam Impact
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
ENERGY
BGR
p_{top} = 13.57 MPa
Clay Seams
t_n
t_t
Clay Seam
Coulomb Friction
$t_t = \mu_c t_n$
δ_h / L_h (%)
δ_v / L_v (%)
t (yr)
$\mu_c = \infty, E_c = \infty$
$\mu_c = 0.2, E_c = 0$
$\mu_c = 0, E_c = 0$
Clean Salt
Anhydrite
Argillaceous Salt
Polyhalite
Reedlunn, B. 2017. Geomechanical Simulations of an Empty WIPP Disposal Room using Explicit Dynamics and Time-Temperature Scaling. Memorandum to Distribution. SAND2017-13593 O.


Clay Seam Impact
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
ENERGY
BGR
t = 0 yr
t = 10 yr
t = 50 yr
t = 200 yr
$\mu_c = \infty, E_c = \infty$
$\mu_c = 0.2, E_c = 0$
$\mu_c = 0, E_c = 0$
Argillaceous Salt
Clean Salt
Anhydrite
Reedlunn, B. 2017. Geomechanical Simulations of an Empty WIPP Disposal Room using Explicit Dynamics and Time-Temperature Scaling. Memorandum to Distribution. SAND2017-13593 O.

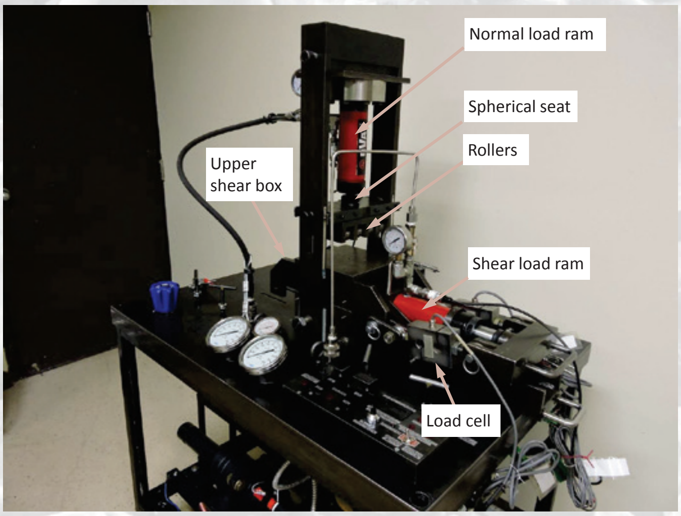
Research Plan

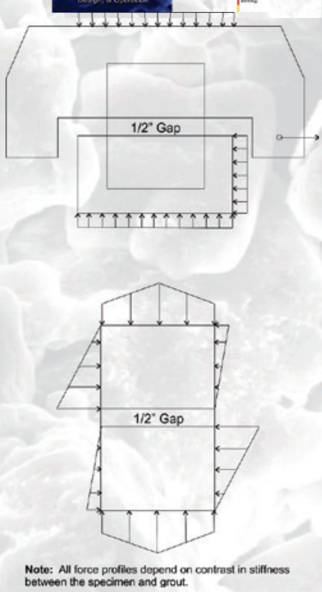
- Laboratory Experiments (TP 17-03)
  - Extraction Sites
    - Salt/Potash mine in the Permian Basin
    - WIPP drifts
  - Samples
    - 10 cm diameter cylinders
    - Various bedding plane constituents
  - Tests
    - Direct shear and/or triaxial cell tests
    - Tensile strength



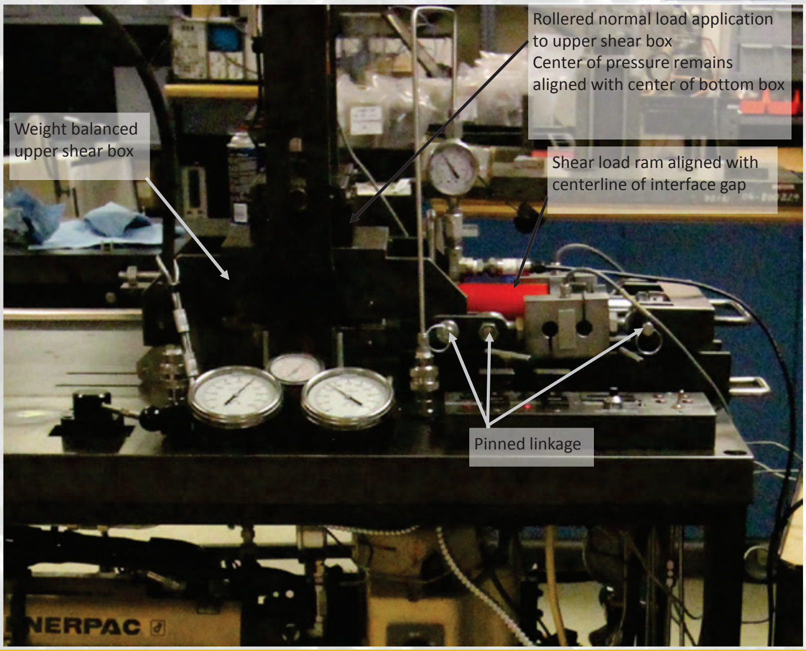
- Modeling
  - Construct constitutive model(s) with Joint Project WEIMOS
- In-Situ Experiment
  - ~1 m cube to quantify size effects
  - Validate models against in-situ test.

Direct Shear Test Setup





Shear Test Setup (Actual Test)



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Laboratory tests to date

- 2018 laboratory tests include following:
  - 10-cm (4-in) cylindrical samples, with existing interface/contact
  - 3.4, 6.8, 10.3, & 16.6 MPa (500, 1000, 1500, & 2400 psi) stress capacity both in axial (compression) and shear loading
  - Fixed normal stress for tests
  - RESPEC direct shear machine (Capacity for 130 kN load, shear velocities 0.25-5 mm/min). Ram advance rate set at 0.25 mm/min for these tests.
- Analysis plan to develop constitutive, numerical model for shear slip at interface from results of 2018 lab tests.

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List of tests performed

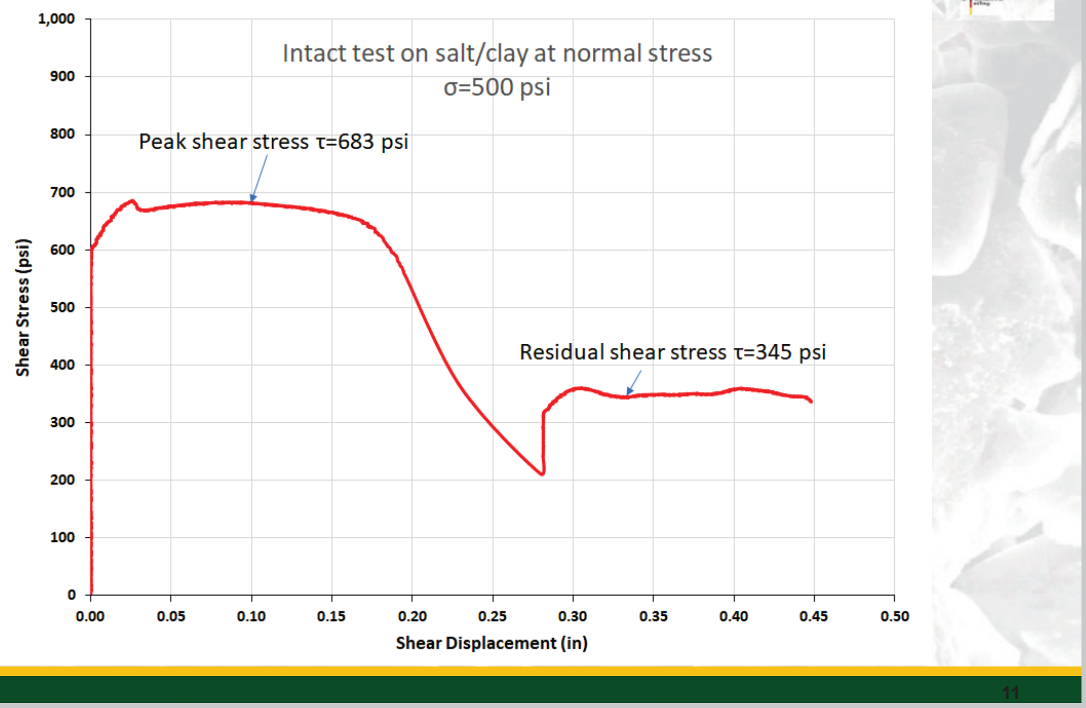
- 24 samples total, 4 intact tests/3 residual tests for each material type
- Normal pressures for intact tests were 500, 100, 1500, 2400 psi
- Post-intact residual tests at higher normal stresses for most samples
- Tests were performed on the following core samples:
  - Canadian halite with clay interface (to test out experimental procedure)
  - New Mexico core – Halite/polyhalite interface
  - New Mexico core – Halite/anhydrite interface
  - New Mexico core – Halite/clay interface
  - New Mexico core – “Pure salt” or “Closer salt” (Intact halite with no interface, 0-40 cm into drift wall; salt had more pure appearance)
  - New Mexico core – “Mixed salt” or “Deeper salt” (Intact halite with no interface, 50+ cm into drift wall; salt had more mixed appearance)

9

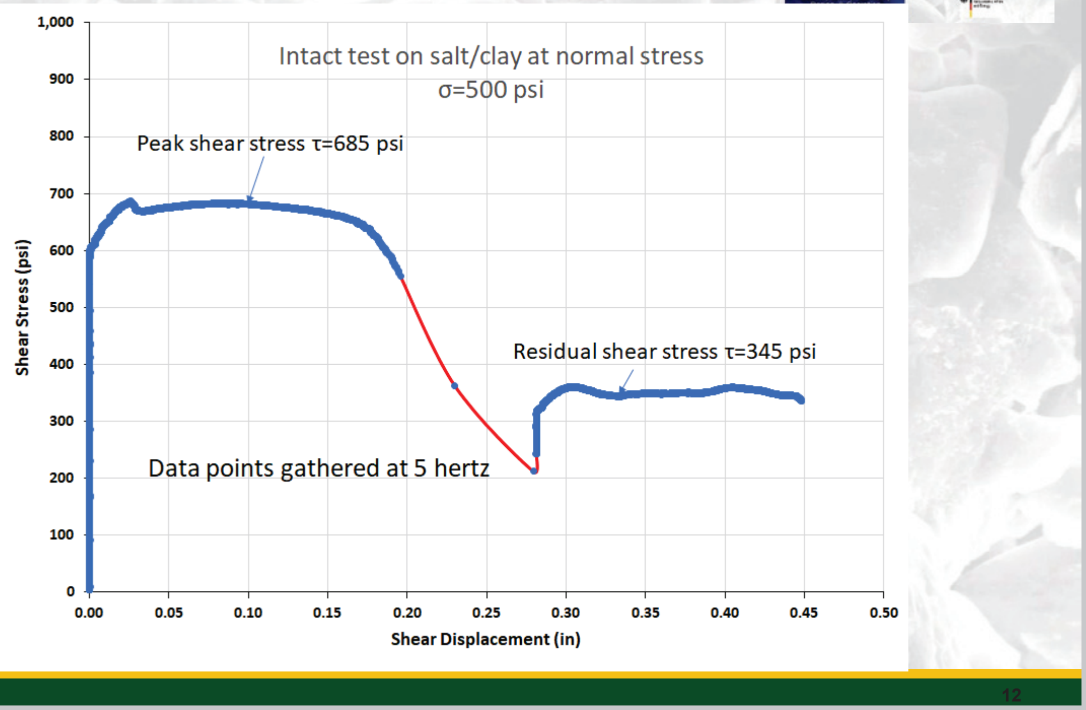
Cutting of Samples from Core

10

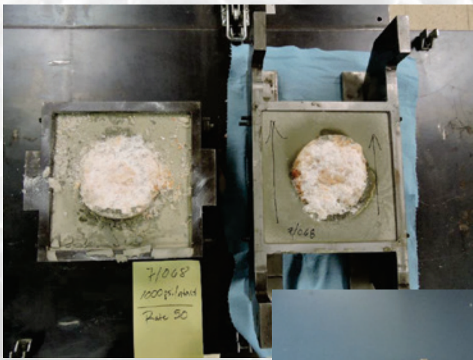
Typical test results



Typical test results



Closer salt tests

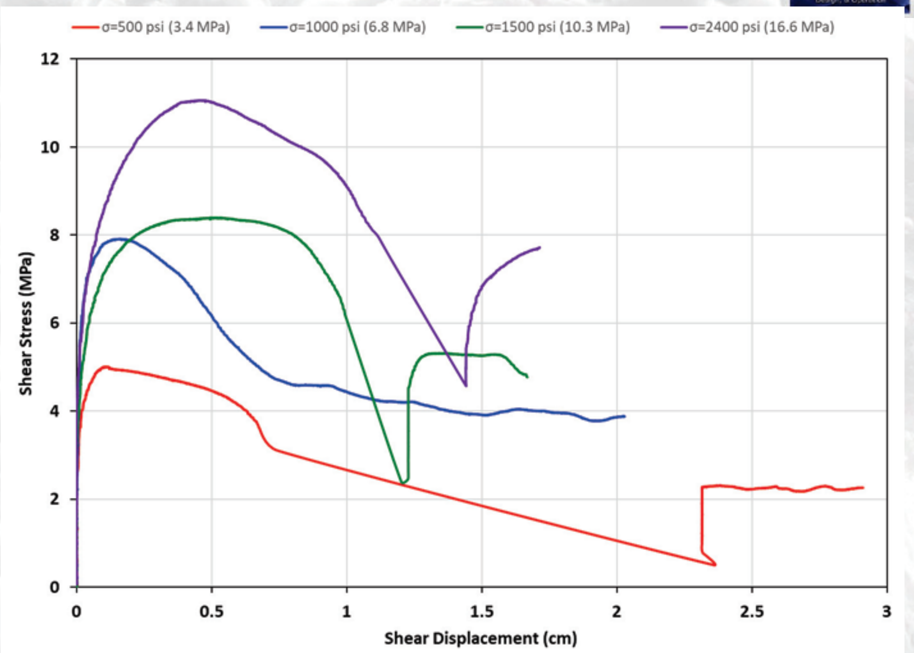


Intact test, σ_n=1000 psi (6.8 MPa)

Intact test, σ_n=1000 psi (6.8 MPa), side view

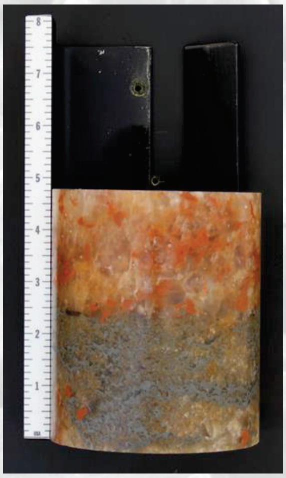
13

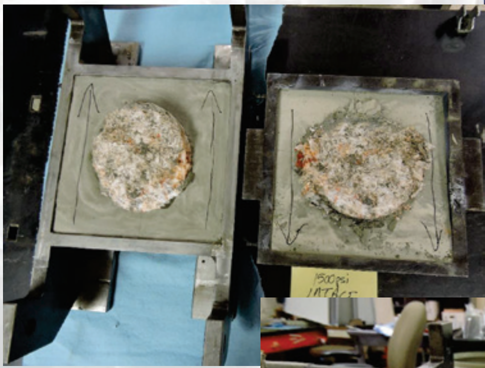
Closer salt tests



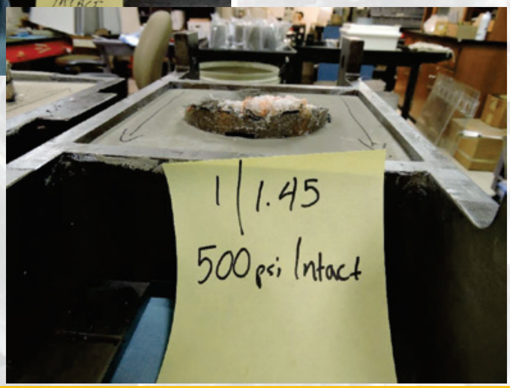
14

Salt/clay tests





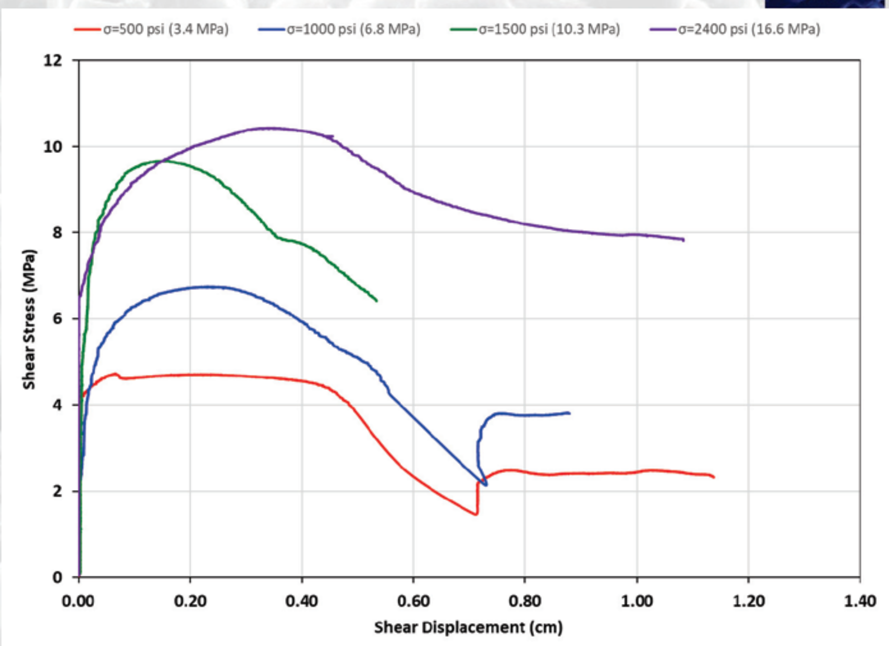
Intact test, σ_n=1500 psi (10.3 MPa)



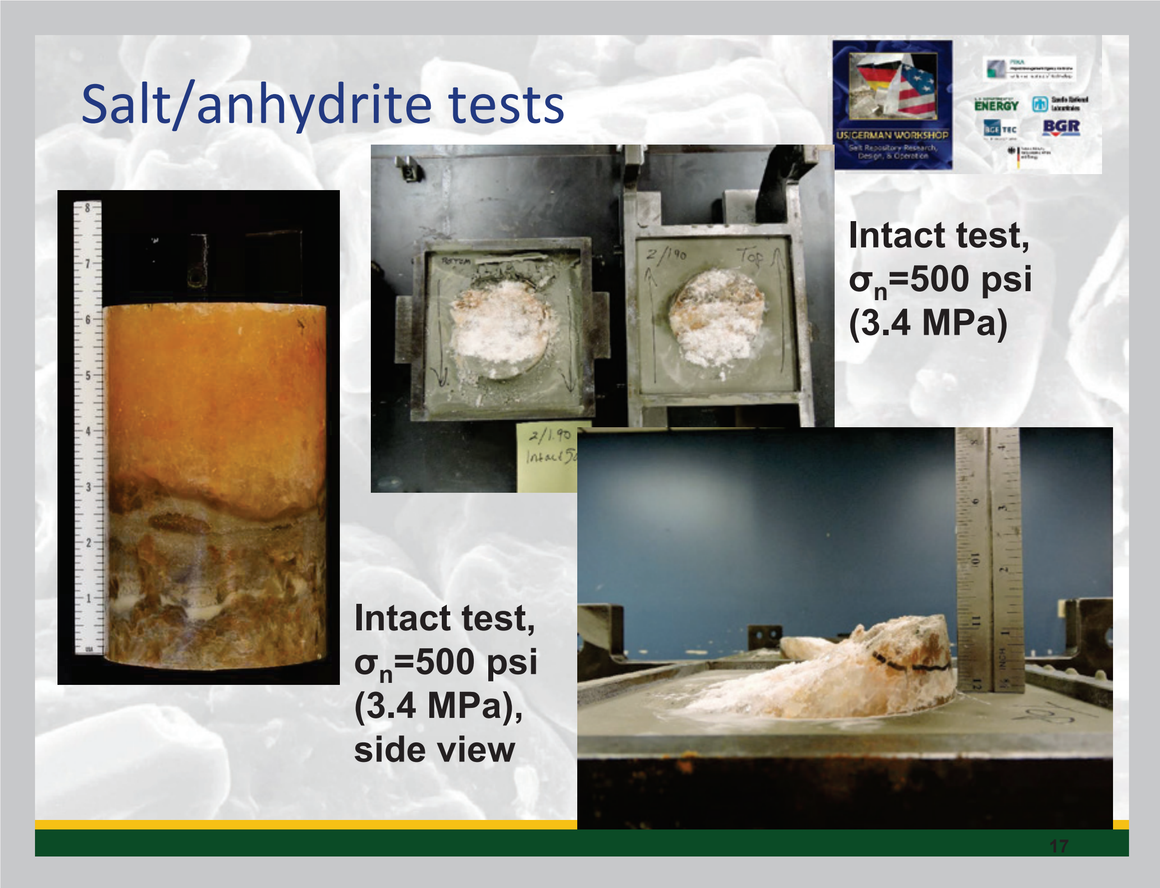
Intact test, σ_n=500 psi (3.4 MPa), side view

15

Salt/clay tests



16



Salt/anhydrite tests
Intact test, σn=500 psi (3.4 MPa)
Intact test, σn=500 psi (3.4 MPa), side view
US/GERMAN WORKSHOP
ENERGY
BGR
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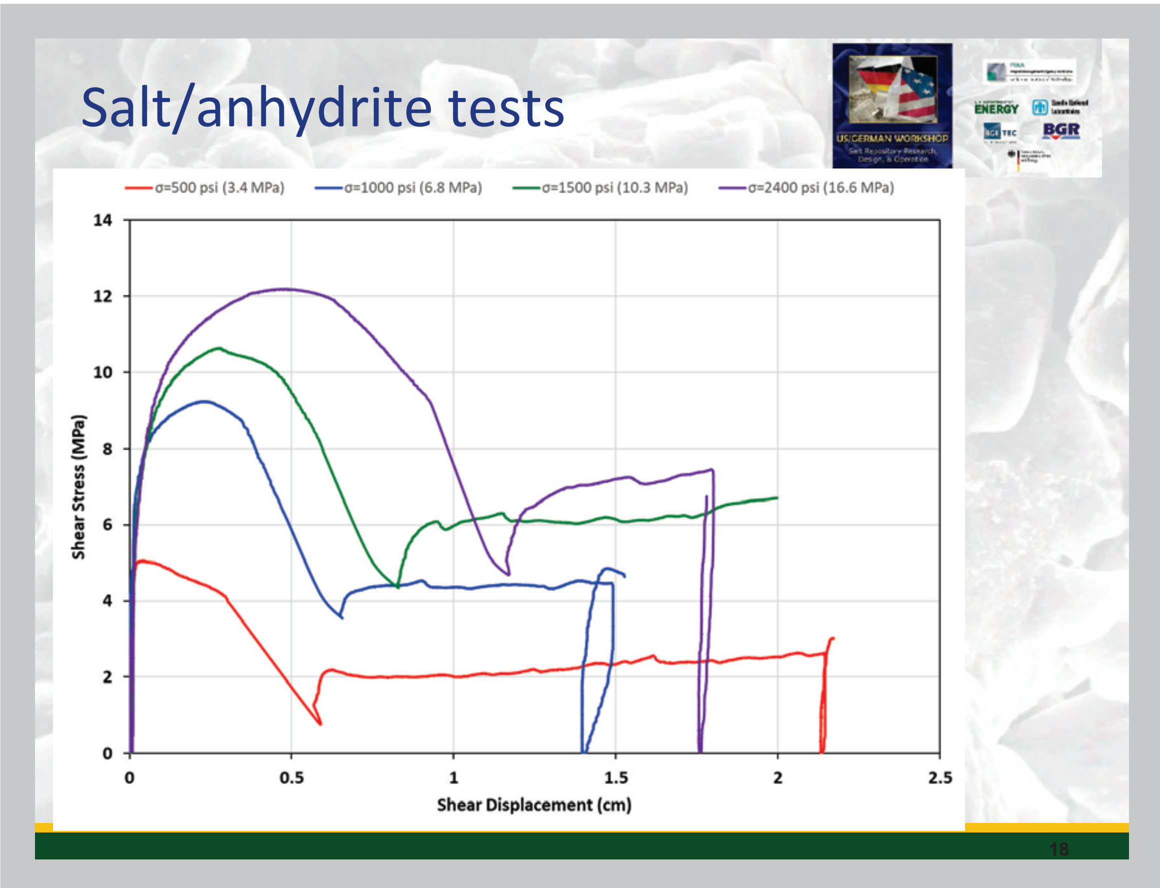
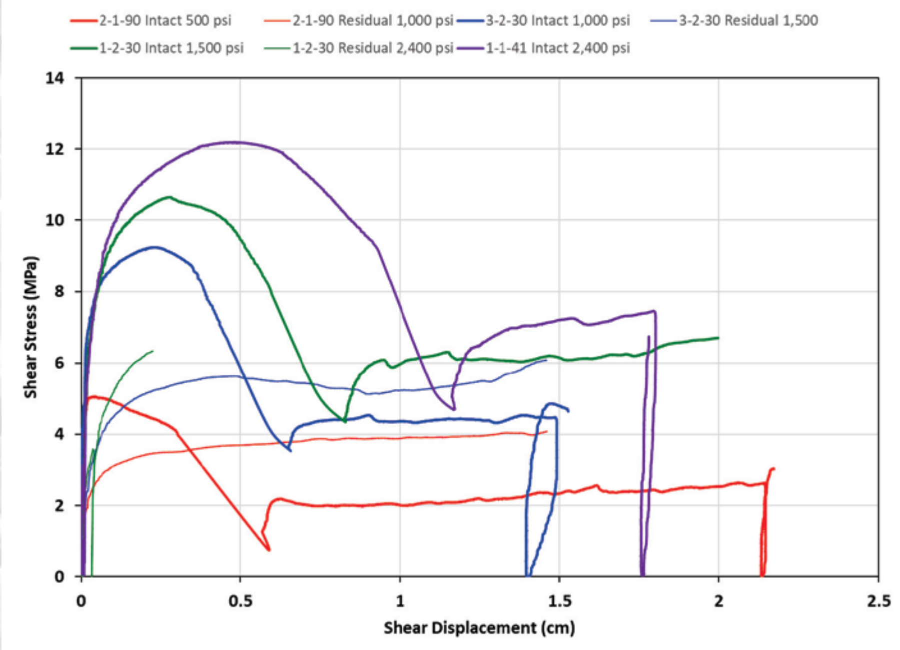
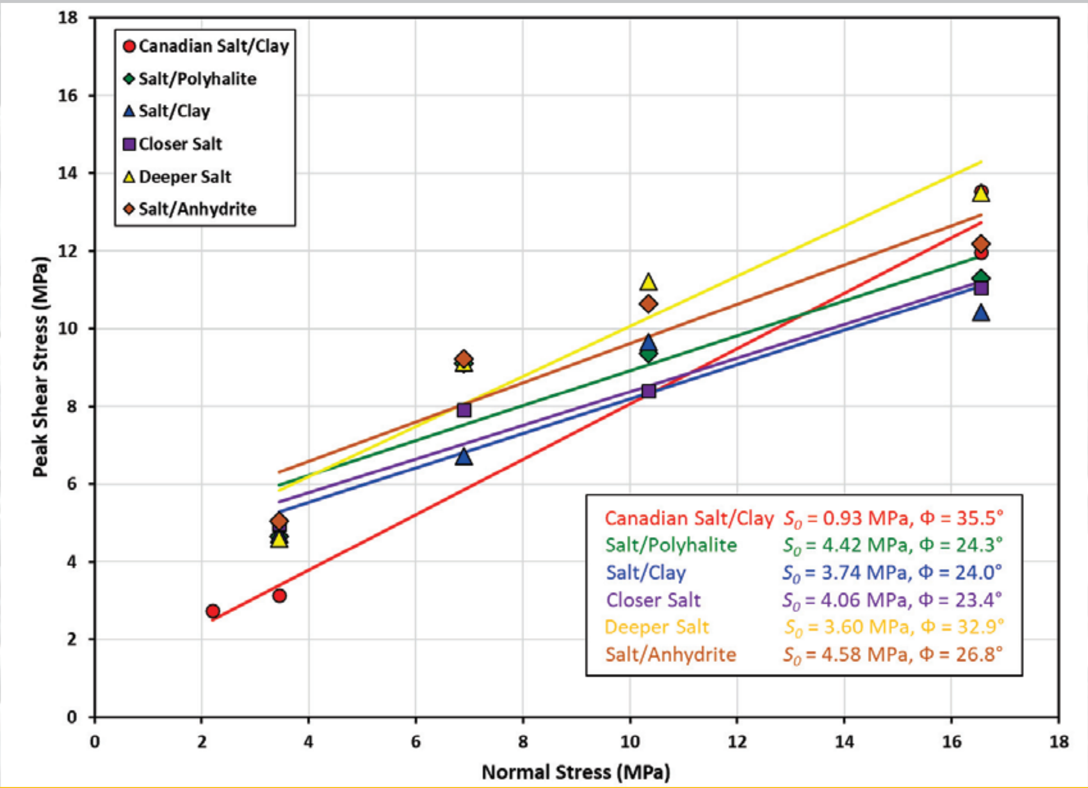


Salt/anhydrite tests
σ=500 psi (3.4 MPa)
σ=1000 psi (6.8 MPa)
σ=1500 psi (10.3 MPa)
σ=2400 psi (16.6 MPa)
Shear Stress (MPa)
Shear Displacement (cm)
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
US/GERMAN WORKSHOP
ENERGY
BGR
18

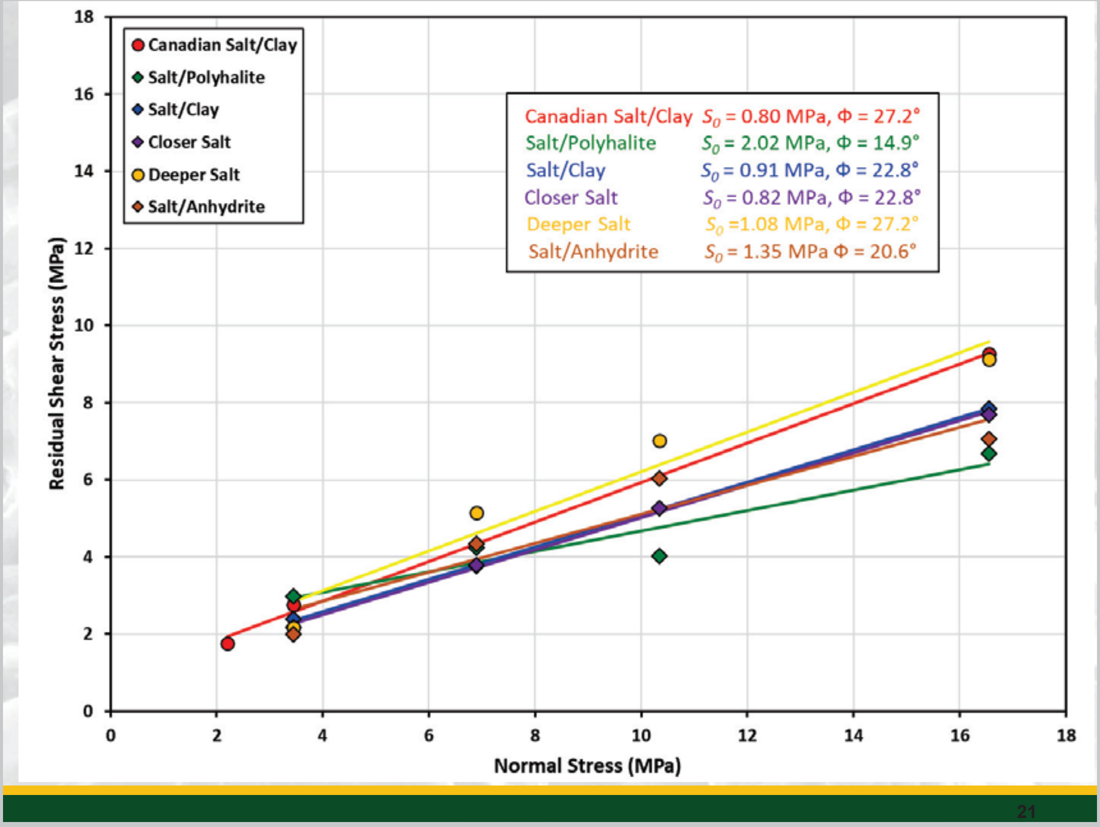
Salt/anhydrite tests (intact, post-intact)



19

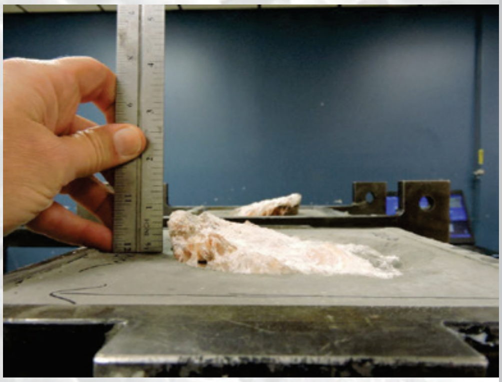


20



Test observations

- Overall testing technique is good
- Two indications test setup might not be ideally rigid:
  - Fractures all tend to occur "top down"
  - Radial cracks in grout
- Able to obtain peak and residual stress curves from most samples



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Conclusions and Next Steps

Conclusions

- Clay/salt contacts much stronger than anticipated
- Sample stiffness much higher than anticipated
- Consistent behavior among different samples on intact tests

Next Steps

- Rerun a few selected tests to improve results
- Begin development of constitutive model based on test results
- Develop test for manufactured clay seam (bentonite?) which may be less stiff

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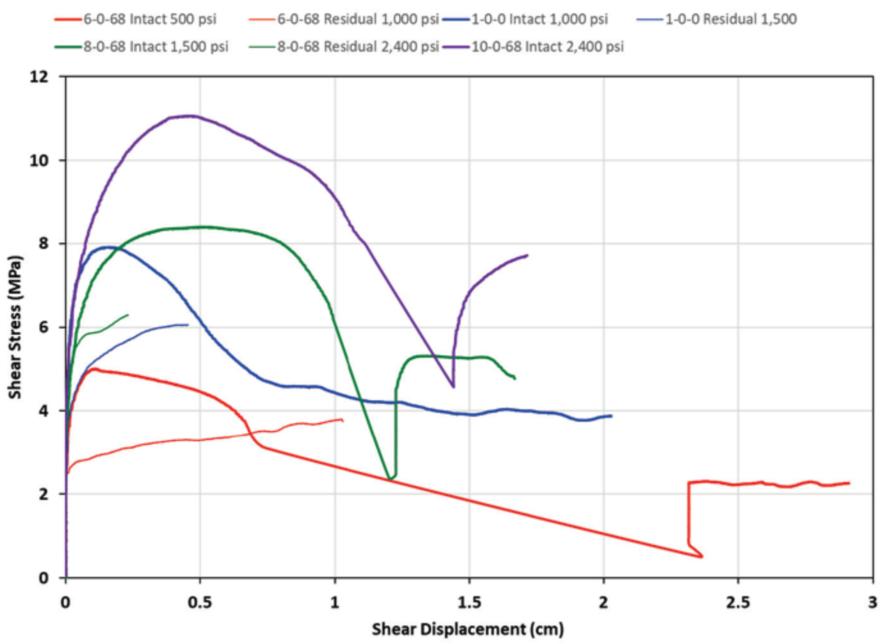
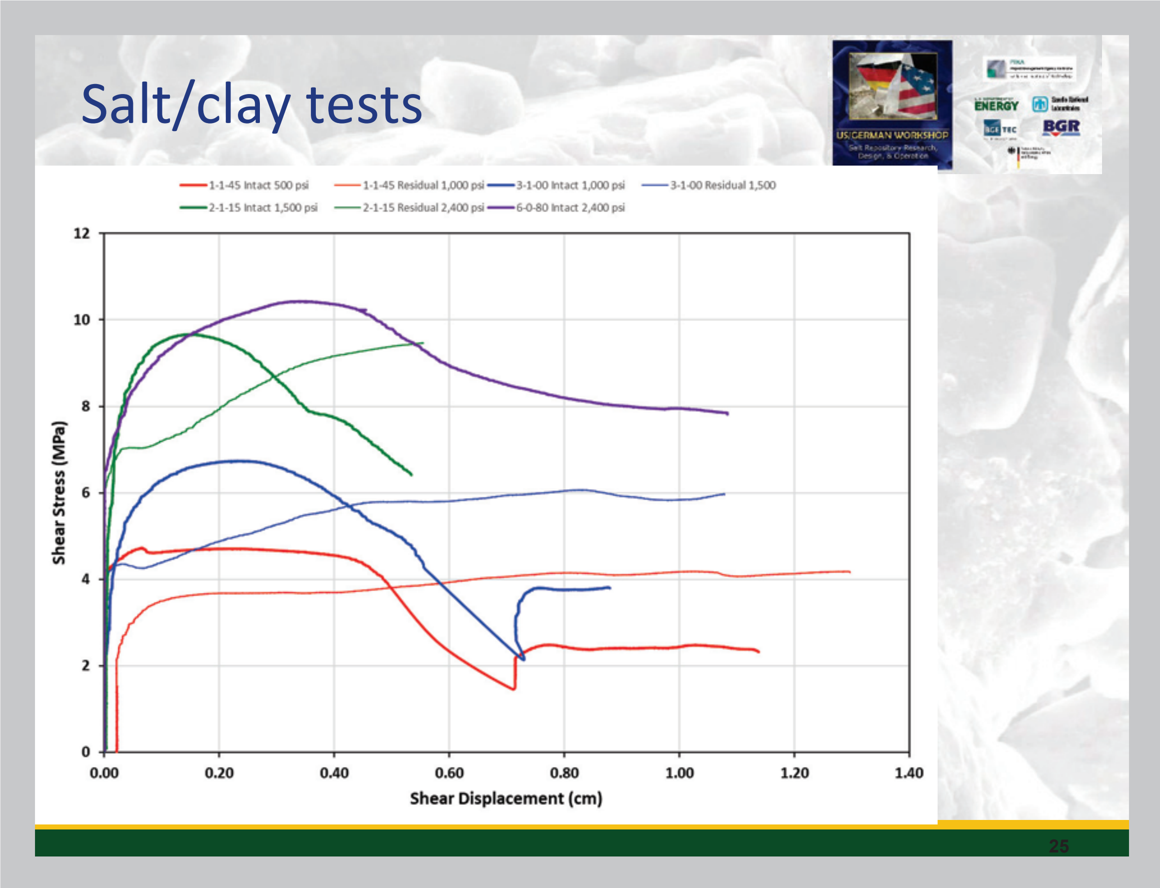
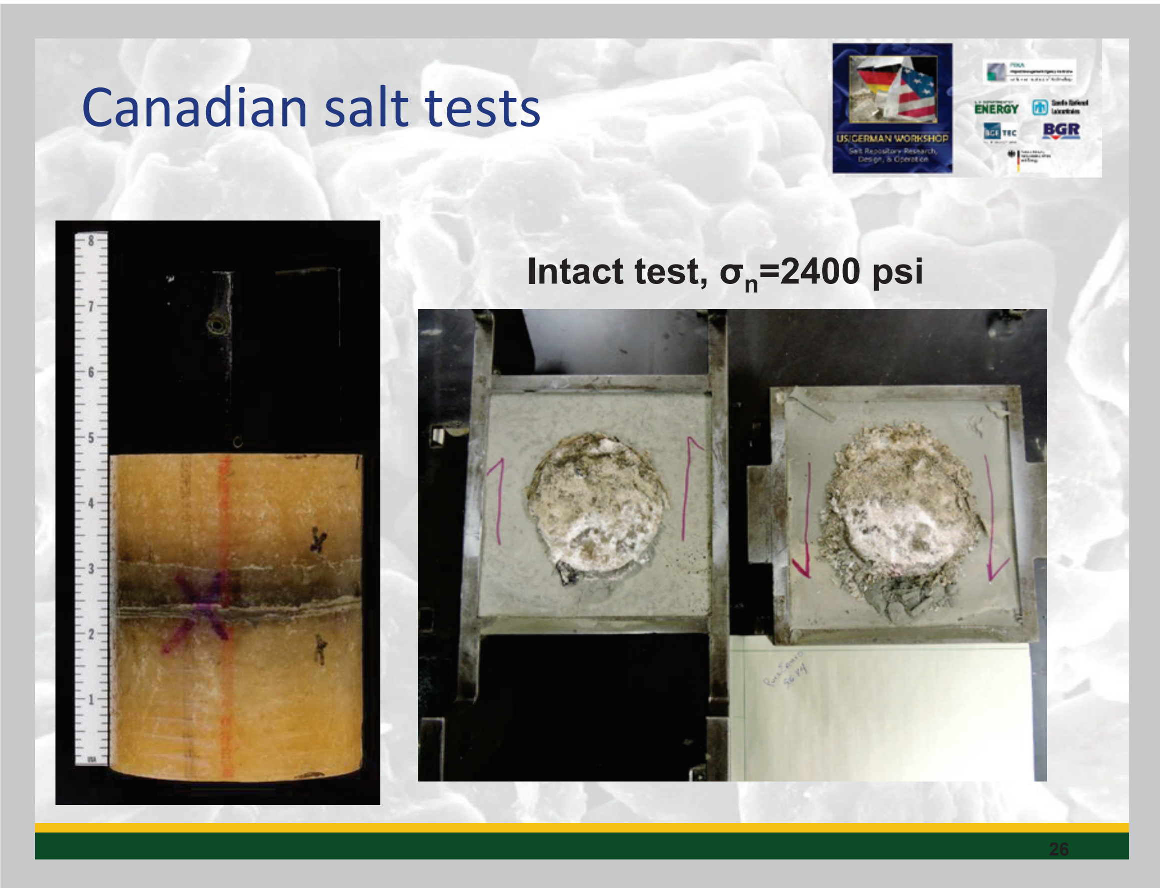
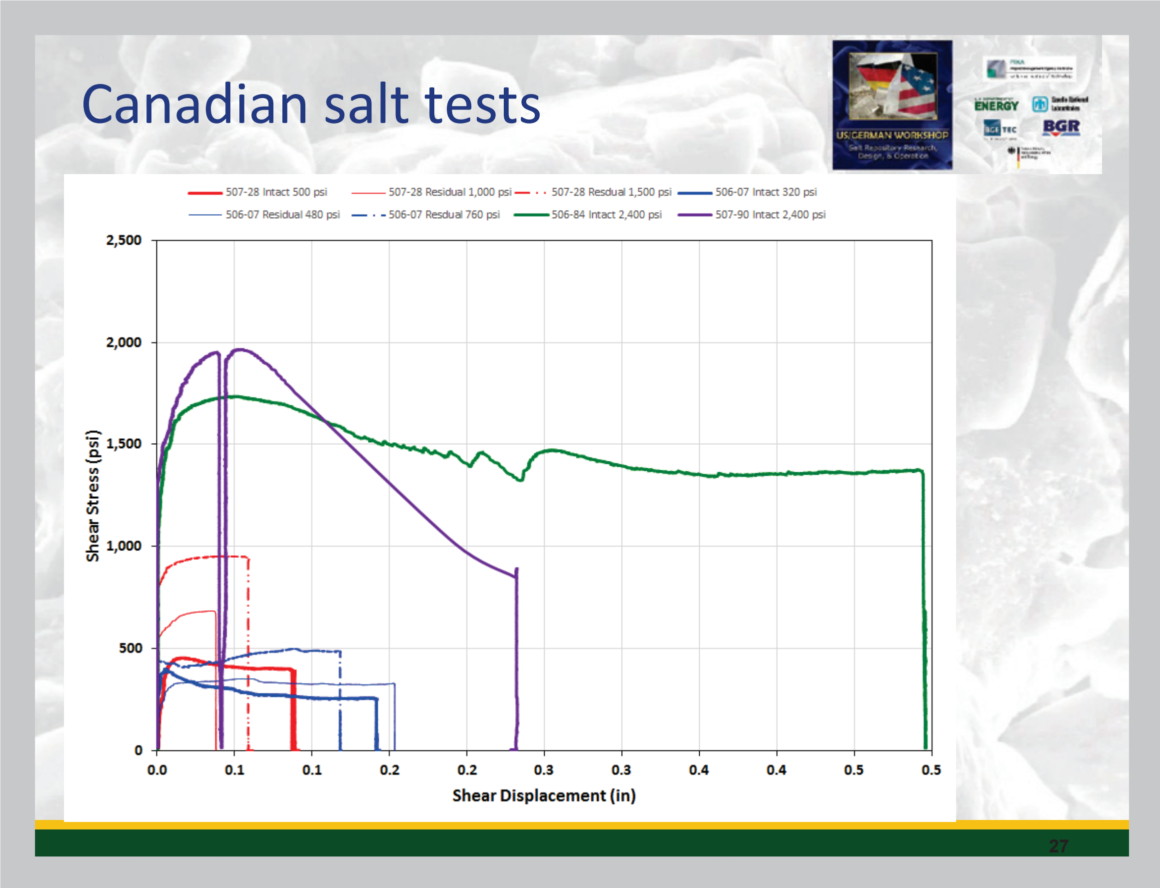
Closer salt tests

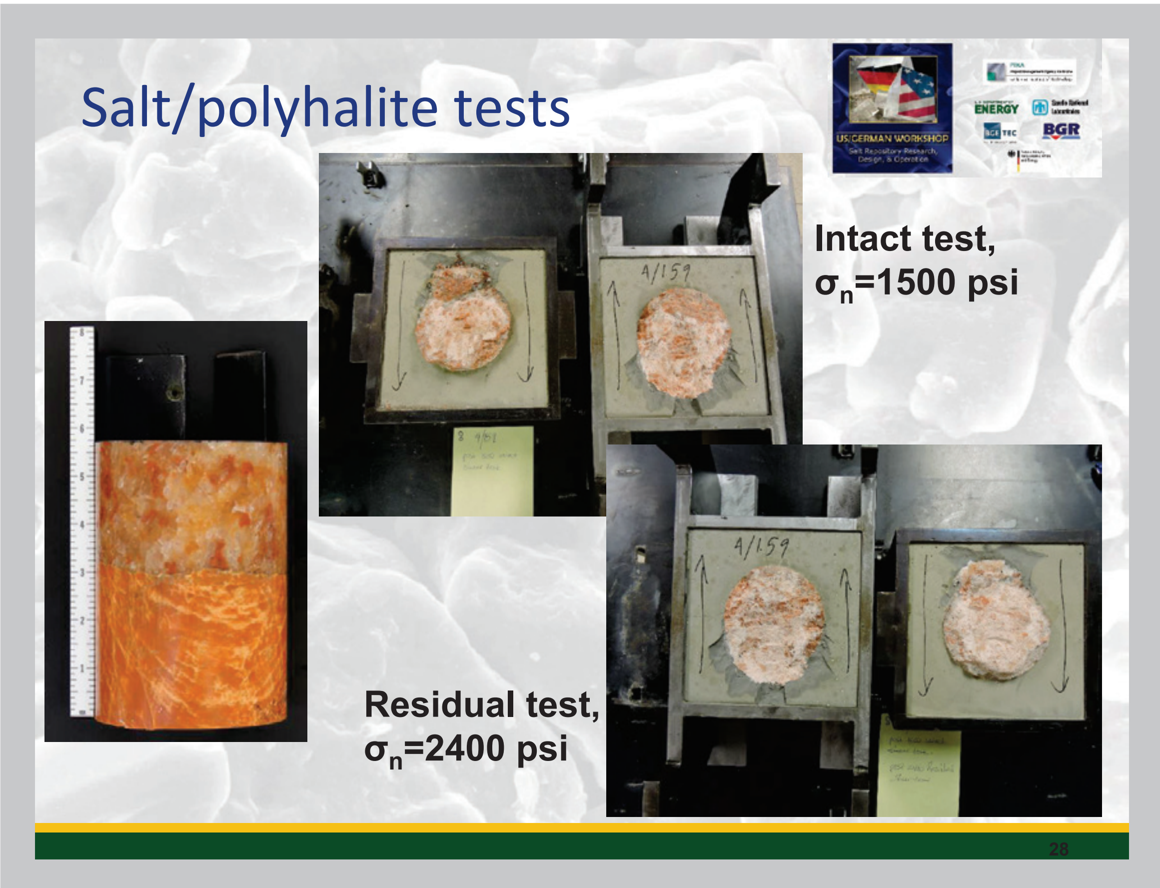


24

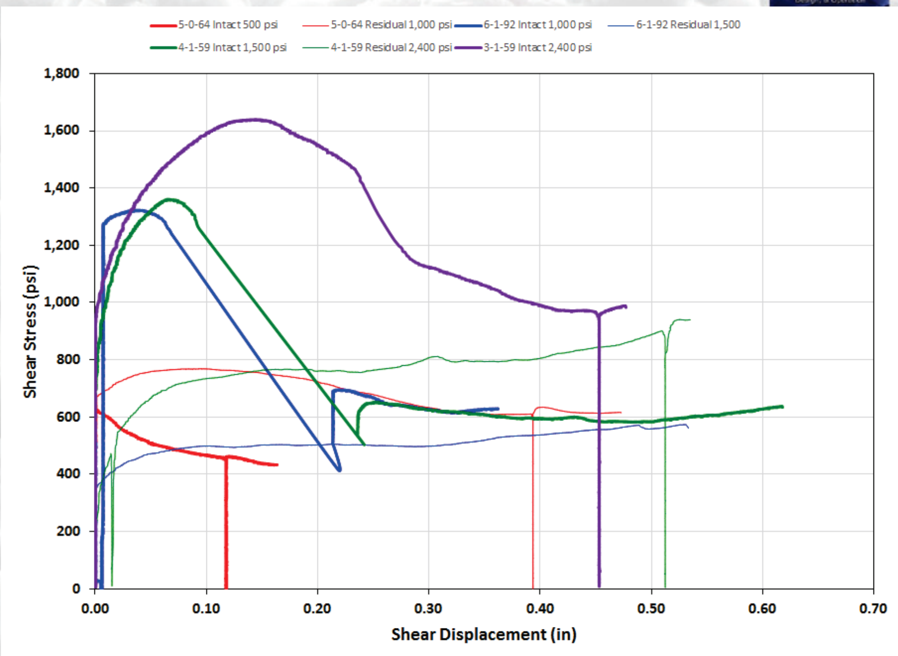

Salt/clay tests
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
ENERGY
BGR
1-1-45 Intact 500 psi
1-1-45 Residual 1,000 psi
3-1-00 Intact 1,000 psi
3-1-00 Residual 1,500
2-1-15 Intact 1,500 psi
2-1-15 Residual 2,400 psi
6-0-80 Intact 2,400 psi
Shear Stress (MPa)
0
2
4
6
8
10
12
Shear Displacement (cm)
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
25


Canadian salt tests
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
ENERGY
BGR
Intact test, σn=2400 psi
26


Canadian salt tests
507-28 Intact 500 psi
507-28 Residual 1,000 psi
507-28 Resdual 1,500 psi
506-07 Intact 320 psi
506-07 Residual 480 psi
506-07 Resdual 760 psi
506-84 Intact 2,400 psi
507-90 Intact 2,400 psi
Shear Stress (psi)
2,500
2,000
1,500
1,000
500
0
0.0
0.1
0.1
0.2
0.2
0.3
0.3
0.4
0.4
0.5
0.5
Shear Displacement (in)
27


Salt/polyhalite tests
Intact test,
σn=1500 psi
Residual test,
σn=2400 psi
28

Salt/polyhalite tests



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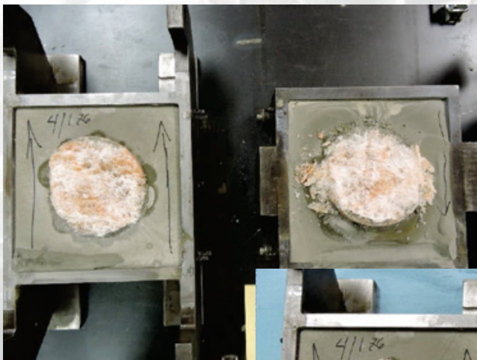
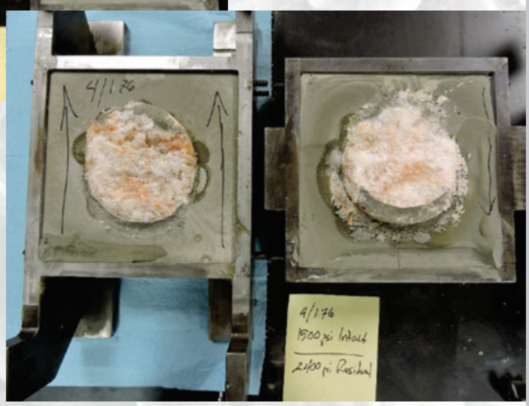
Mixed salt tests



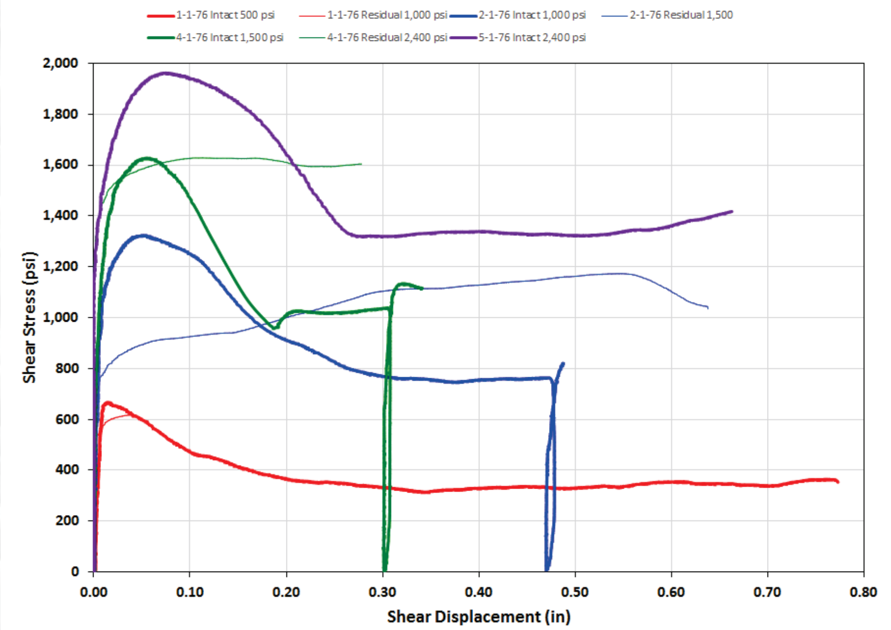
Intact test, σ_n=1500 psi

Residual test, σ_n=2400 psi



30

Mixed salt tests



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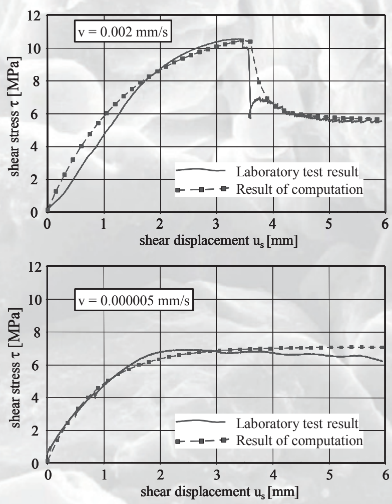
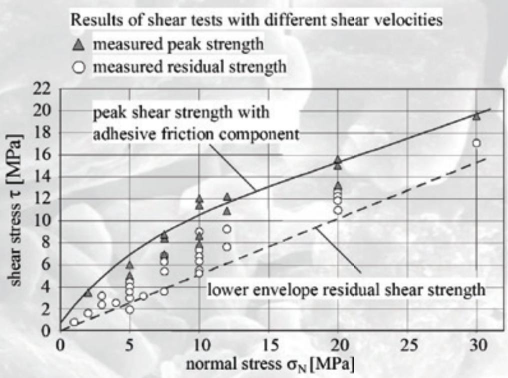
Carnallite on Salt Direct Shear Results

Two Individual Tests



Summary of Test Results



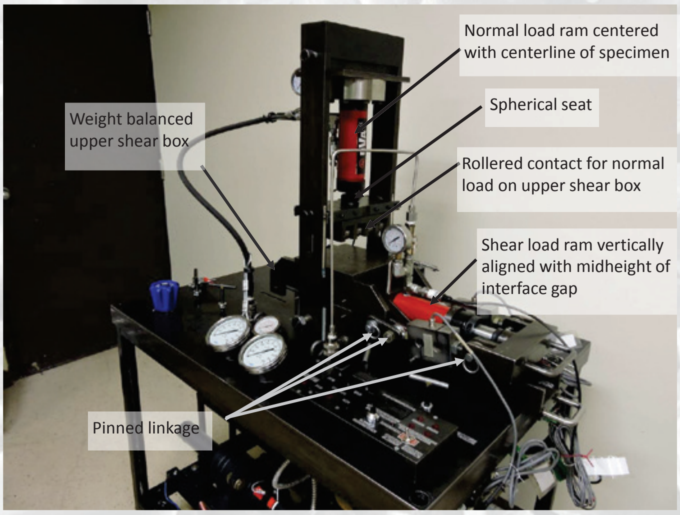
Coulomb Friction?

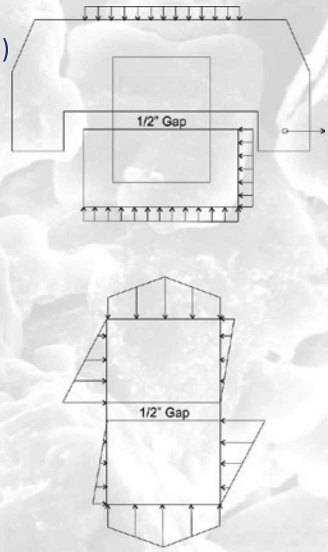
$$\tau = \mu_C \, \sigma_n$$

Minkley, W. and J. Mühlbauer. 2007. Constitutive Models to Describe the Mechanical Behavior of Salt Rocks and the Imbedded Weakened Planes. Wallner, M., K-H Lux, W. Minkley, H.R. Hardy, eds. The Mechanical Behavior of Salt: Understanding of THMC Processes in Salt. Taylor & Francis/Balkema, Leiden, The Netherlands.

Shear Test Setup

- Similar to Minkley test setup
- RESPEC direct shear machine
- Eliminates bending force due to shear (box that holds specimen)





Note: All force profiles depend on contrast in stiffness between the specimen and grout.

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Additional tests to be run

- Rerun halite/polyhalite intact tests for 500, 1000 psi normal stress
- Rerun halite/clay intact test for 1500 psi
- Rerun pure salt test for 1000 psi
- Rerun mixed salt test for 500 psi
- Rerun halite/anhydrite test for 500 psi
- Others upon request from WEIMOS participants
- Many more test samples have been made – saving some for possible tension tests
- Not doing rate dependence test, as apparatus cannot operate at slower speeds

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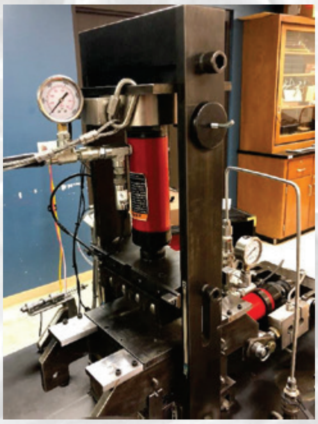
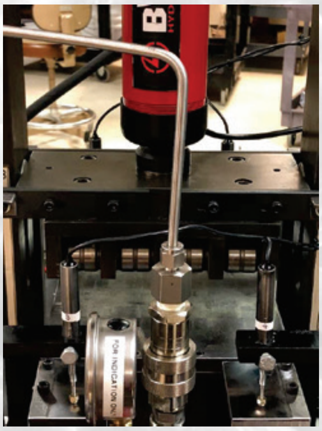
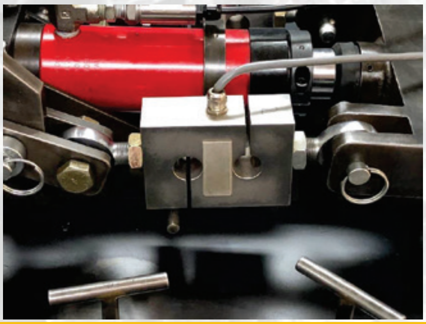
Direct shear test machine







- S-shaped load cell – gaps opened during some tests
- 4 normal displacement gages, average displacement used to calculate stiffness

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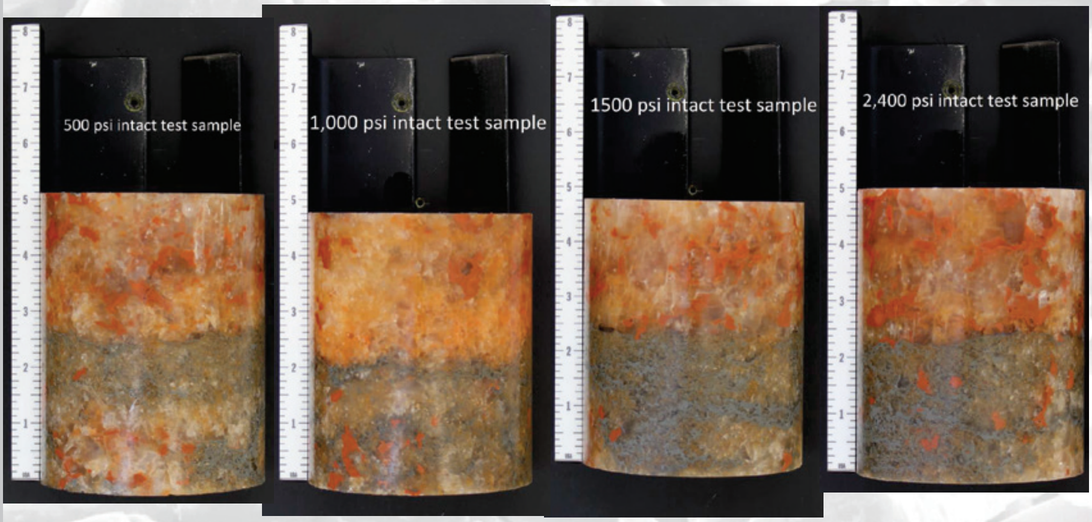
4 clay test samples



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M. M. Mills

Micromechanical Investigations: Low Deviatoric Stress

Melissa M. Mills
Sandia National Laboratories

Hanover, Germany
September 10-11, 2018

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Introduction

- Creep mechanism between intermediate and low equivalent stresses observed in salt, however only theories as to what the mechanism is.
- Due to low strains, a mechanism is difficult to identify and could be overlapped by relictic microstructures.

2

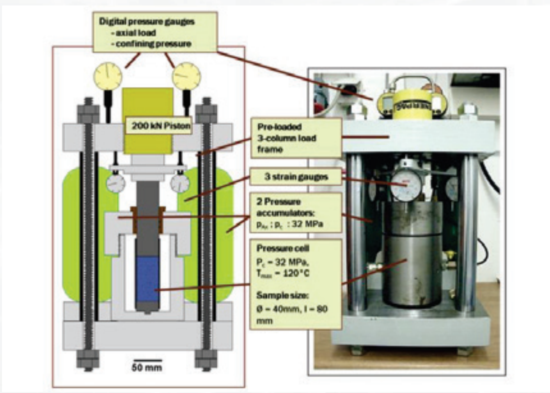
Why is this important?

- Low stress creep influences long-term performance and safety
- Knowledge of a dominating mechanism at low deviatoric stress important for understanding micro-mechanics of creep
- Allow constitutive models to intelligently account for creep at low deviatoric stresses.
- Vast amount of studies on deformation mechanisms in salt, but not on samples tested under these specific conditions and/or timescales

3

Low Deviatoric Tests

- Work Package 1 of the Joint WEIMOS Project
- High precision triaxial creep tests performed my IfG
  - Ran for long periods of time to reach stationary phase
  - Climate controlled



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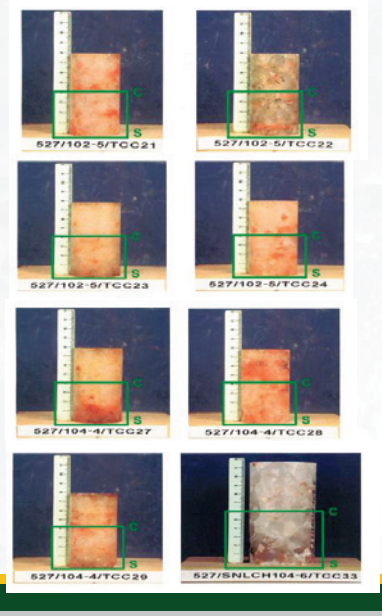
Samples

No.	T	Duration [d]	σ_1 [MPa]	$\sigma_3 = p$ [MPa]	$\Delta\sigma$ [MPa]
TCC 24	25°C	10	20	20	0
		50	28		8
		80	26		6
		80	26	22	4
	60°C	80	26		4
TCC 21	25°C	10	20	20	0
		50	26		6
		80	24		4
		80	24	22	2
	60°C	80	24		2
TCC 22	25°C	10	20	20	0
		50	24		4
		80	22		2
		80	22	21	1
	60°C	80	22		1
TCC 23	80°C	10	20	20	0
		50	28		8
		80	26		6
		80	26	22	4
		80	26	20	6
TCC 27	80°C	10	20	20	0
		50	26		6
		80	24		4
		80	24	22	2
		80	24	20	4
TCC 29	80°C	10	20	20	0
		50	24		4
		80	22		2
		80	22	21	1
		80	22		1
TCC 28	25°C	10	20	20	0
	25°C	50	24		4
	40°C	50	24		4
	60°C	50	24		4
	80°C	50	24		4
	100°C	50	24		4

- Received 8 creep tested WIPP core samples from IfG (March 2017)



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Issues

- Funding
  - After samples were received, the previous funding source required certain paperwork and test plans to be in place before work could continue
  - After paperwork was completed, was then notified the funding source could not support the research at that time
  - March 2018 – Separate funding source agreed to support the investigative work
- Sample preparation
  - Additional slices of each sample were made to be further utilized for thin sections, but time constraints were imminent as well as equipment
  - Special care taken when disaggregating remaining sample to find whole, individual grains for cleaving to not disrupt microstructure

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Approach

- Etching
  - Submerge in saturated solution of $PbCl_2$ and methanol, stopping by rinsing in butanol and drying completely
  - Quality of results affected by several factors: solution, time of immersion, agitation in etchant, effectiveness of stopping rinse, and drying
  - Takes practice and multiple tries to yield an ideal etch
- Microscopes
  - Leitz optical reflected light to examine etch quality
  - Tescan Vega scanning electron microscope to take high magnification images
- Free dislocation density
  - Count pits in standard area within each image, typically inside of a subgrain
  - ImageJ

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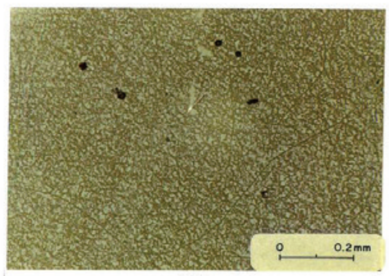
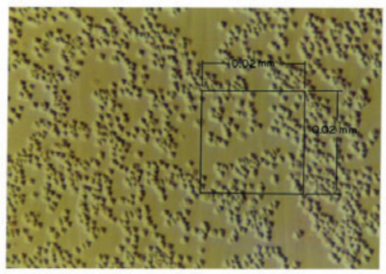
Previous WIPP Substructures

- Hansen (1988)
- Three samples of untested salt from the WIPP site
  - Free dislocation density
  - Subgrain size
- Average count of etch pits
  - 183 ± 29
  - 138 ± 35
  - 149 ± 25
- Average dislocation density (cm^{-2})
  - $4.58 \pm 0.73\ 10^7$
  - $3.45 \pm 0.88\ 10^7$
  - $3.73 \pm 0.63\ 10^7$
- Subgrain Size (mm) (85 measurements)
  - 237 ± 119

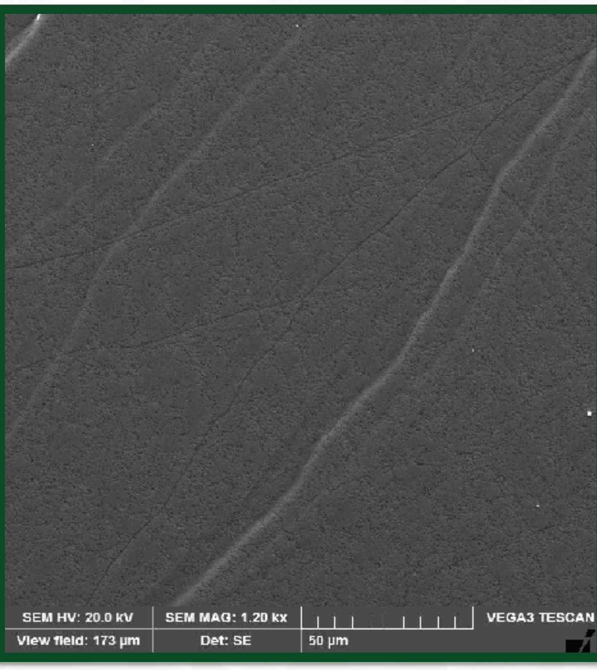


(A)


(B)

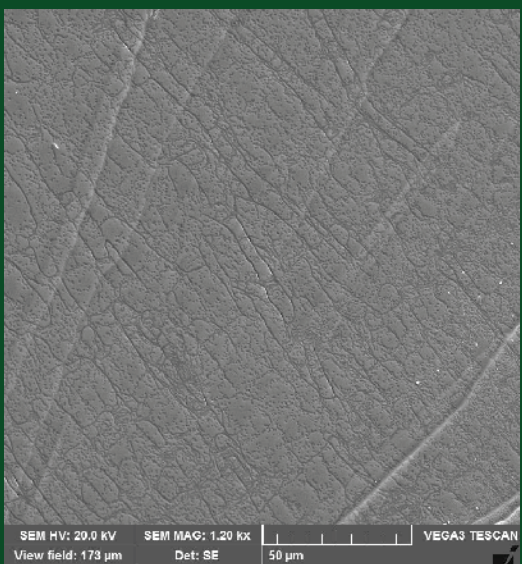
8

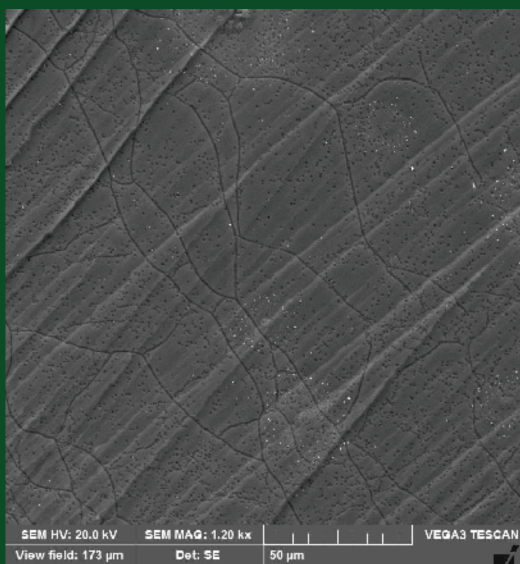
Recent Native WIPP Structure



9

Preliminary Results: TCC21 vs. TCC23





TCC21: $\sigma_3 = 20$ $\sigma_1 = 26 \rightarrow 24$ $\sigma_3 = 20 \rightarrow 22$ T = 25°C → 60°C

TCC23: $\sigma_3 = 20$ $\sigma_1 = 28 \rightarrow 26$ $\sigma_3 = 20 \rightarrow 22 \rightarrow 20$, T = 80°C

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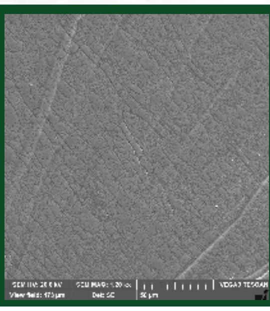
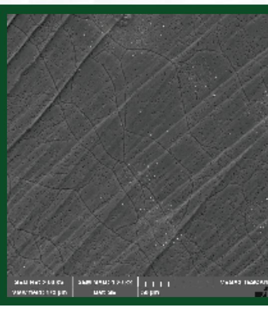
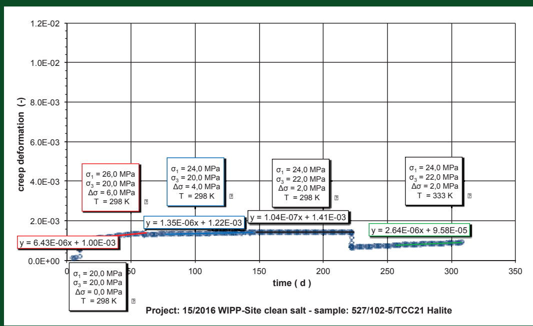
Preliminary Results: TCC21 vs. TCC23

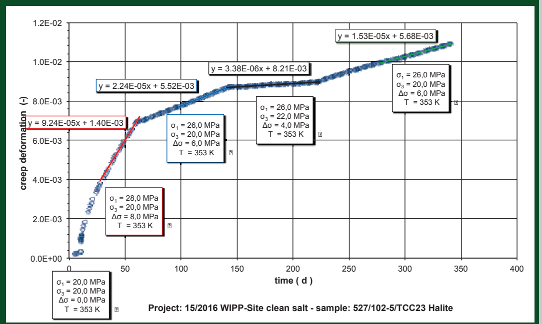
TCC21





TCC23





Max strain = 2E-03

Max strain = 1.1E-02

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Future Activities

- Continue to investigate free dislocation density and subgrain size of the remaining samples
  - Image Software
  - Manual Analysis
  - Neutron Diffraction
  - Irradiation
- Further sample preparation in order to investigate grain boundaries and other mechanisms in samples (thin sections)
- Additional samples from future experiments

12

B. Reedlunn, J. Bean

Simulations of Canister Compaction at the WIPP

Benjamin Reedlunn and James Bean
Sandia National Laboratories

Hanover, Germany
September 10-11, 2018

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US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation

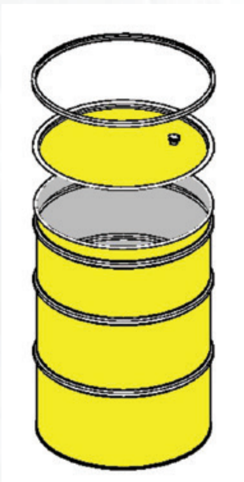
Outline

- Background
- Model Setup
  - Numerical Approach
- Results
  - Sensitivity to Canister Behavior
  - Sensitivity to Clay Seam Behavior
- Summary and Potential Future Work

Background

Standard Canisters

Schematic

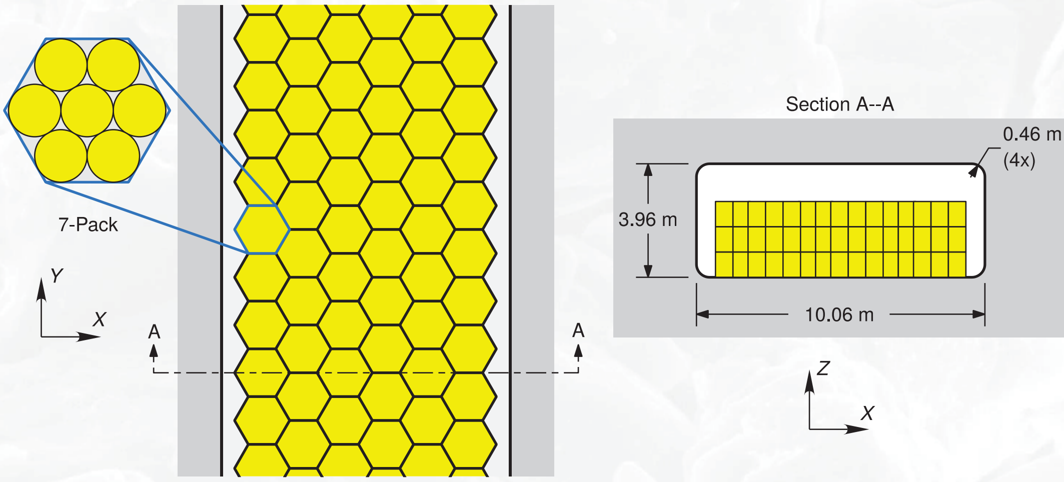


Park, B.Y. and Hansen, F. D., “Determination of the Porosity Surfaces of the Disposal Room Containing Various Waste Inventories for WIPP PA”, 2005, SAND2005-4236

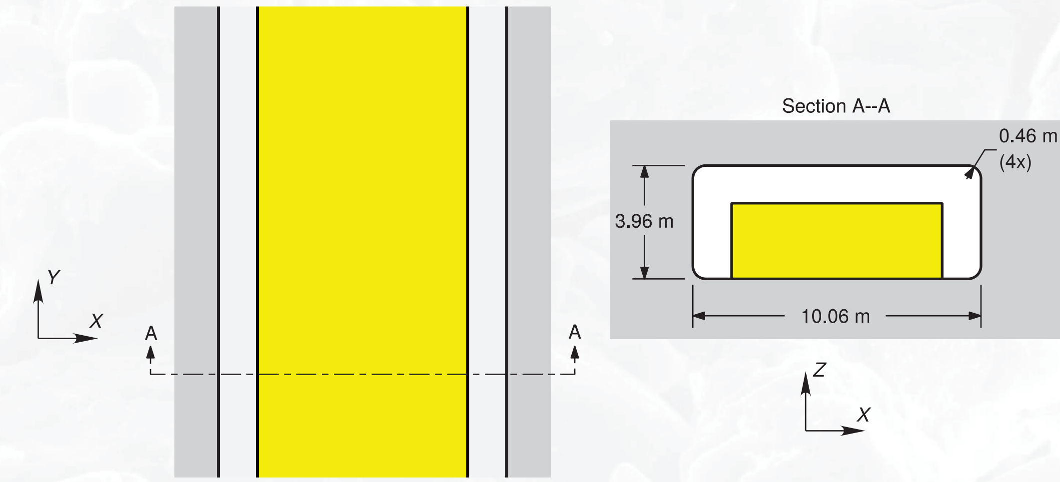
Photo
(with surrogate waste)

Broome, S.T., Ingraham, M.D., Flint, G.M., Hileman, M.B., Barrow, P.C., and Herrick, C.G., “Laboratory Testing of Surrogate Non-degraded Waste Isolation Pilot Plant Materials”, 2016, American Rock Mechanics Assoc., ARMA 16-120

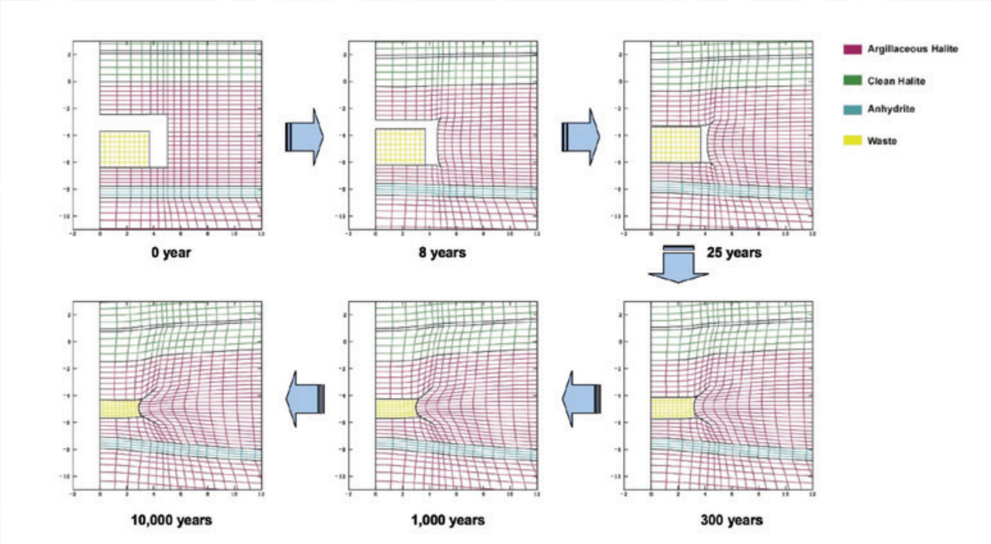
Canister Emplacement



Idealized Model



Idealized Model Results



Park, B.Y. and Hansen, F. D., "Determination of the Porosity Surfaces of the Disposal Room Containing Various Waste Inventories for WIPP PA", 2005, SAND2005-4236

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New Canister Design

Schematic

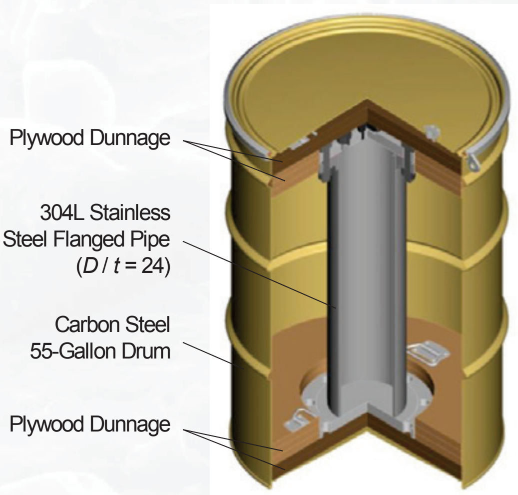


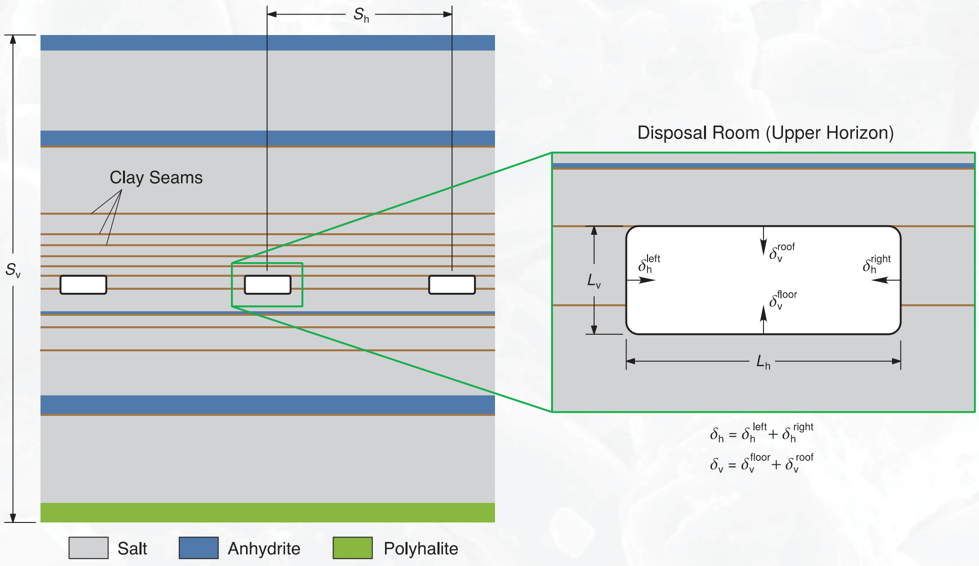
Photo
(lid and upper dunnage removed)

8

Model Description

9

Idealized Stratigraphy



$$\delta_h = \delta_h^{left} + \delta_h^{right}$$
$$\delta_v = \delta_v^{floor} + \delta_v^{roof}$$

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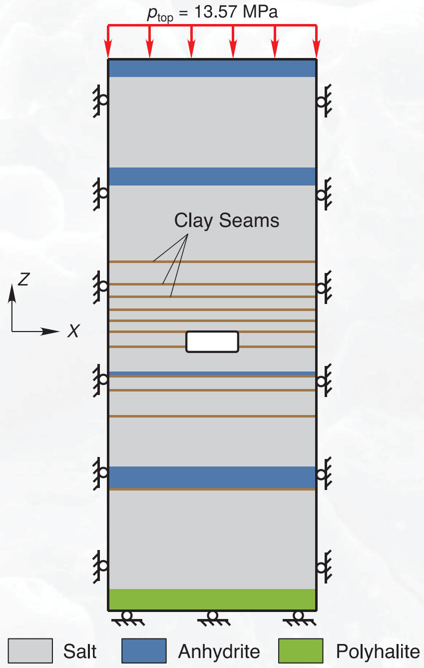
Boundary Conditions and Geomaterial Models



- Salt
  - Munson-Dawson Model
  - Calibration 3B (most recent)
- Anhydrite and Polyhalite
  - Elastic-Perfectly Plastic
  - Drucker-Prager Plasticity
- Clay Seams
  - Coulomb Friction

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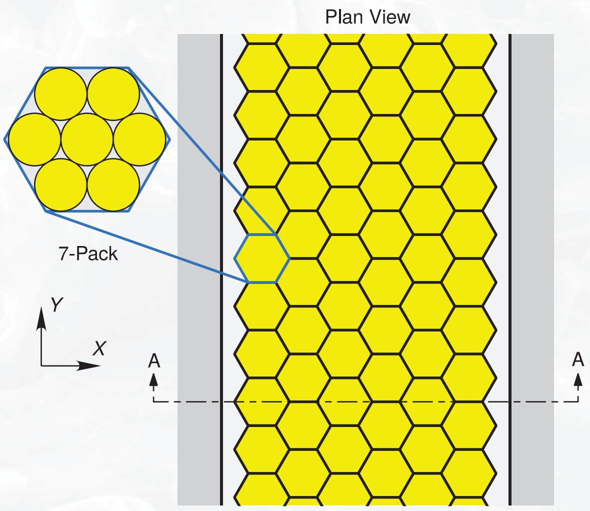
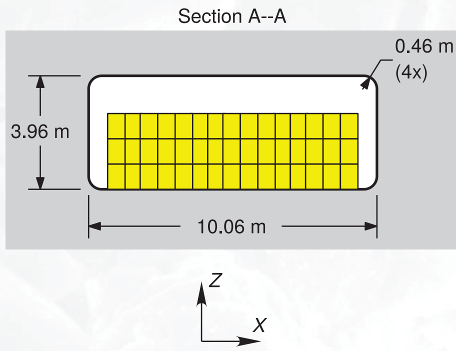
Canister Configuration and Boundary Conditions





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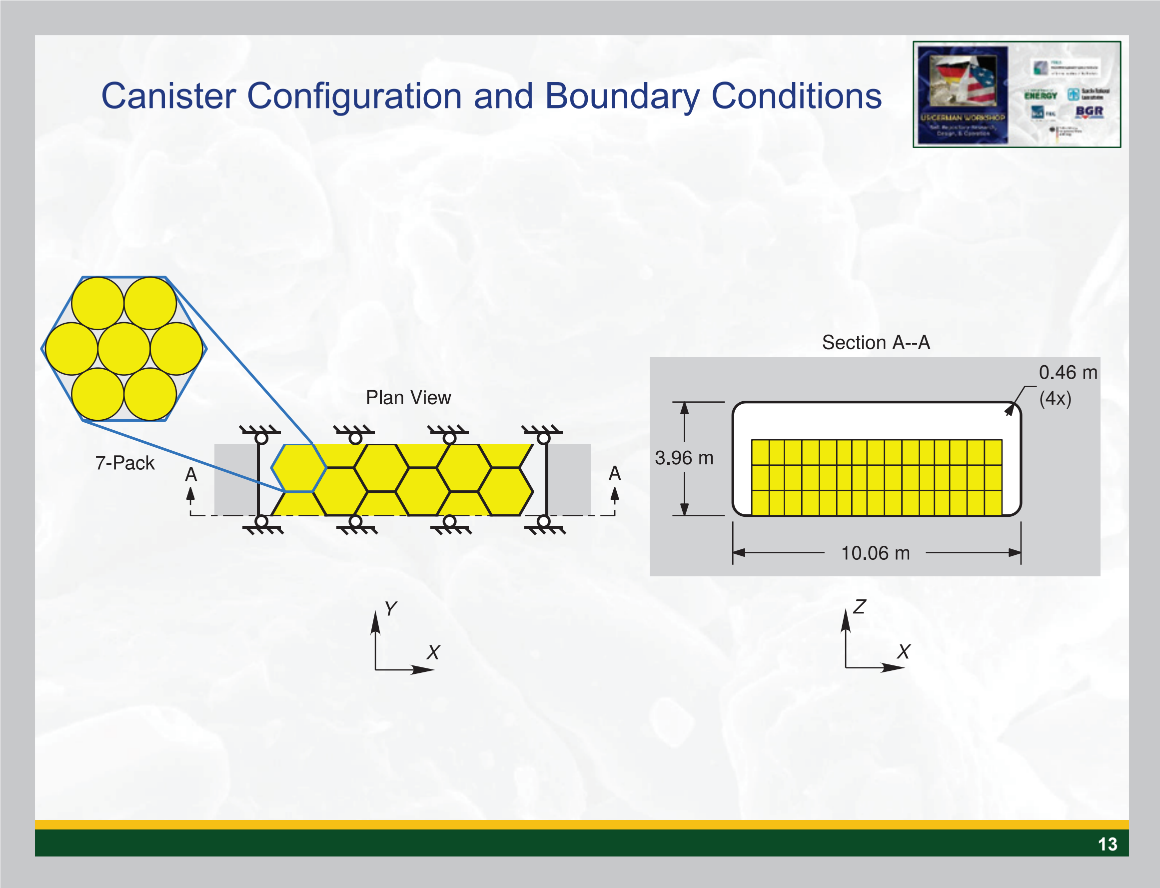
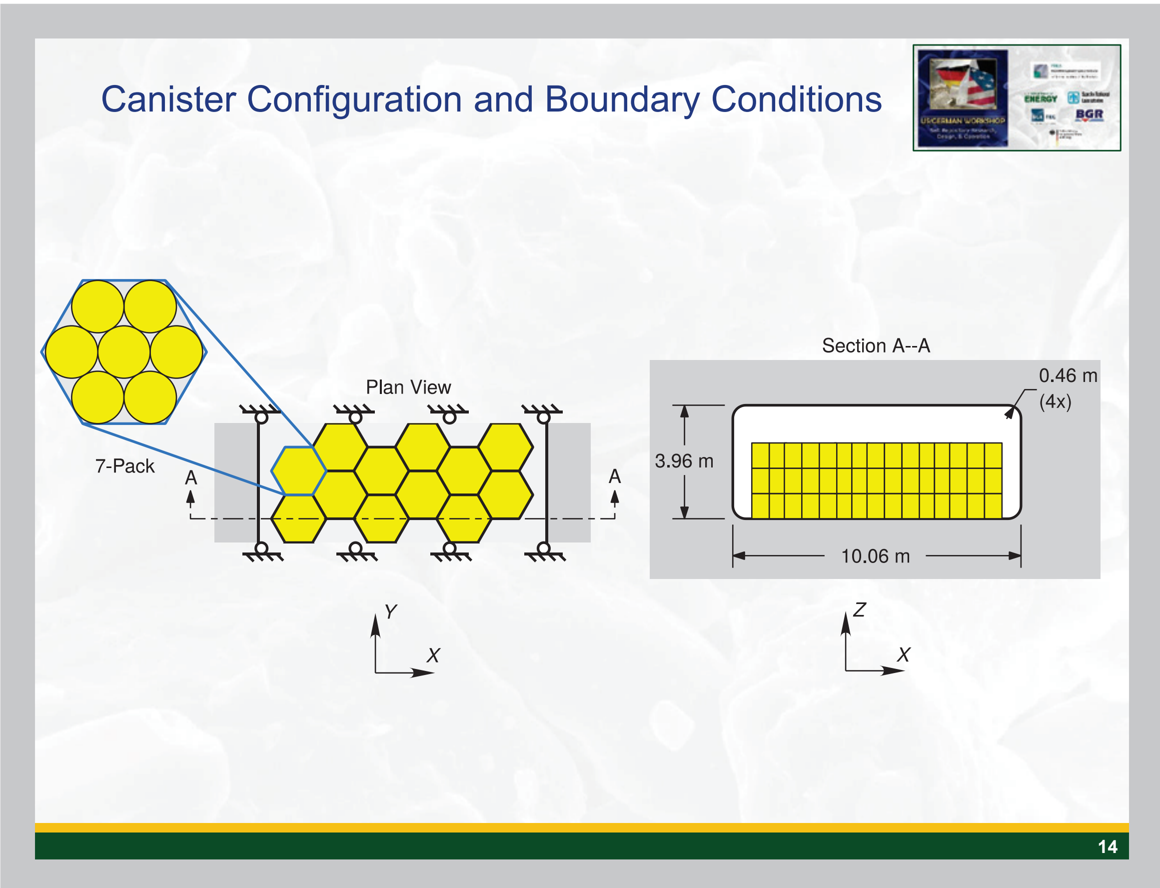
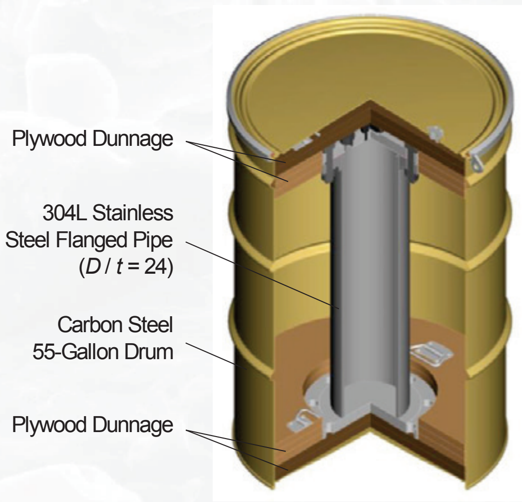

Canister Configuration and Boundary Conditions
7-Pack
Plan View
A
A
Y
X
Section A--A
0.46 m
(4x)
3.96 m
10.06 m
Z
X
13

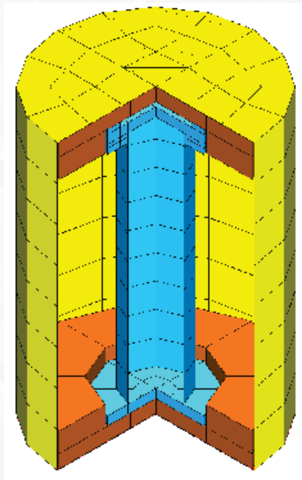

Canister Configuration and Boundary Conditions
7-Pack
Plan View
A
A
Y
X
Section A--A
0.46 m
(4x)
3.96 m
10.06 m
Z
X
14

Canister Finite Element Model

Schematic



Finite Element Mesh



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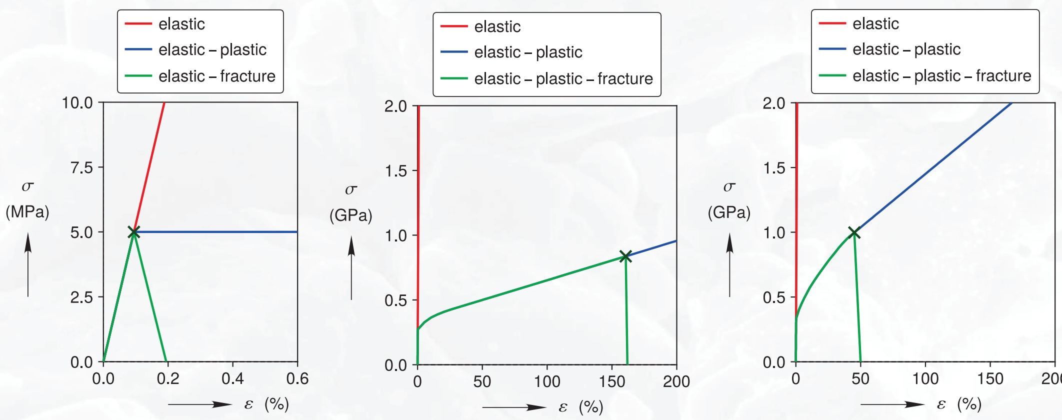
Canister Material Models: Uniaxial Tension



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Potential Numerical Approaches

- Standard approaches:
  - Explicit Dynamics
    - Robust
    - Issue: time step is ~1 μs
  - Implicit Quasi-statics
    - Relatively robust, arbitrarily large time steps
    - Issue: solver cannot converge due to rigid body translations
  - Implicit Dynamics
    - Relatively unused, arbitrarily large time steps
    - Issue: contact and implicit dynamics do not play nice together

- Innovative Approaches:
  - Uncouple geomechanics from canister deformation
    - Enables explicit dynamics
    - Issue: difficult to determine final state
  - Speed up salt viscoplasticity
    - Enables explicit dynamics
    - Issue: cannot go too fast

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Results

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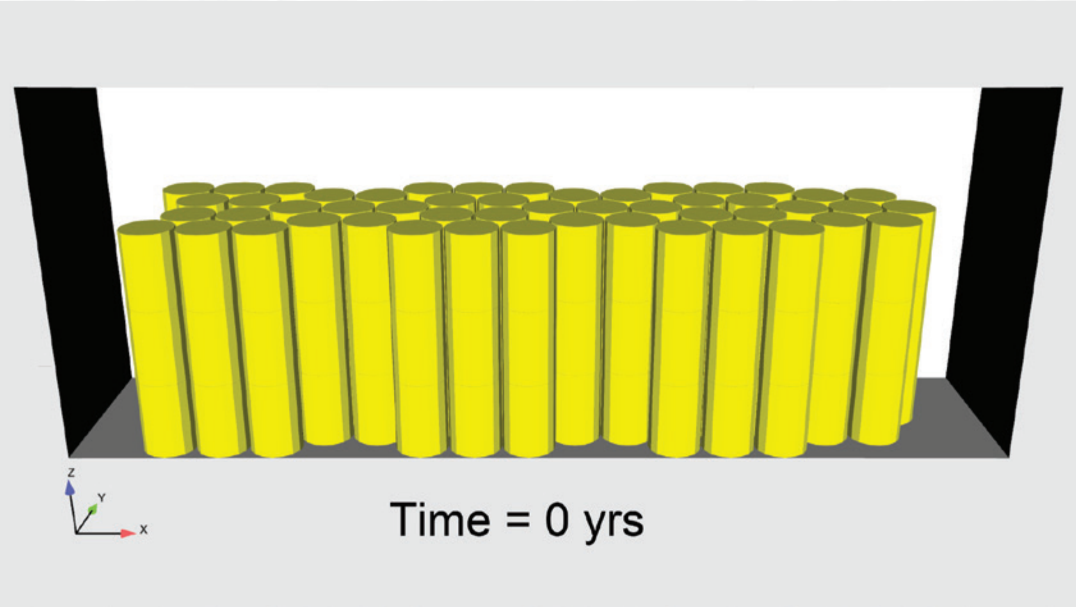
Elastic Canisters



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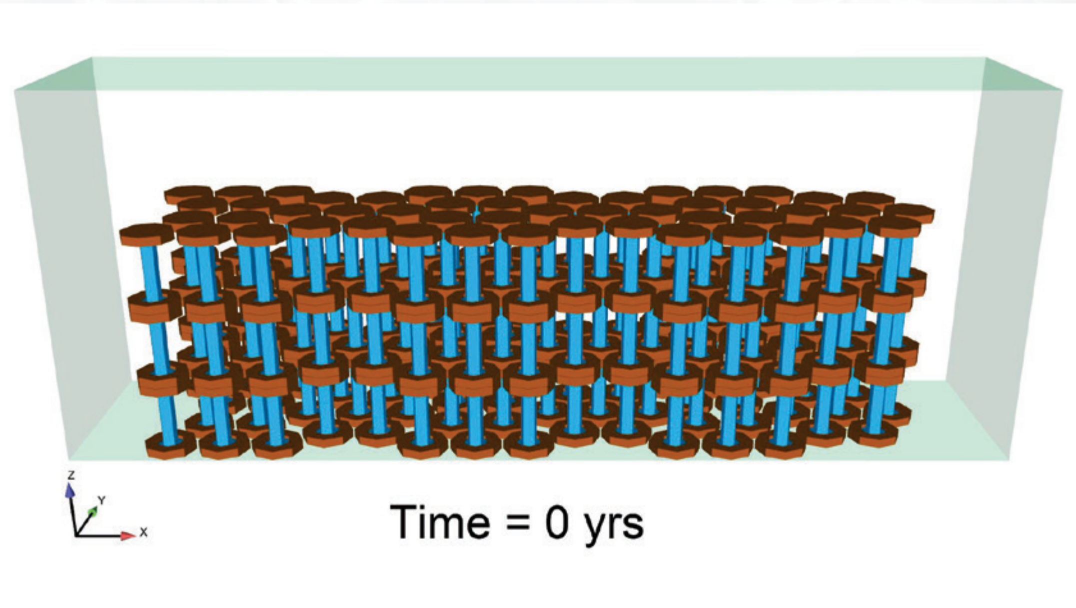
Elastic Canisters



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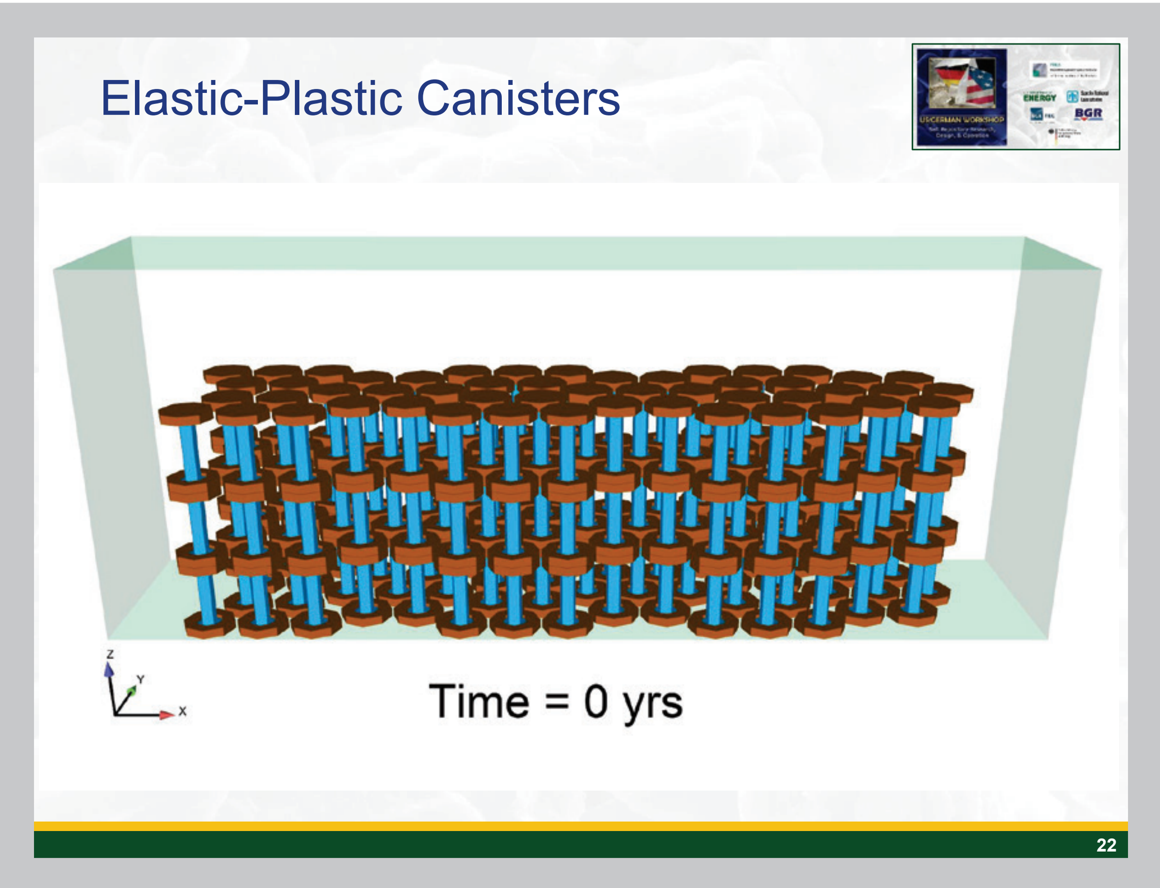
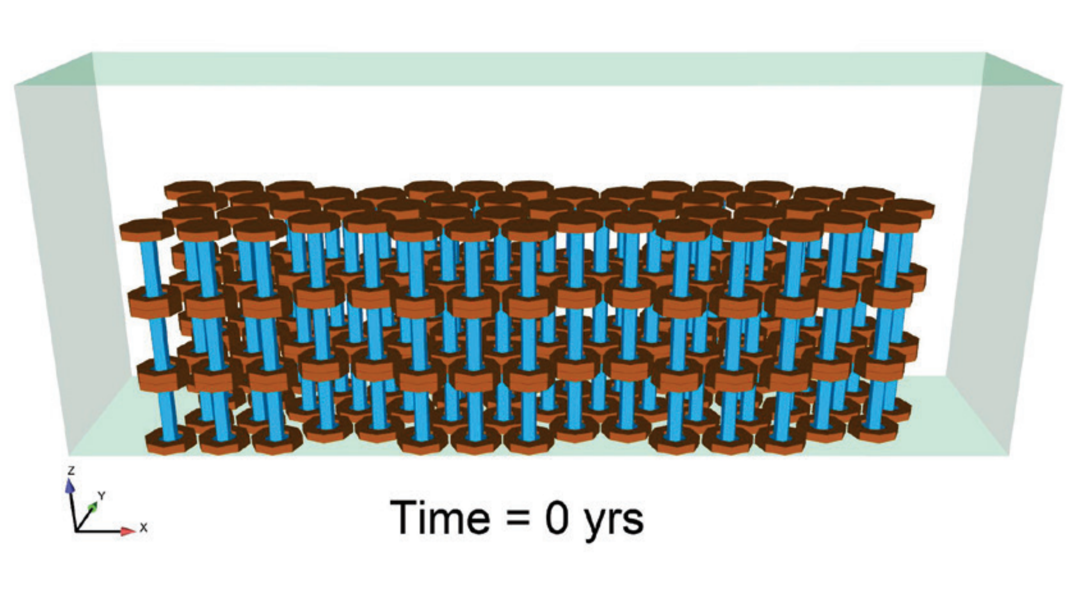
Elastic Canisters
Time = 680 yrs
von Mises (Pa)
2.5e+09
2.0e+09
1.5e+09
1.0e+09
5.0e+08
0.0e+00
21


Elastic-Plastic Canisters
Time = 0 yrs
22

Elastic-Plastic-Fracturing Canisters



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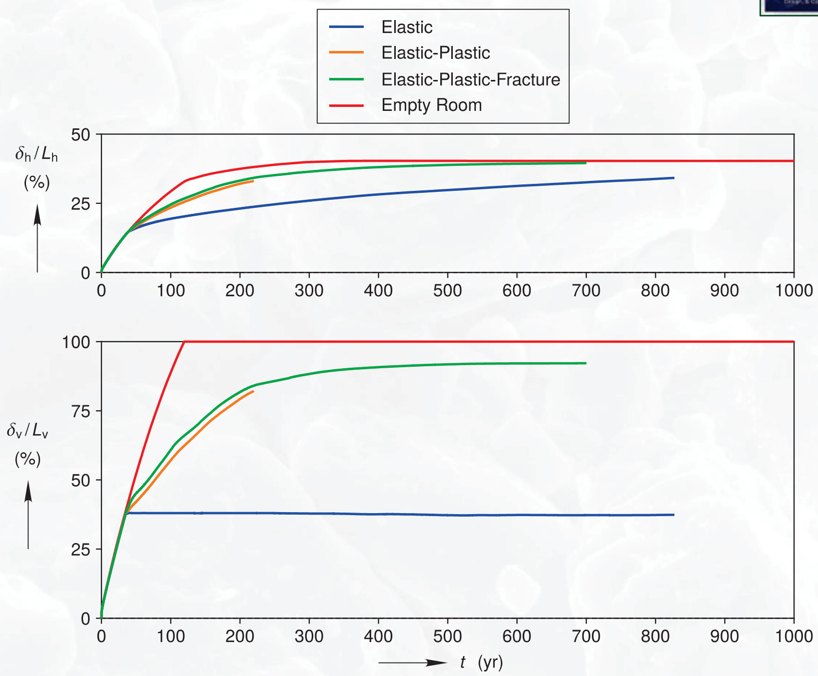
Quantitative Comparisons



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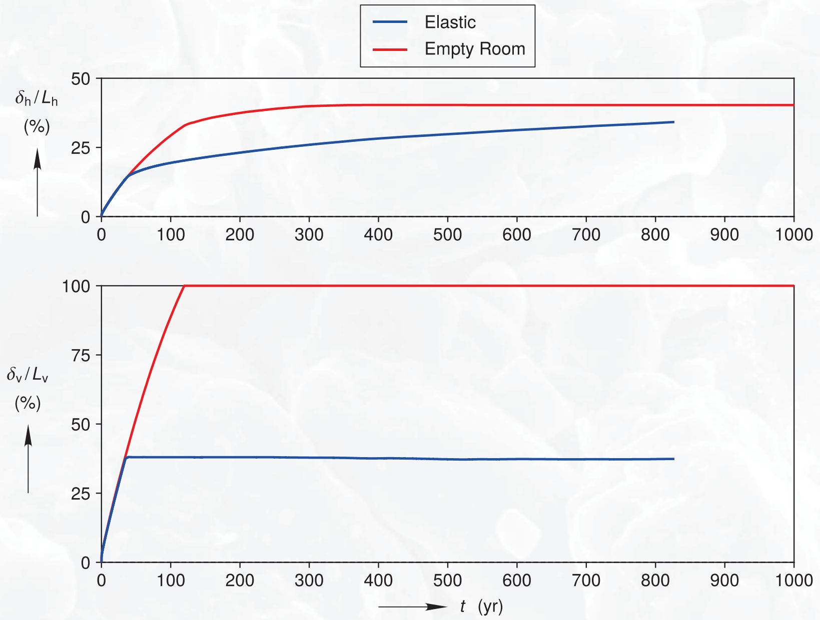
Quantitative Comparisons



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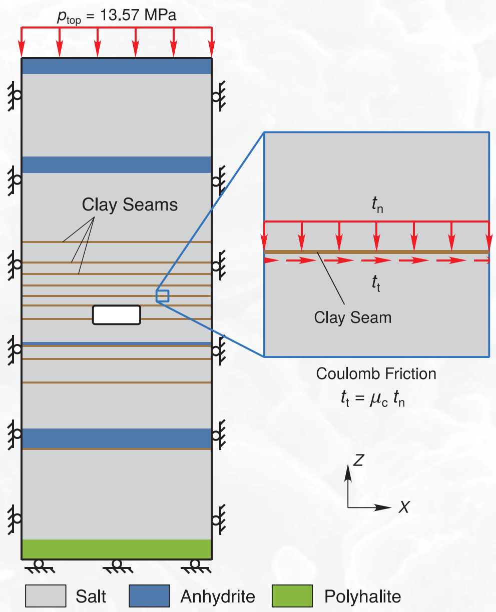
Impact of Clay Seams



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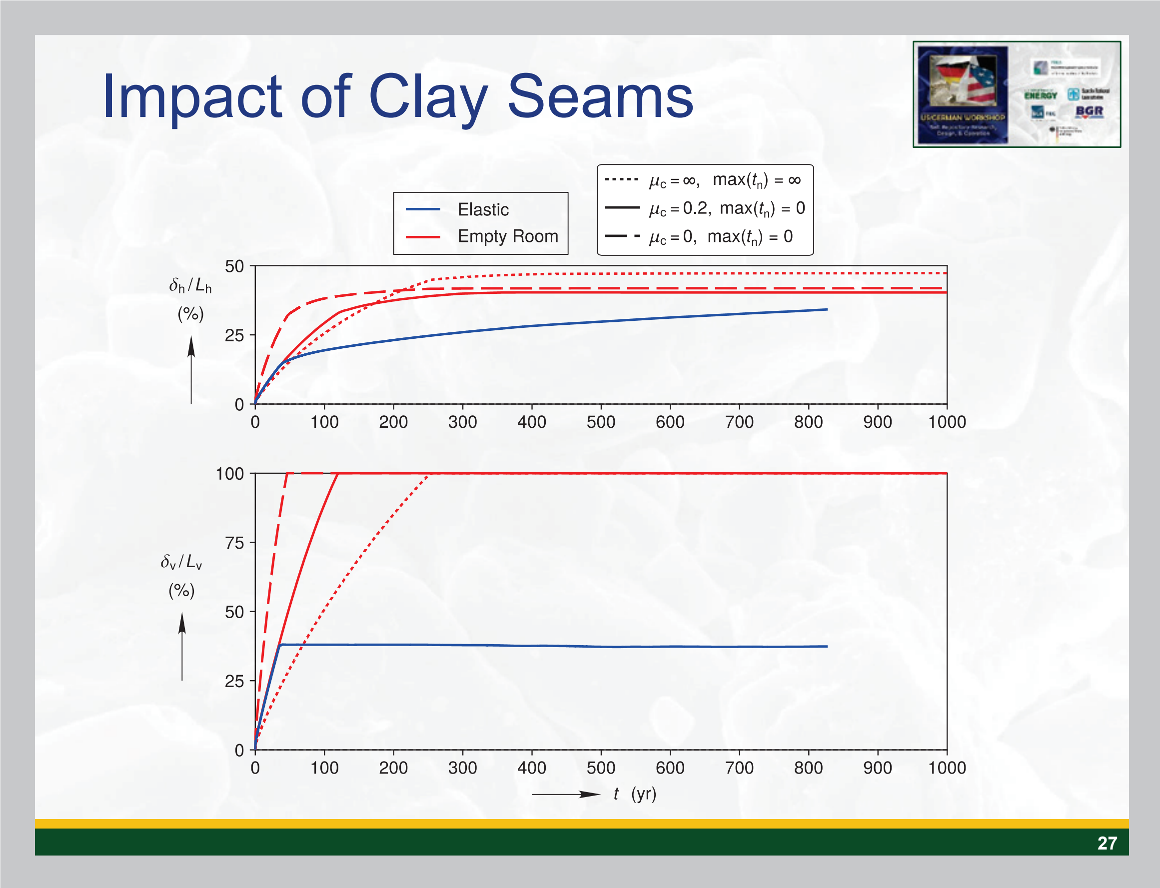
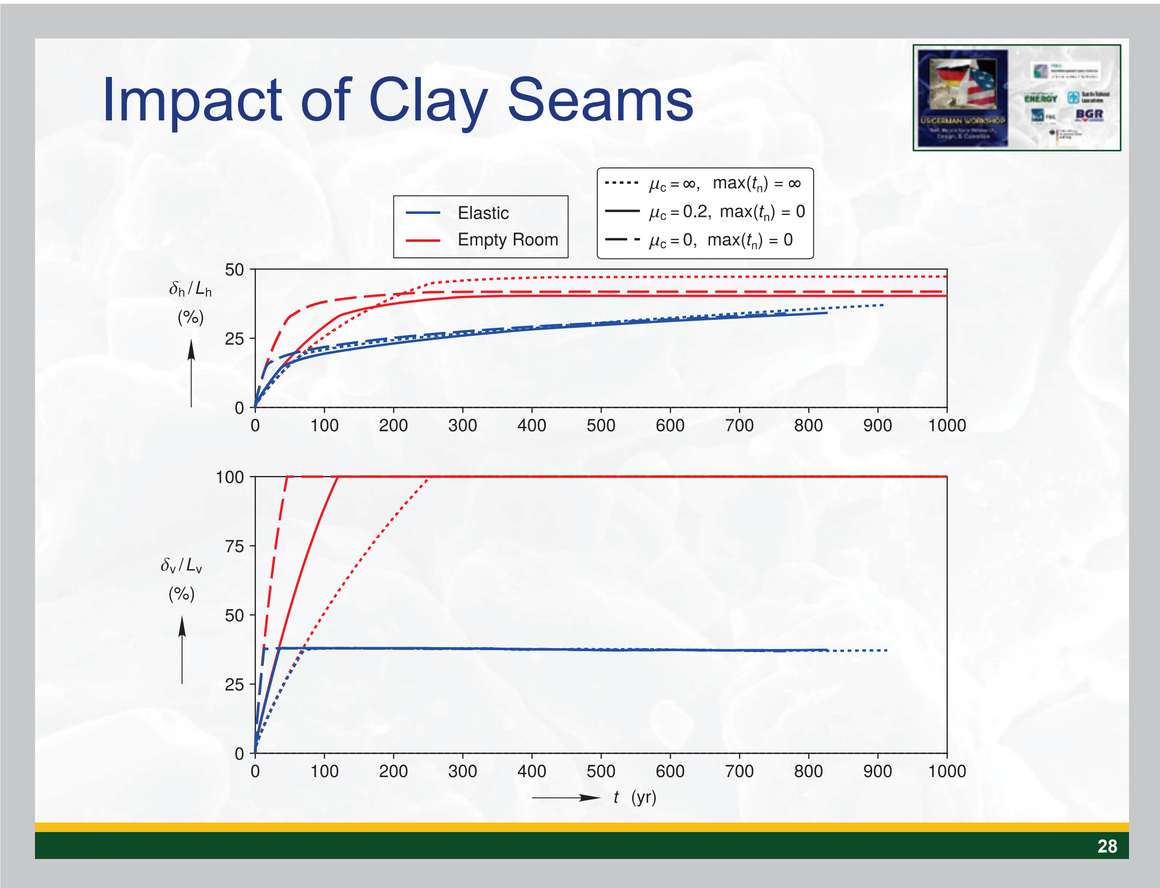

Impact of Clay Seams
Elastic
Empty Room
μc = ∞, max(tn) = ∞
μc = 0.2, max(tn) = 0
μc = 0, max(tn) = 0
δh / Lh
(%)
δv / Lv
(%)
t (yr)
0 100 200 300 400 500 600 700 800 900 1000
0 25 50
0 25 50 75 100
27


Impact of Clay Seams
Elastic
Empty Room
μc = ∞, max(tn) = ∞
μc = 0.2, max(tn) = 0
μc = 0, max(tn) = 0
δh / Lh
(%)
δv / Lv
(%)
t (yr)
0 100 200 300 400 500 600 700 800 900 1000
0 25 50
0 25 50 75 100
28

Summary and Potential Future Work

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Summary

- Explicitly modeled each canister and sped up the salt viscoplasticity to squeeze 1000's of years into seconds
- Elastic canisters had highest horizontal closure rate at 800 yr, but the stresses were unreasonably high.
- Elastic-Plastic canisters deformed in a highly heterogeneous manner, calling homogenization into question.
- Elastic-Plastic-Fracturing canisters were almost identical to Elastic-Plastic canisters and similar to an empty room.
- Glued clay seams produce most empty room horizontal closure.
- More than 50 % horizontal closure appears unlikely.

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Potential Future Work

- Numerics
  - Investigate why plywood disappears
  - Stop half canisters from penetrating the walls
  - Refine mesh
- Geomechanics
  - Switch to lower horizon and/or rooms near edges of panels
  - Attempt to include roof falls
- Canisters
  - Adjust stainless steel parameters to match published data
  - Build a homogenized canister model to compare against
  - Vary frictional behavior
  - Add viscous effects to stainless steel and plywood
  - Add MgO sacks
  - Include gas pressure due to degradation
  - Include more canister rows
  - Stack canisters off-center
  - Allow canister materials to corrode and rot

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Extra Slides

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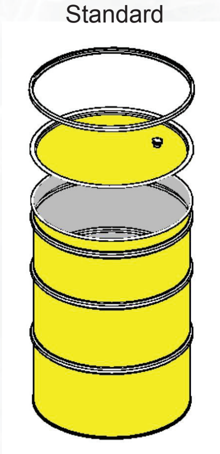
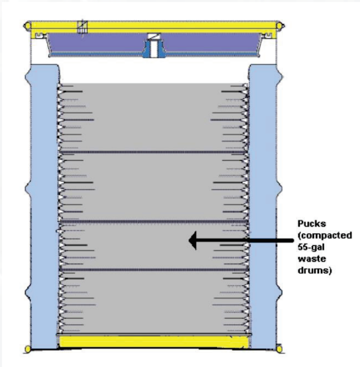
Current Canister Design Examples

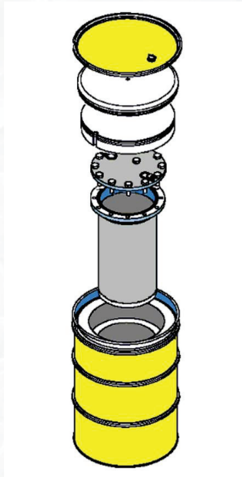
Standard



Supercompacted



Pipe Overpack



Park, B.Y. and Hansen, F. D., "Determination of the Porosity Surfaces of the Disposal Room Containing Various Waste Inventories for WIPP PA", 2005, SAND2005-4236

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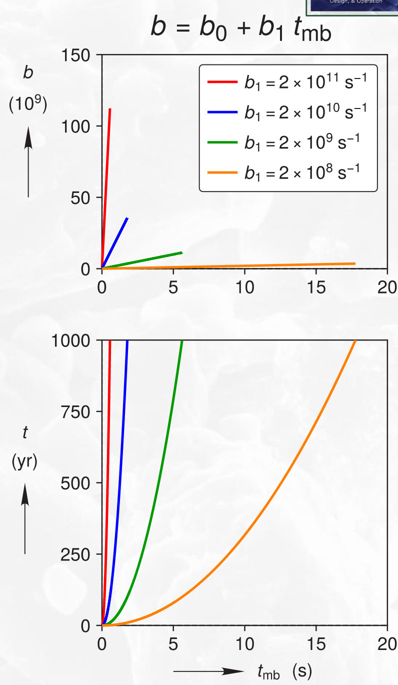
Speeding Up the Viscoplasticity

$$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{vp} + \dot{\varepsilon}^{th}$$

$$\dot{\bar{\varepsilon}}^{vp} \propto A\, b\, \exp\left(-\frac{Q}{R\,T}\right) \bar{\sigma}^{n}$$

$$b = \frac{dt}{dt_{mb}}$$



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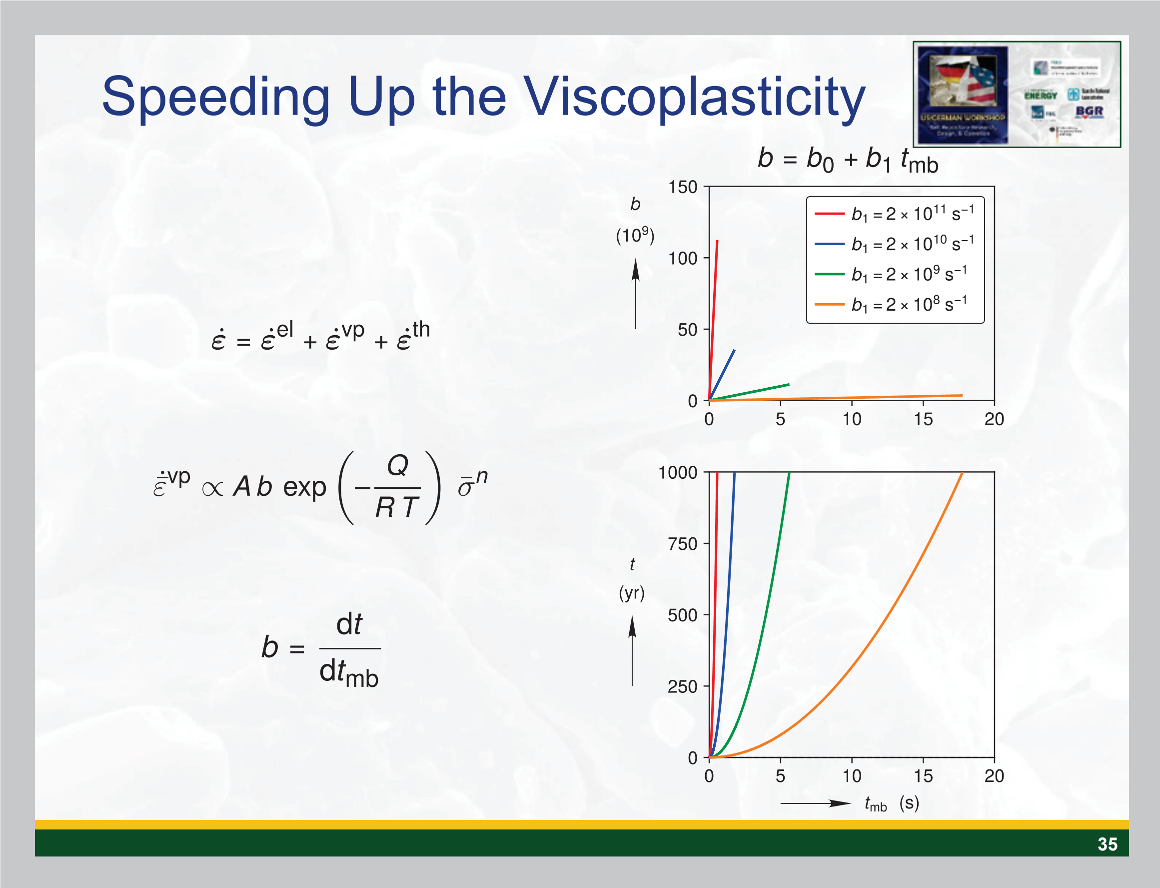
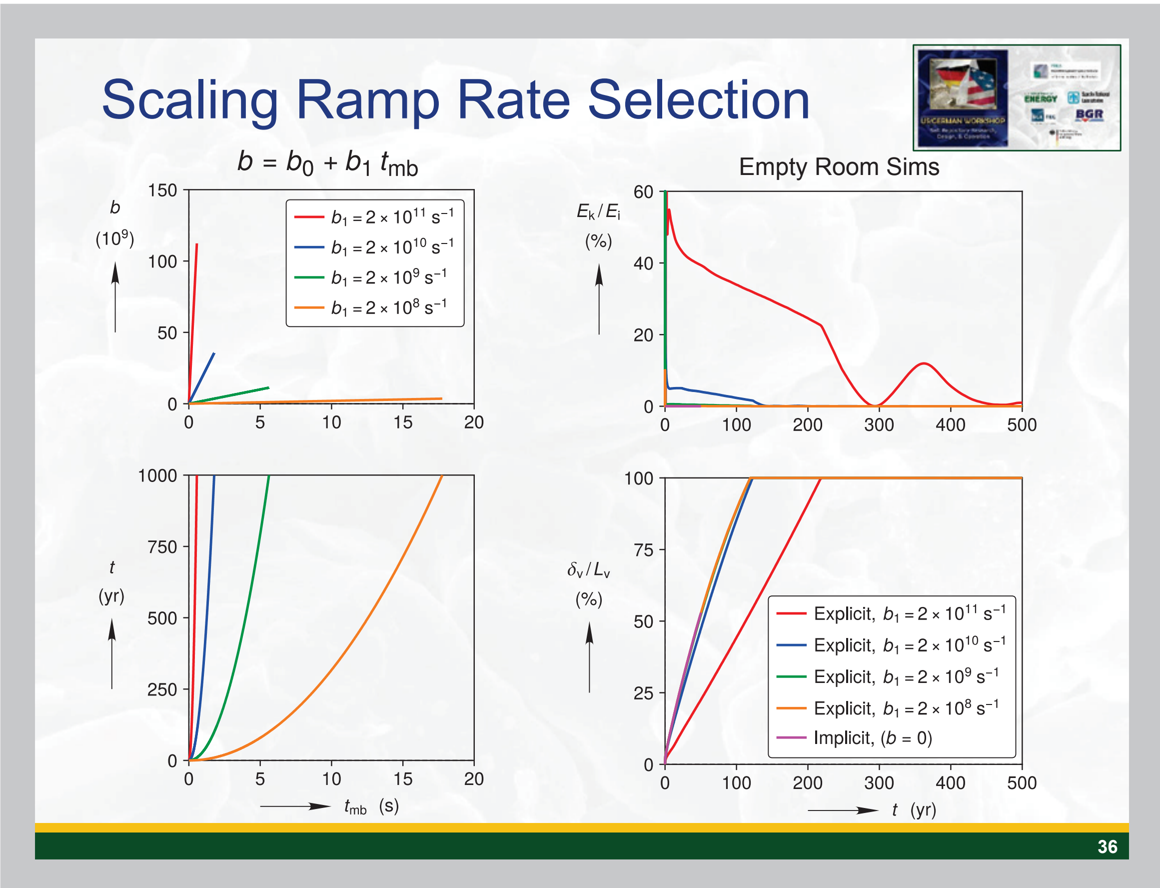
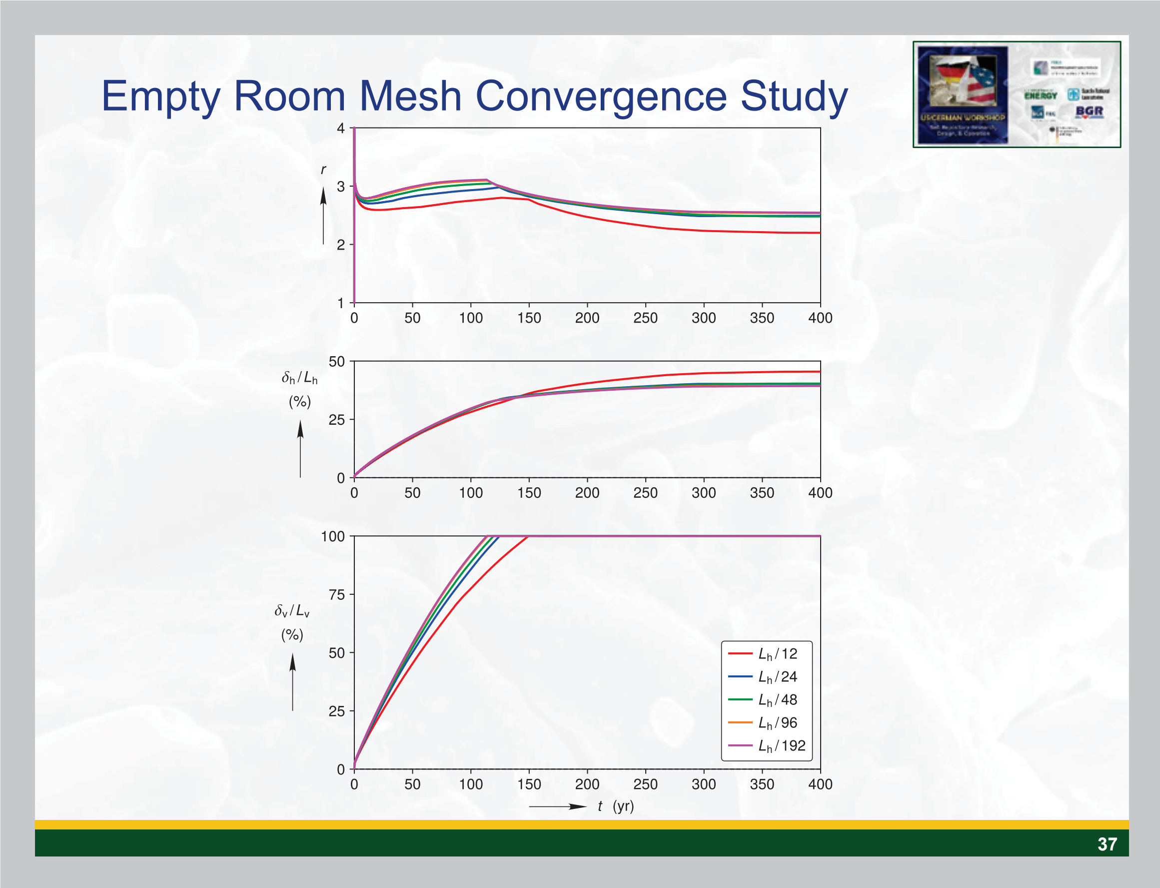
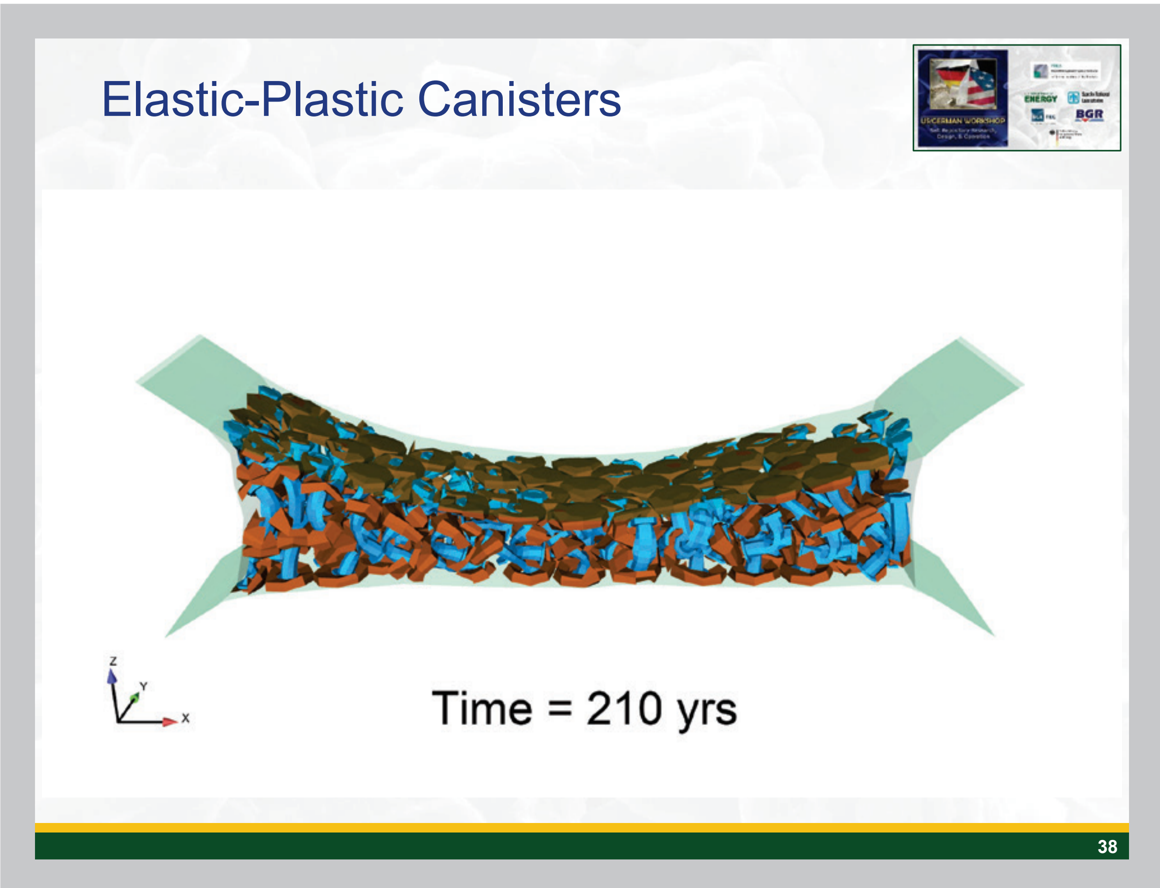


Speeding Up the Viscoplasticity
$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{vp} + \dot{\varepsilon}^{th}$
$\dot{\bar{\varepsilon}}^{vp} \propto A\, b \exp\left(-\frac{Q}{R\,T}\right) \bar{\sigma}^n$
$b = \frac{dt}{dt_{mb}}$
$b = b_0 + b_1\, t_{mb}$
b (10^9)
$b_1 = 2 \times 10^{11}$ s^{-1}
$b_1 = 2 \times 10^{10}$ s^{-1}
$b_1 = 2 \times 10^{9}$ s^{-1}
$b_1 = 2 \times 10^{8}$ s^{-1}
t (yr)
t_{mb} (s)
35



Scaling Ramp Rate Selection
$b = b_0 + b_1\, t_{mb}$
b (10^9)
$b_1 = 2 \times 10^{11}$ s^{-1}
$b_1 = 2 \times 10^{10}$ s^{-1}
$b_1 = 2 \times 10^{9}$ s^{-1}
$b_1 = 2 \times 10^{8}$ s^{-1}
t (yr)
t_{mb} (s)
Empty Room Sims
E_k / E_i (%)
δ_v / L_v (%)
Explicit, $b_1 = 2 \times 10^{11}$ s^{-1}
Explicit, $b_1 = 2 \times 10^{10}$ s^{-1}
Explicit, $b_1 = 2 \times 10^{9}$ s^{-1}
Explicit, $b_1 = 2 \times 10^{8}$ s^{-1}
Implicit, (b = 0)
t (yr)
36


Empty Room Mesh Convergence Study
r
δh / Lh
(%)
δv / Lv
(%)
Lh / 12
Lh / 24
Lh / 48
Lh / 96
Lh / 192
t (yr)
37


Elastic-Plastic Canisters
Time = 210 yrs
Z
Y
X
38

J. Aurich


R&D Project ELSA II
Compaction of crushed salt-clay-mixtures
with high compaction energy
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Jan Aurich
TU Bergakademie Freiberg
Hanover, Germany
September 10-11, 2018


A joint project of:
Prof. Wolfram Kudla
Jan Aurich
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TU Bergakademie Freiberg
Institute of Mining and Special Civil Engineering
Philipp Herold
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BGE TECHNOLOGY GmbH
BGE TECHNOLOGY GmbH
Department Research and Development
Coordination
PTKA
Projektträger Karlsruhe
im Karlsruher Institut für Technologie
Karlsruhe Institute of Technology (KIT)
Project Management Agency Karlsruhe (PTKA)
Funding
Bundesministerium für Wirtschaft und Energie
Federal Ministry for Economic Affairs and Energy (BMWi)
GSES
TERRA-MIX
IBU tec
TS BAU
Institut für Gebirgsmechanik GmbH
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Introduction

The R&D Project ELSA II – *Concept development for shaft seals and testing of sealing elements for HAW repositories* aims at:

- development of shaft sealing concepts for salt and clay rock formations, which meets the requirements of safety for a HAW repository
- testing multiple shaft sealing elements made of bentonite, asphalt, MgO concrete or crushed salt-clay-mixture in a pilot plant scale
- modelling the behavior of sealing elements in the context of construction and future hydraulic evolution
- simulating possible earth quake induced settlements in backfilled shafts

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Compaction experiments

host rock
(salt rock formations)

- mechanical properties
- chemical properties
- hydraulic properties

shaft sealing element
(crushed salt & clay)

- support element
- chemical compatibility
- hydraulic barrier

Target: Development of a backfill material with nearly host rock properties after compaction.

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Compaction experiments

Optimization of the composition:

- multiple Marshall tests
- fuller distribution
- minimum porosity
- maximum density
- determination compaction energy

initial components	Friedland Clay Powder (FCP)	fine salt (FS)	band 8 (B8)	band 6 (B6)	oversize grain (OG)	water
Distribution $d_5 - d_{95}$ [mm]	0.001 - 0.04	0.04 – 0.3	0.1 – 1.2	0.4 - 4	3 - 10	-

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Compaction experiments

Preliminary results of Marshall tests:

mixtures			STM-1	STM-2	STM-3
fractions	OG	[wt%]	23.6	46.6	-
	B6	[wt%]	22.0	19.1	56.1
	B8	[wt%]	35.8	10.6	16.8
	FS	[wt%]	-	13.0	13.0
	FCP	[wt%]	14.3	7.8	10.4
	added water	[wt%]	4.37	2.98	3.79
gross density		[g/cm³]	2.109	2.115	2.101
grain density		[g/cm³]	2.240	2.206	2.220
total porosity		[vol.%]	10.37	7,28	9.30
air voids		[vol.%]	0.17	0.32	0.55
effective compaction energy		[MJ/m³]		15.01	

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Compaction experiments

In-situ experiments

- maximize the density of a salt-clay-mixture in a pilot plant scale shaft
- minimize porosity of a sealing element under real conditions
- testing the handling of high compaction energies
- obtain consistent compaction of the material over cross section

Terra Mix impulse compaction unit:
(hydraulic powered falling weight)

- falling weight: 9,000 kg
- falling height: 15 cm to 120 cm
- single hit: 0.013 MJ to 0.053 MJ
- cumulative induced energy during the test: 15.01 MJ/m³

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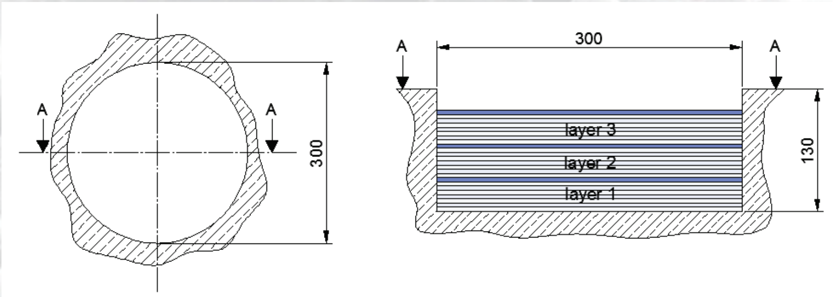
Compaction experiments

Field test set-up:

- half scale shaft in a hard rock quarry
- diameter of 300 cm and a depth of 130 cm
- three layers with eight sublayers each
- every sublayer pre-compacted with a small vibratory plate
- every second sublayer pre-compacted with a heavy vibratory plate
- every main layer compacted with an impulse compaction unit



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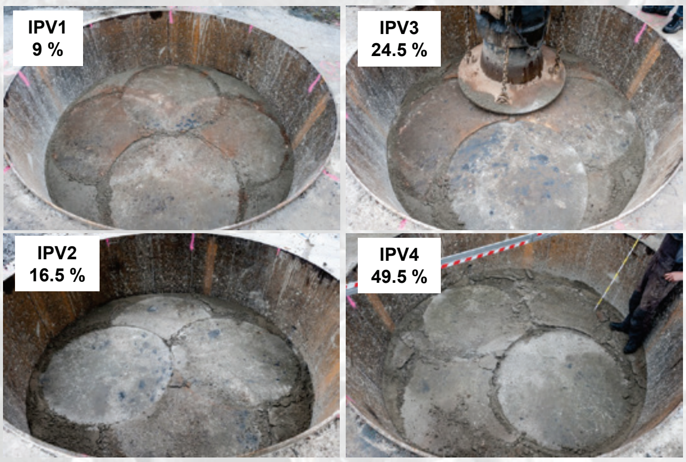
Compaction experiments

1st field test in 2015:

- rotation of the compactor foot to equalize energy input
- evaluation of all three mixtures
  - STM-2 (layer 1)
  - STM-3 (layer 2)
  - STM-1 (layer 3)



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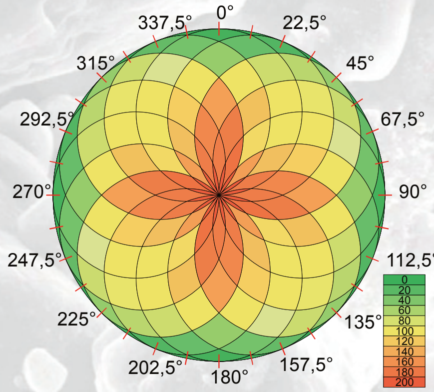
Compaction experiments

1st field test in 2015:
occurring problems on surface:

- standard circular foot leads to an irregular energy input ⇨a high compacted center and low compacted outer zone



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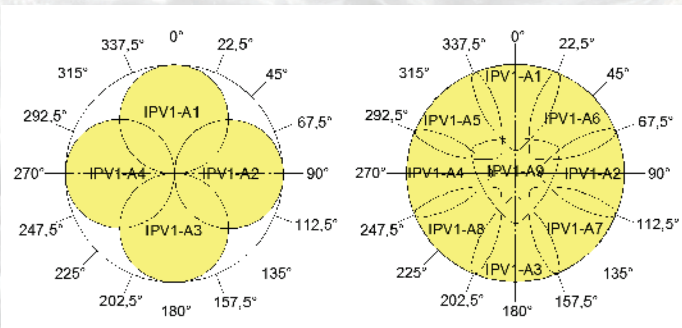
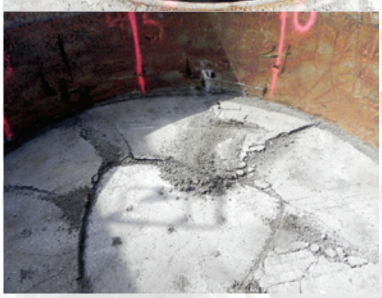
Compaction experiments

equipment modifications for a 2nd test in 2017:

- replacing the circular geometry with a bend triangle
- adding steel plates to reduce surface bulking





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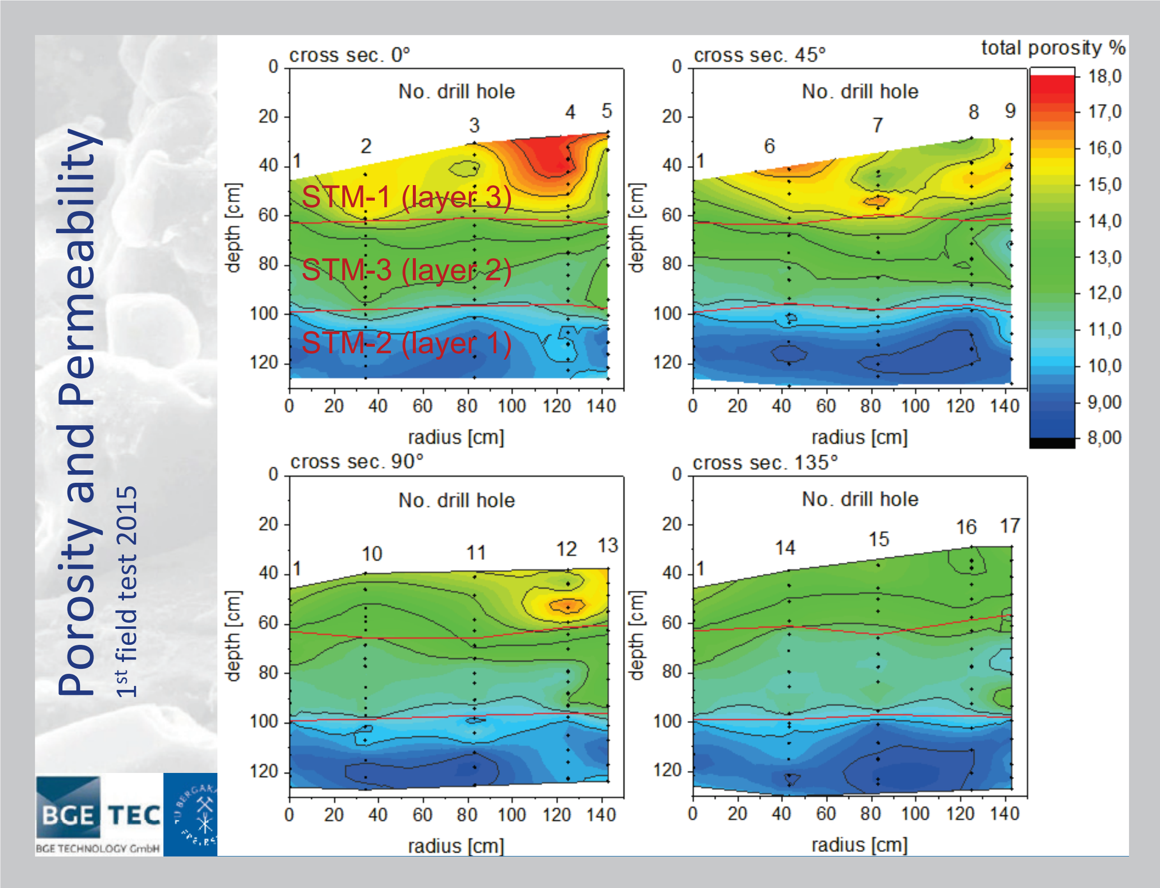
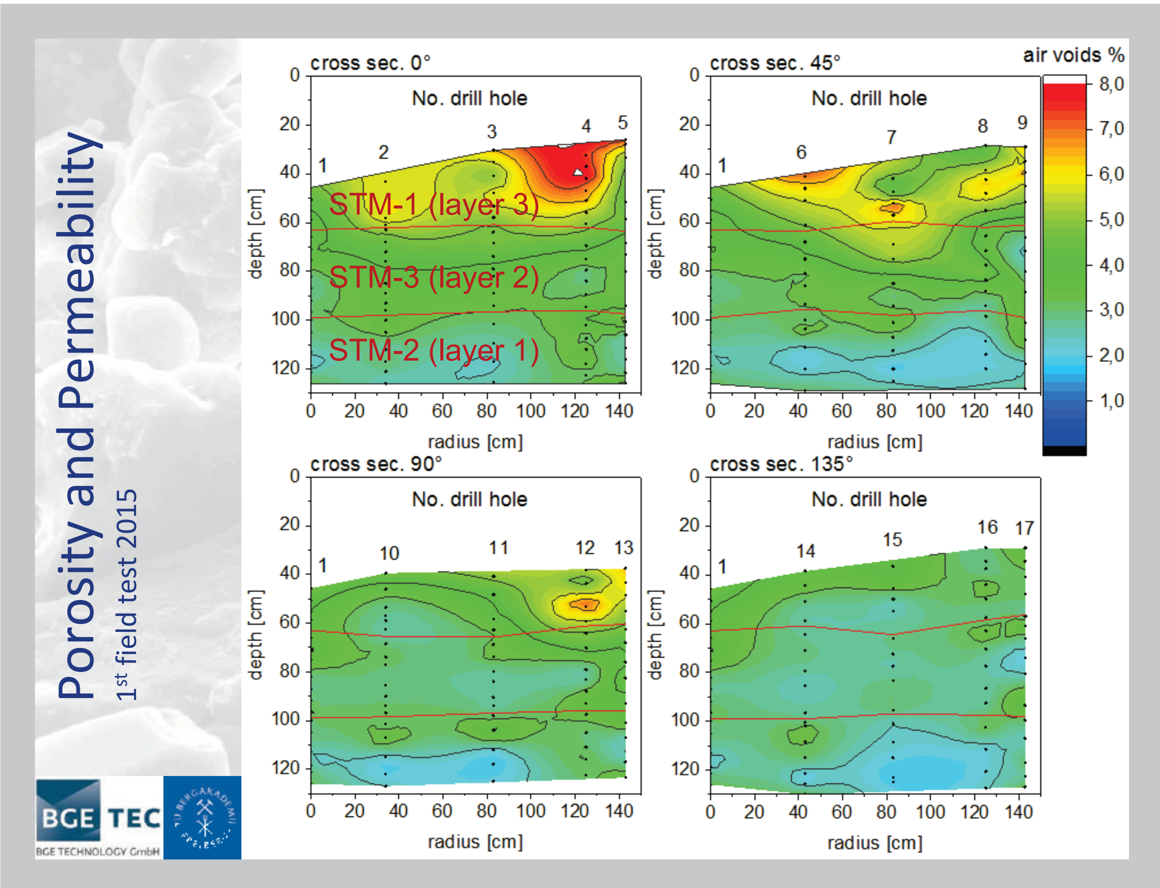
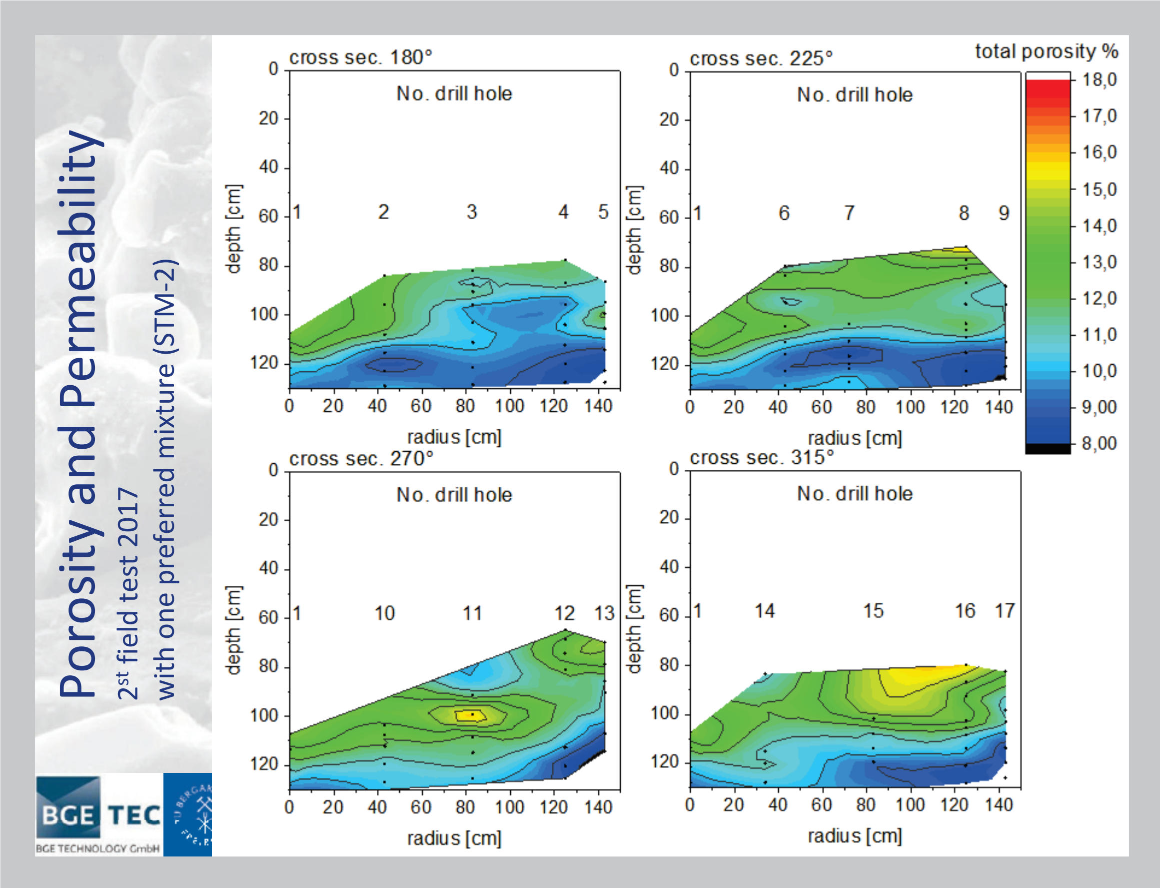
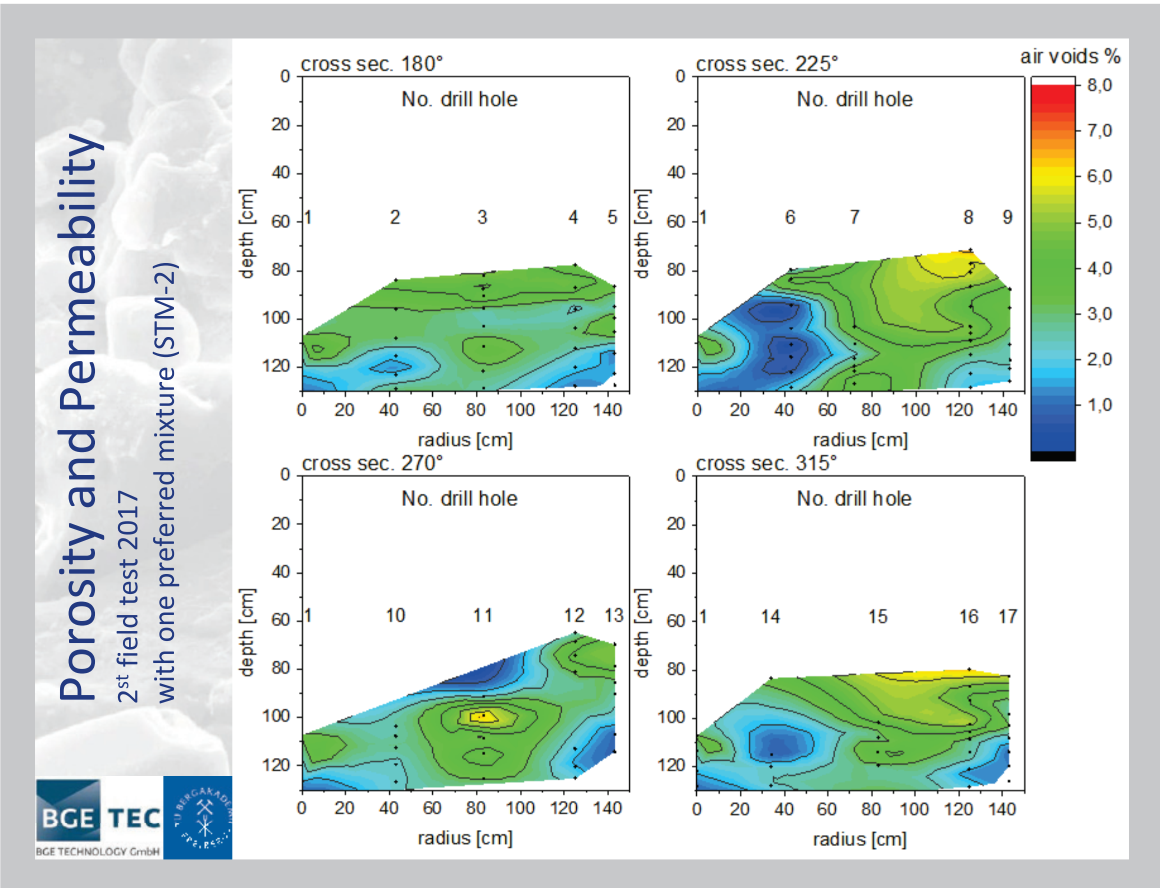
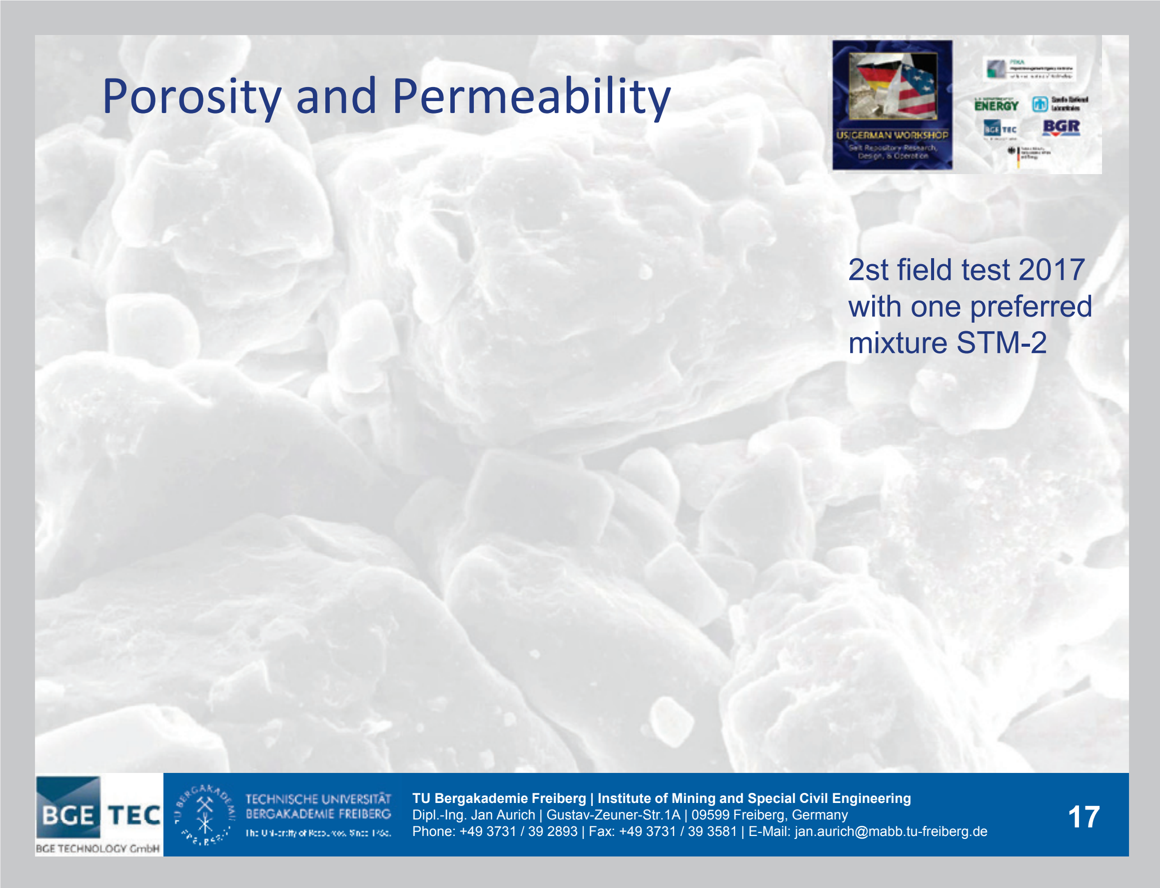

Porosity and Permeability
1st field test 2015
BGE TEC
BGE TECHNOLOGY GmbH
cross sec. 0°
No. drill hole
STM-1 (layer 3)
STM-3 (layer 2)
STM-2 (layer 1)
depth [cm]
radius [cm]
cross sec. 45°
cross sec. 90°
cross sec. 135°
total porosity %
18,0
17,0
16,0
15,0
14,0
13,0
12,0
11,0
10,0
9,00
8,00


Porosity and Permeability
1st field test 2015
BGE TEC
BGE TECHNOLOGY GmbH
cross sec. 0°
No. drill hole
STM-1 (layer 3)
STM-3 (layer 2)
STM-2 (layer 1)
depth [cm]
radius [cm]
cross sec. 45°
cross sec. 90°
cross sec. 135°
air voids %
8,0
7,0
6,0
5,0
4,0
3,0
2,0
1,0


Porosity and Permeability
2st field test 2017
with one preferred mixture (STM-2)
BGE TEC
BGE TECHNOLOGY GmbH
total porosity %
cross sec. 180°
cross sec. 225°
cross sec. 270°
cross sec. 315°
No. drill hole
depth [cm]
radius [cm]


Porosity and Permeability
2st field test 2017
with one preferred mixture (STM-2)
BGE TEC
BGE TECHNOLOGY GmbH
air voids %
cross sec. 180°
cross sec. 225°
cross sec. 270°
cross sec. 315°
No. drill hole
depth [cm]
radius [cm]



Porosity and Permeability
US/GERMAN WORKSHOP
ENERGY
BGR
2st field test 2017
with one preferred
mixture STM-2
BGE TEC
BGE TECHNOLOGY GmbH
TECHNISCHE UNIVERSITÄT
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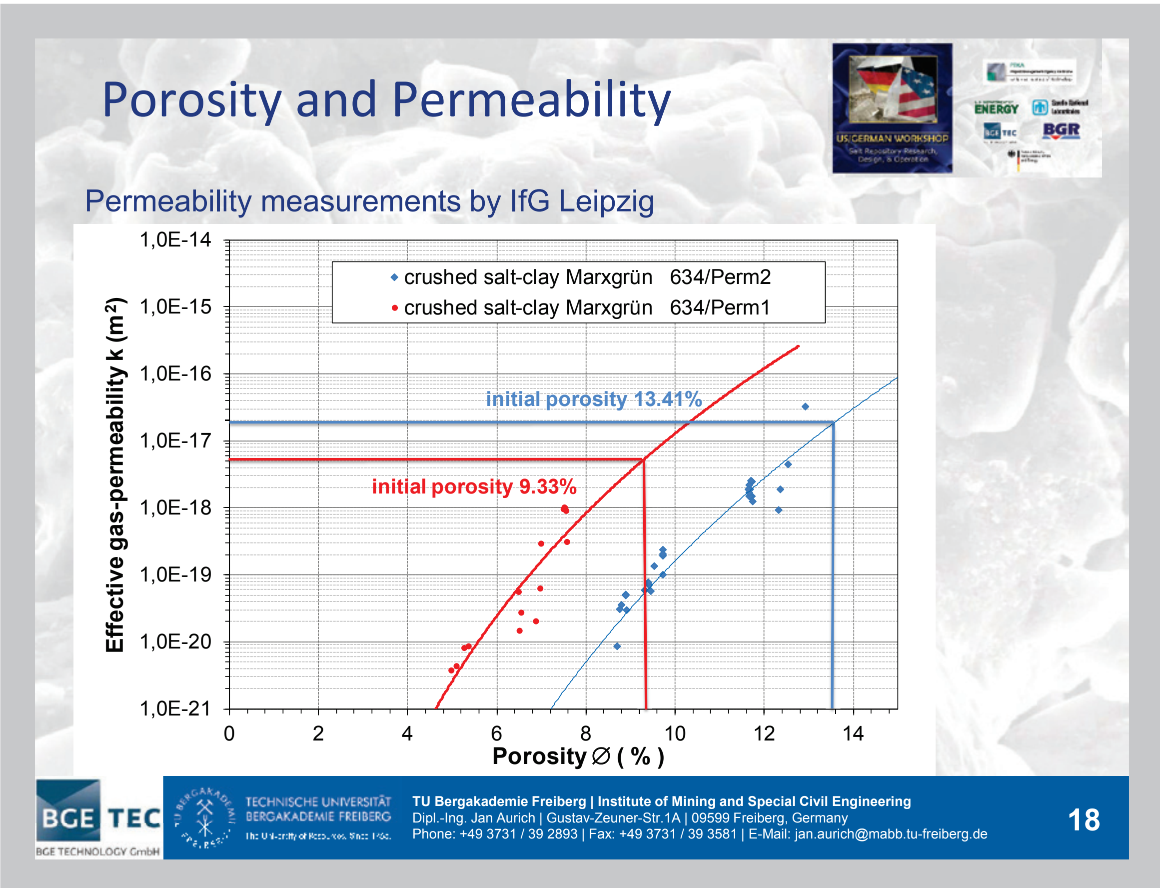

Porosity and Permeability
US/GERMAN WORKSHOP
ENERGY
BGR
Permeability measurements by IfG Leipzig
crushed salt-clay Marxgrün 634/Perm2
crushed salt-clay Marxgrün 634/Perm1
initial porosity 13.41%
initial porosity 9.33%
Effective gas-permeability k (m²)
1,0E-14
1,0E-15
1,0E-16
1,0E-17
1,0E-18
1,0E-19
1,0E-20
1,0E-21
0
2
4
6
8
10
12
14
Porosity ∅ (%)
BGE TEC
BGE TECHNOLOGY GmbH
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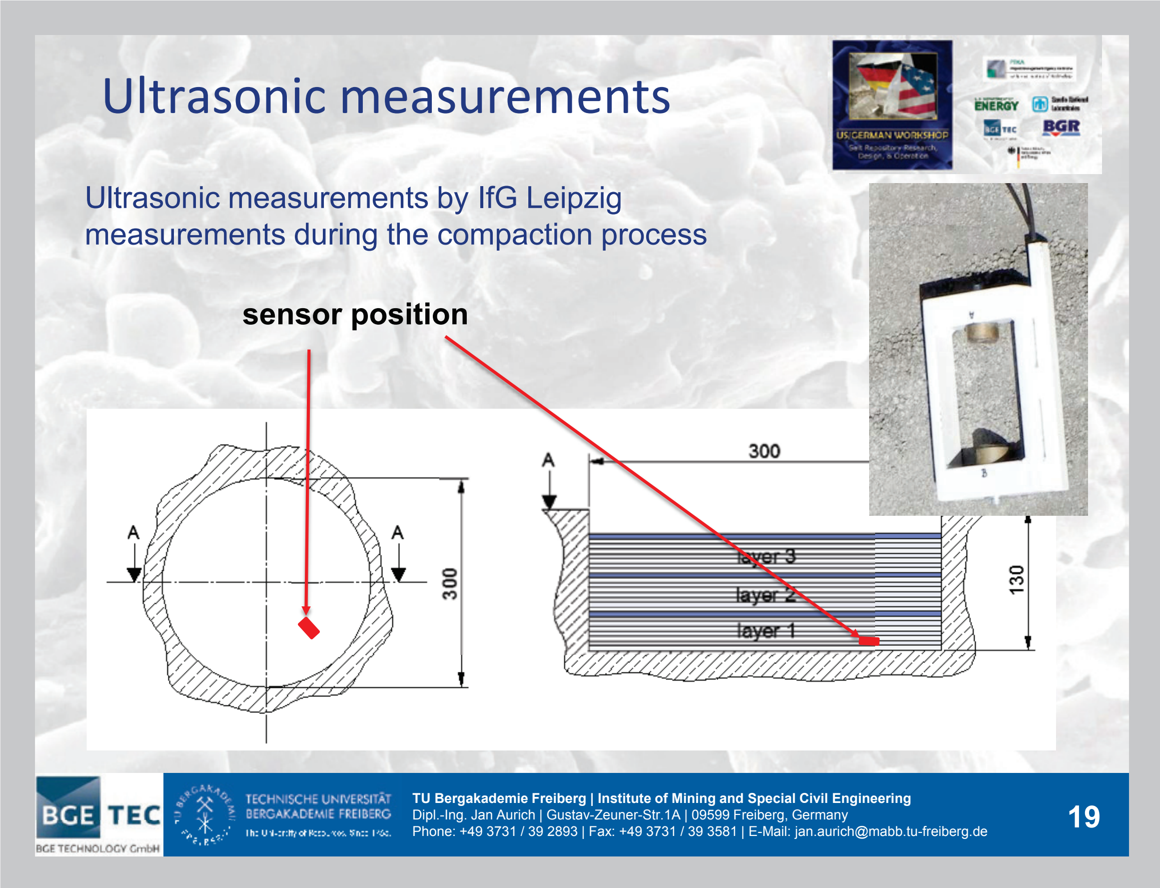
Ultrasonic measurements
Ultrasonic measurements by IfG Leipzig
measurements during the compaction process
sensor position
A
A
300
A
300
layer 3
layer 2
layer 1
130
TU Bergakademie Freiberg | Institute of Mining and Special Civil Engineering
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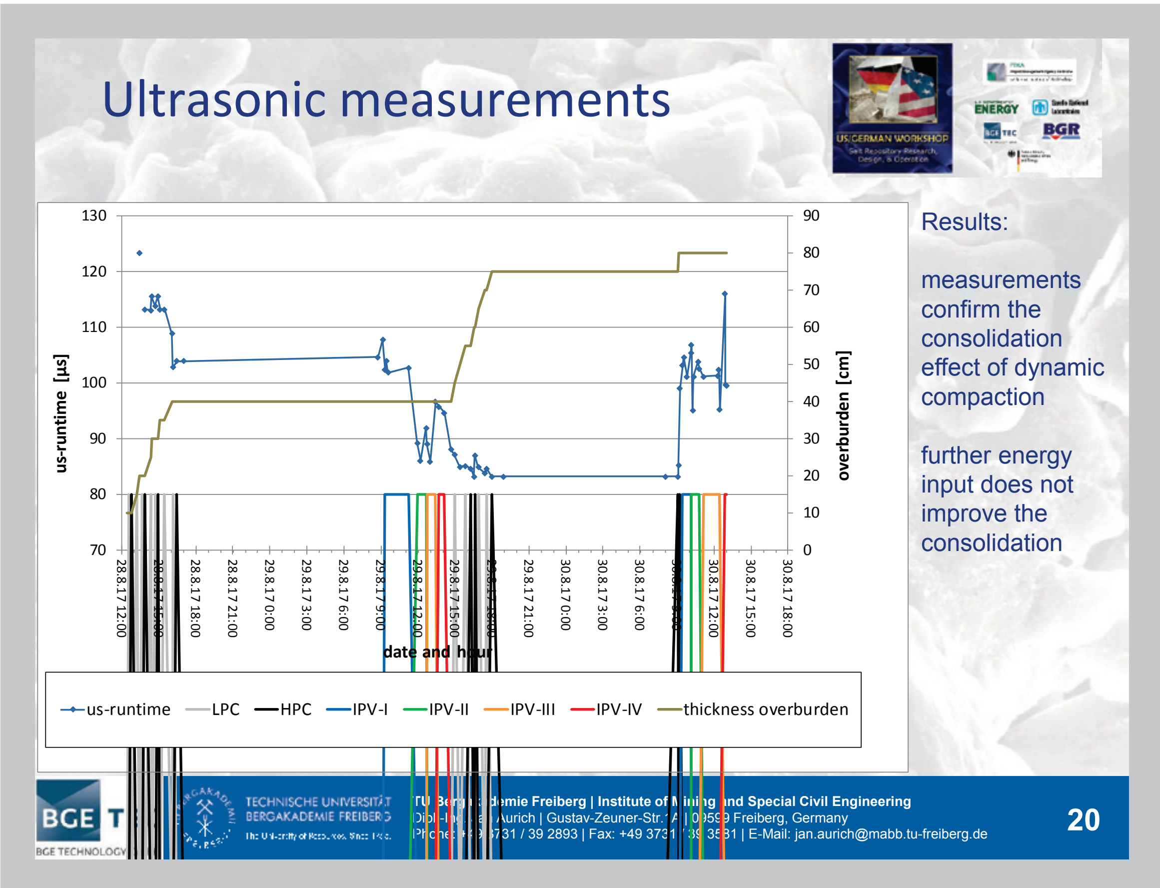
Ultrasonic measurements
us-runtime [µs]
overburden [cm]
date and hour
us-runtime
LPC
HPC
IPV-I
IPV-II
IPV-III
IPV-IV
thickness overburden
Results:
measurements confirm the consolidation effect of dynamic compaction
further energy input does not improve the consolidation
TU Bergakademie Freiberg | Institute of Mining and Special Civil Engineering
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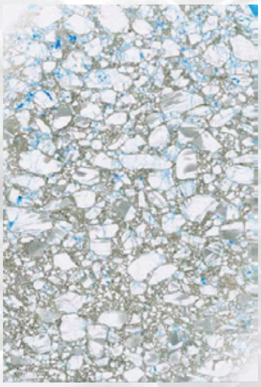
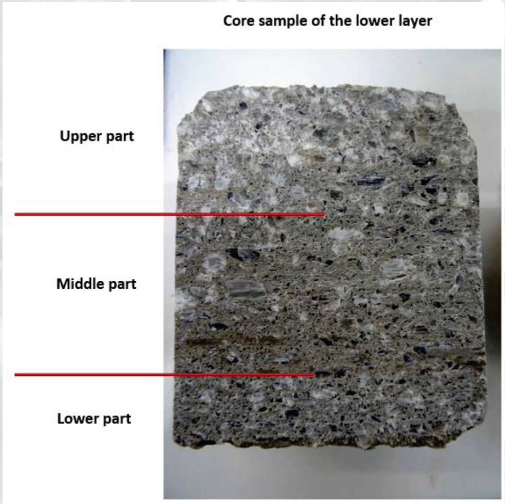
Micro section analysis

Micro section analysis by BGE TECHNOLOGY
- preparation of several micro sections
- analysis does not indicate inner boundaries as an result of the assembling technology





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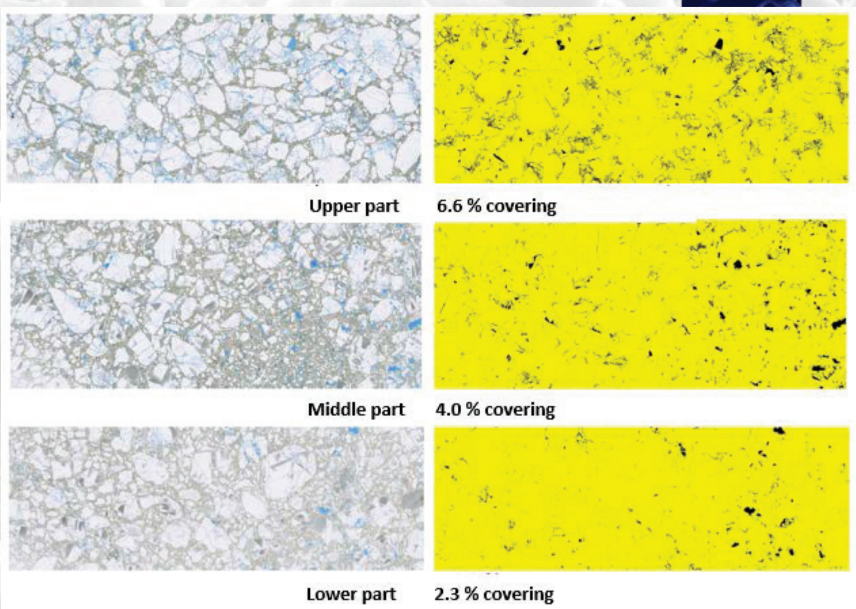
Micro section analysis



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Summary

Marshall-tests:
- Optimization of material composition for a salt-clay mixture
- Evaluation of necessary compaction energy input

1st field test:
- Transfer of impulse compaction technology from laboratory to field conditions
- In-situ produced densities and total porosities meet expectations
- Improvement of hydraulic properties under realistic conditions

2nd field test:
- Development of adapted foot geometry for falling weight to improve compaction process in the border area
- Reduction of surface bulking during dynamic compaction process
- Review of the compaction energy input via ultra sonic measurements

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Seals and Seal Materials for a Generic Salt Repository in the US

Ed Matteo
Sandia National Laboratories
Albuquerque, NM

Hanover, Germany
September 10-11, 2018

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2018-9943 C..

Outline

- Overview/ Background
  - Seals for a Salt Repository
    - Salt backfill
    - Compacted salt, Clay, Asphalt
    - Salt concrete, Ultrafine grout
- History of Seal Tests in the US
  - WIPP Borehole Plugging Program
    - Predecessor - Salt Vault Program (early 1970's)
    - ERDA No. 10 (1977)
    - Bell Canyon Test (1979)
    - Waterways Experiment Station (WES) Grout Studies (70's and 80's)
  - Small-Scale Seal Performance Tests (at WIPP)
- WIPP Seal Design vs. Salt HLW Repository
- Current WIPP Heater Test
    - Materials? Test design?

2

A Brief Timeline of Seal Testing

- 1974 - US Atomic Energy Commission (AEC) -
  - Salt Vault Borehole Plugging Test in Lyons, Kansas in 1972
  - Test led by Union Carbide, Oak Ridge, TN (ORNL)
- 1975 - AEC split into Energy Research and Development Agency (ERDA) and NRC, ERDA -> US DOE in 1977
- 1977 - ERDA No. 10 Test
  - Test led by SNL
- 1978 - Office of Nuclear Waste Isolation (ONWI) assumes lead of Borehole Sealing (and DHLW in Salt site)
- 1979 - Bell Canyon Test
- 1980's - Underground testing at WIPP of seal elements and various materials

3

ERDA No. 10 - Cement Plugs

- Plugs were set Oct. 1977
- Plug 1 (deepest in Bell Canyon Fm.) cored 48 hours after it was emplaced
- Plug 1, 2, 3 included a fine granulated salt to make a salt water mixture
- Plug 4 (in the surface casing) was mixed in fresh water to prevent casing corrosion

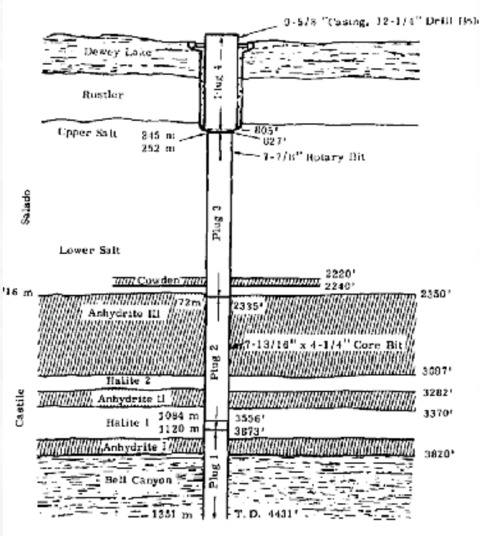


Figure 1. ERDA No. 10 Drill Hole

Gulick 1979

4

ERDA No. 10 - Grout and Analysis

- Test Procedures
  - Field sample core from Plug 1 (deepest)
  - Test cores (poured at surface)
- Grout Formulations
- Sample Analysis was limited
  - Time series mineralogy and strength on surface cores
- ERDA-10 Conclusions
  - Was the purpose to demonstrate that a borehole into the Bell Canyon Formation could be plugged?

ERDA-10 Grout Mixture Data*

	Units	Plug 1** 30% Salt	Plugs 2, 3** 36% Salt	Plug 4** Fresh Water
Cement, Class C(SR)	lb/ft^3	42.90	39.58	54.83
Fly ash	lb/ft^3	14.47	13.35	18.50
Salt gel (Attapulgite)	lb/ft^3	1.15	1.06	--
Bentonite gel	lb/ft^3	--	--	1.47
Salt, D44	lb/ft^3	10.77	14.15	--
Silica sand, D30	lb/ft^3	3.26	3.01	--
Dispersant, D45	lb/ft^3	0.06	0.05	0.29
Dispersant, D65	lb/ft^3	--	--	--
Calcium chloride (S1)	lb/ft^3	1.15	1.06	--
Water	lb/ft^3	36.6	39.3	36.0
Density	lb/ft^3	108.5	107.0	112.2
Density	lb/gal	14.5	14.3	15.0
Yield	ft^3/sack	1.5	1.7	1.2
Water content	gal/sack	6.6	7.8	5.2
Water/cement ratio		0.85	0.99	0.66
Water/cement and fly ash ratio		0.64	0.74	0.49
Thickening time	hr:min	4:35	7:45	5:05
Unconfined compressive strength				
24 hr	psi	712	420	1210
48 hr		1543	1032	1522
72 hr		1888	1275	2080

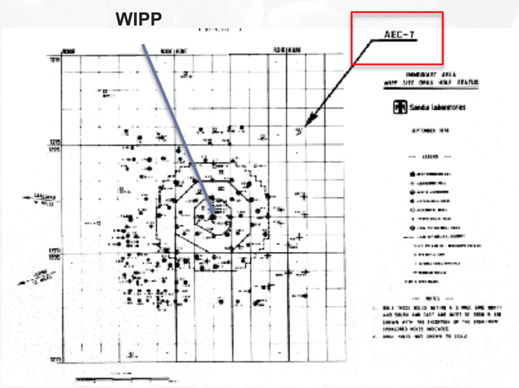
* This was Table 1 in Reference 6.
** Plug 1 cured at 128° F, 2445 psi; Plugs 2, 3 cured at 125° F, 2112 psi; Plug 4 cured at 80° F, 445 psi.

From Buck and Mather 1982

5

Bell Canyon Test (BCT) -1979

- AEC-7 borehole, originally an exploratory borehole drilled by ORNL in 1974
- Reconditioned by DOE in 1977 to evaluate the performance (permeability and durability) of state-of-the-art borehole seal technology
- 5 miles northeast of WIPP site



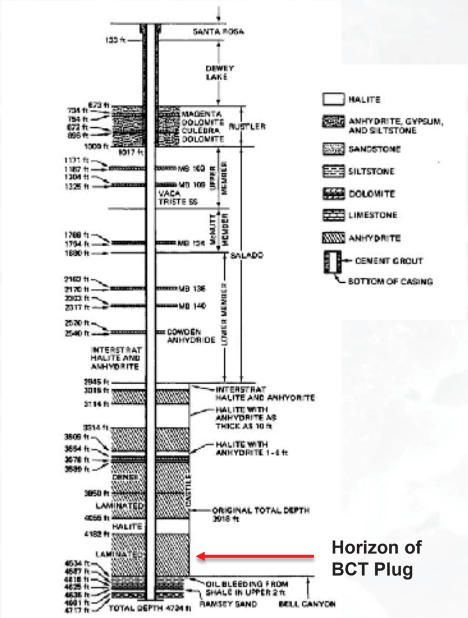
Scale bar ~ 4 miles

Christensen 1979

6

Bell Canyon Test - Plugs

- Plug 217 from a potash mine
  - High w/c =0.7
  - Cement : formation perm
    - 5-50 mD (10^{-6} m^2)
  - Deemed inconclusive since details of formulations were unknown
- BCT Plug
  - 2 m in length
  - 20 cm diameter borehole
  - 12.4 MPa pressure differential
  - Emplaced in the Castile anhydrite



Christensen 1981

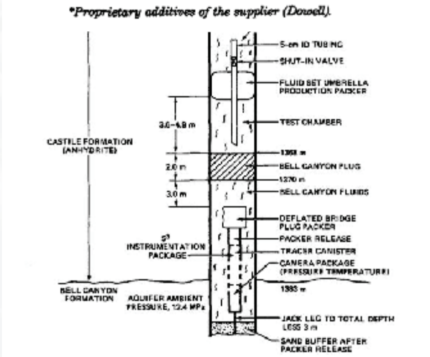
7

Bell Canyon Test - Grout

- Prior to emplacement Waterways Experimental Station (WES) grouting studies narrowed to two candidate grouts:
  - 6% salt (BCT-1F)
  - Freshwater (BCT-1FF)
- On the basis of lab tests for permeability and bond strength push-out tests, BCT-1FF, the freshwater grout was chosen for emplacement
- Measured 50 uD downhole in the BCT

	BCT-1F	BCT-1FF
Ingredients, wt.%		
Class H cement	50.1	52.2
Expansive additive*	6.7	7.0
Fly ash	16.9	17.6
Salt (NaCl)	6.5	
Dispersant*	0.2	0.2
Defoamer*	0.02	0.02
Water	19.5	23.0
Properties		
Water-to-cement ratio	0.26:1.0	0.30:1.0
Fluid density, g/cm³	2.04	1.98

*Proprietary additives of the supplier (Dowell).



Christensen 1981

8

Bell Canyon Test - Highlights

- It is notable that the salt water grout showed poor bonding to anhydrite in lab tests. The freshwater samples did not, and thus were chosen for the BCT.
- Demonstration of:
  - pressurized cementitious seal that exhibited an expected low permeability
  - execution produced a plug seal that bonded well with the host and cement that was set and cured properly.

	BCT-1F	BCT-1FF
Ingredients, wt.%		
Class H cement	50.1	52.2
Expansive additive*	6.7	7.0
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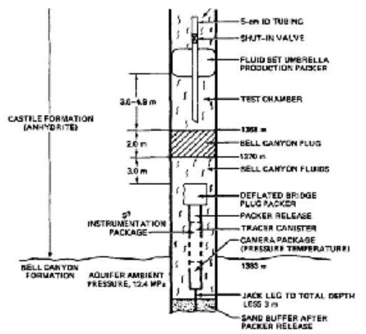


Christensen 1981

9

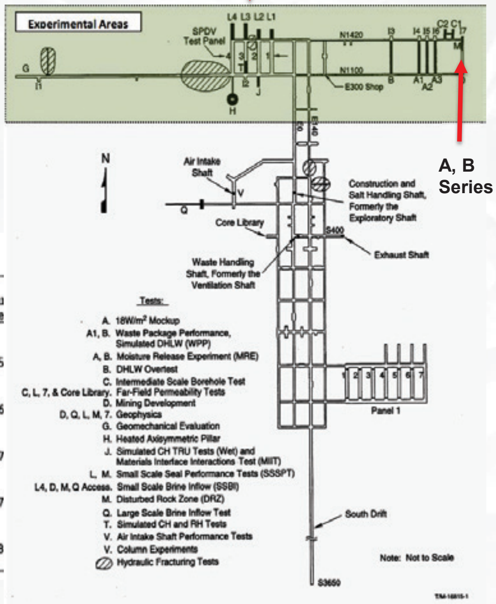
Small-Scale Seal Performance Tests (SSSPT)

- WIPP Experimental Area - Rooms L, M
- Vertical and horizontal boreholes
- Expansive Salt Concrete (ESC), Salt blocks, salt/bentonite blocks and backfill, ultrafine grout (F series)

Test Series Schedule

Test Series	Seal Material	Direction	Schedu Emplace
A	Salt-based concrete	Vertical	7/85
B	Salt-based concrete	Horizontal	2/86
C	Salt and bentonite block and mortar	Horizontal	3/87
D	Salt and bentonite backfill	Vertical	9/87
E	Salt-based concrete	Vertical (thru Marker Bed 139)	3/88

From Stormont 1987



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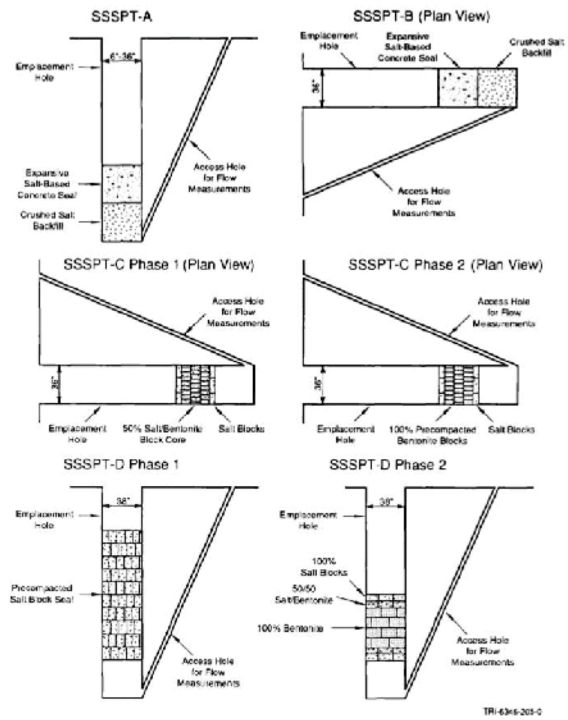
SSSPT Configurations

TABLE 1. TEST SERIES CURRENTLY PLANNED FOR SSSPT				
Test Series	Seal Material	Seal Emplacement Orientation	Emplacement Date	Measurements*
A	Salt-Based Concrete	Vertical	7/85	Seal Pressure; Displacement and Temperature; Gas and Brine Flow
B	Salt-Based Concrete	Horizontal	2/86	Seal Pressure; Gas and Brine Flow
C Phase 1	Salt and 50/50% Salt/Bentonite Block	Horizontal	9/86	Seal Pressure; Brine Flow
C Phase 2	Bentonite Block	Horizontal	12/90	Seal Pressure; Brine flow
D Phase 1	Salt Block	Vertical	1/88	Seal Pressure; Hole Closure; Floor Heave; Gas Flow
D Phase 2	Bentonite Block (short-term)	Vertical	9/89	Seal Pressure; Brine Flow

* Note: Instruments include strain gages, stress meters, thermocouples, pressure cells, borehole displacement gages, Multiple Point Borehole Extensometers (MPBX), and the Four Packer Fracture Flow Tool (FPFFT) for fluid flow measurements.



From Finley et al. 1992

11

SSSPT Highlights, 1/2

- SSSPT Tests provide confidence to Performance Asessment in the form of *in situ* data on permeability and mechanical performance

Table III. Summary of SSSPT Seal System Permeabilities

Test Fluid	Concrete Permeability (m^2)	Concrete Permeability (m^2)	50%/50% Salt/bentonite Permeability (m^2)	100% Bentonite Permeability (m^2)
Test Period	(1985-1987)	(1993-1995)	(1986-1990)	(1988-1995)
Gas	$10^{-17} – 10^{-20}$	$10^{-19} – 10^{-23}$	–	see Figure 3
Brine	$\sim 10^{-19}$	$10^{-19} – 10^{-22}$	$\sim 10^{-16}$	$\sim 10^{-19}$

From Knowles and Howard 1995

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SSSPT Highlights, 2/2

- Expansive Salt Concrete Seals
  - Exhibited sub-microdarcy permeability for both gas and brine (9 seals tested)
  - Flow path decreased within a year of emplacement (tracer test)
  - Emplaced using commercial equipment
  - AND optimized for key operational attributes including:
    - slump, limited bleed, segregation, limited air entrainment, self-leveling behavior, and workability
  - BUT…, in the late 80's the expansive agent became commercially unavailable (enter Salado Mass Concrete)
- Lessons learned with respect to cement formulations (from Wakeley 1987)
  - Simpler is better … for prediction, batching, sourcing, etc.
  - Working time is a critical property
  - By the late 80's, it became evident that **concrete** (not grout) would play a central role at WIPP as components in the sealing system for bulkheads and drift, panel, and shaft seals - as opposed to the primary seal
    - Lifetime requirements on the order of 100 years instead of 10,000 years

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Salado Mass Concrete

- Incorporates the lessons from WES Grout Studies
- Dry batched at the surface, mixed underground
- As with previous grout/concrete studies, lab and field tests worked iteratively to meet targets for material properties

Table 3-1. SMC-3 and SMC-5 Mixture Proportions

Material	SSD Batch Quantities, lb/yd^3*	
	SMC-3	SMC-5
Cement, API Class H	278	221
Class F Fly Ash	207	247
Chem Comp III	134	112
Fine Aggregate	1255 to 1292**	1283
Coarse Aggregate	1579 to 1615**	1645
Salt	88	86
Water	216 to 260 ***	226 to 295***

* $kg/m^3 = (lb/yd^3) \times (0.59)$
** Quantities may change with aggregate density or grading; see ACI, 1991.
*** Changes with w/c

From Wakeley, Harrington, and Hansen 1995

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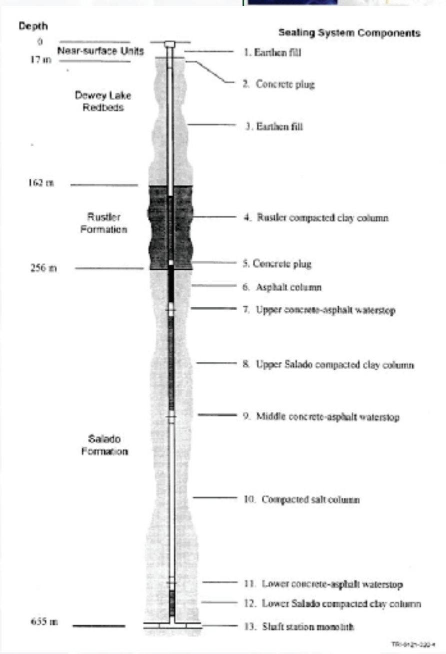
Design Bases, 1/2

- Seal performance standards (WIPP)
  - Concrete/grouts:
    - Have been proven/tested in the WIPP underground
    - Provide design redundancy as one element in a suite of seal materials in the overall seal design (**salt**, clay, asphalt)
- WIPP vs. DHLW
  - Increased radiologic source term
  - Thermal effects - cracking of seal materials
  - Chemical evolution in shaft and drift seals
    - Low pH cement?



FROM HANSEN AND KNOWLES 1999

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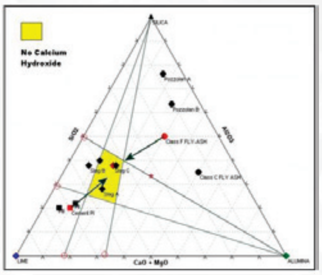
Design Bases, 2/2

- Why low pH cement?
  - Concern that $Ca(OH)_2$ dissolution increases RN solubility and mobility
  - Dehydration of cement introduces water into the repository
  - Superplasticizers -> increased colloid mobility
  - Organics -> microbial growth
- Low pH cement
  - Pore solution pH ~ 10
  - Low $Ca(OH)_2$ content
  - Fly ash, silica fume, basalt furnace slag increase available silica -> more CSH, less $Ca(OH)_2$
  - Denser, less permeable paste



Dole et al. 2004

16

Cementitious Seals Test 1/2

- Key issues for Cementitious Seal Performance Evaluation
  - Autogenous shrinkage of seal (during setting)
    - Gap formation at cement/salt interface
    - Crack formation in cement plug
  - Heat output of mass concretes
    - Crack formation in cement plug
  - Material selection (i.e., Sorel cement, salt concrete, low pH?)
  - Effects of salt host closure on the seal
- Why do a field-scale test of seals in bedded salt
  - Most recent field tests have been in domal salt (saltcrete, Sorel)
  - Bedded salt tests at WIPP - Small Scale Seal Performance Tests Series A, B, C
    - Used a very specific formulation of “Expansive Salt Concrete”
    - Key ingredients are unavailable and potential difficult to reproduce

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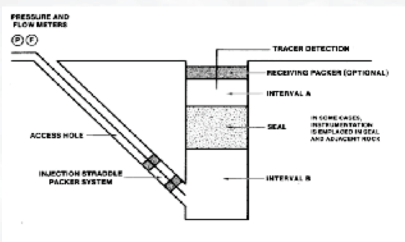
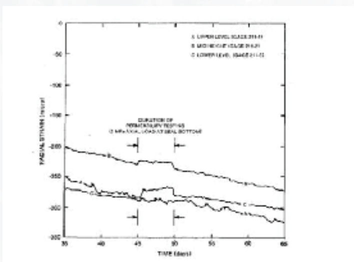
Cementitious Seals Test 2/2

- Relevant Tests in Domal Salt
  - Lab-scale Tests for DOPAS (Czaikowski et al. 2016)
  - ERAM Test Seal - salt concrete
  - Asse tests - Sorel cement and salt concrete

From Czaikowski et al. 2016

- Create a seal test at WIPP with the concept of a potential HLW Salt Repository in mind (with relevance to some generic, bedded salt site)
  - Measure borehole closure and permeability of the seal





From Stormont 1987

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U. Düsterloh

9th US/German Workshop on Salt Repository Research, Design, and Operation

apl. Prof. Dr.-Ing. habil. U. Düsterloh
Clausthal University of Technology

Hanover, Germany
September 10-11, 2018

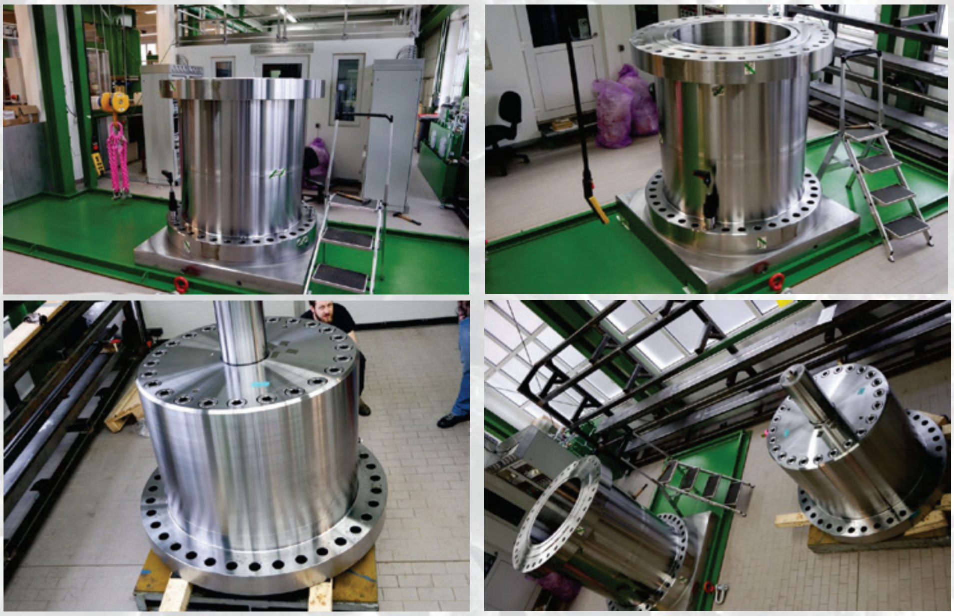
Description of a large scale pilot plant designed to analyse sealing systems of cut salt bricks

- MECHANICAL BEHAVIOR of SALT VIII / Rapid City, SD USA
  May 26-28, 2015
  Design of a pilot plant to analyze sealing systems based on rock salt bricks

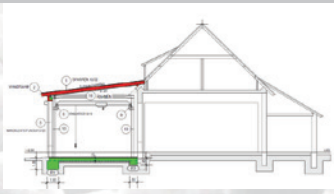
US/GERMAN WORKSHOP / Hannover, Germany
September 10-11, 2018
Description of a large scale pilot plant designed to analyze sealing systems of cut salt bricks

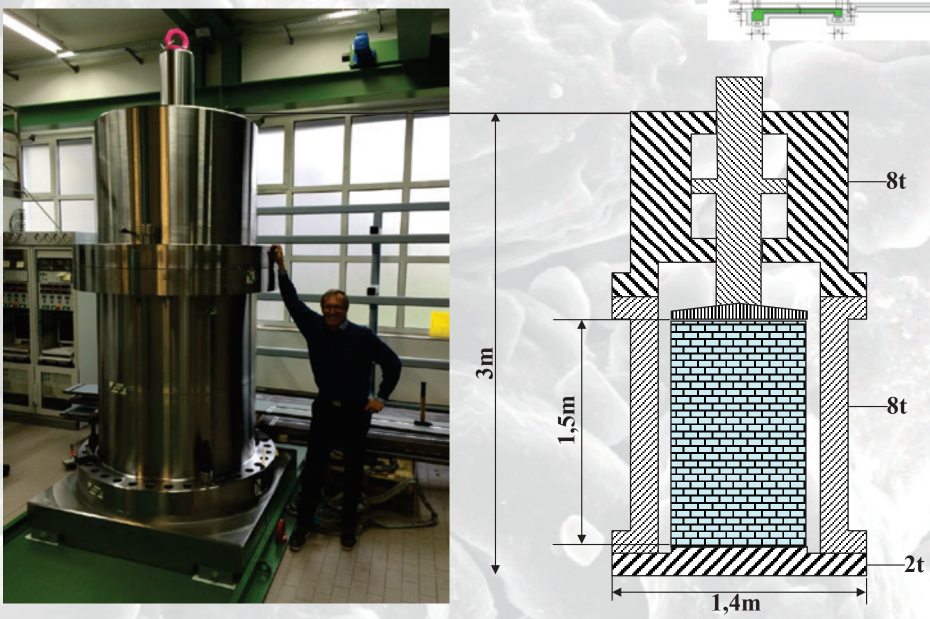
Content of presentation = progress of work
- steel manufacture, hydraulics, electrics, electronics to realize the pilot plant
- preliminary tests to calibrate and check functionality of pilot plant
- construction of sealing systems
- preparation of bricks
- numerical investigations into the mechanical load bearing behavior

composition of a pilot plant – steel manufacture

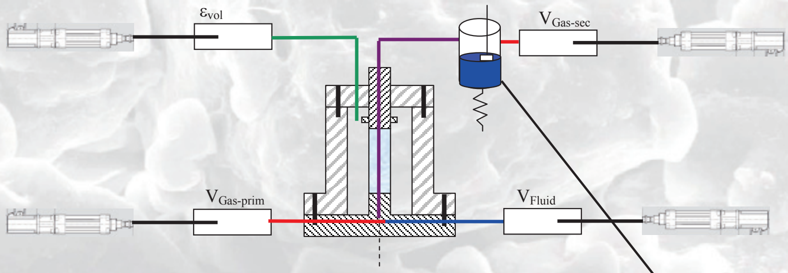


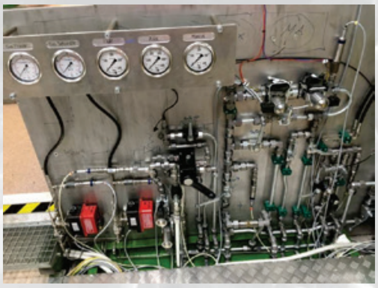
composition of a pilot plant – steel manufacture

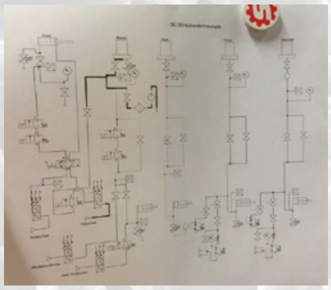




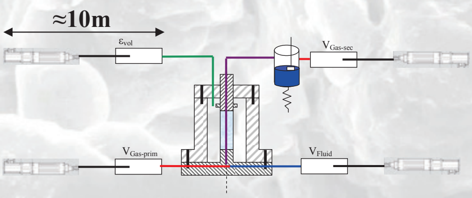
composition of a pilot plant – hydraulic systems



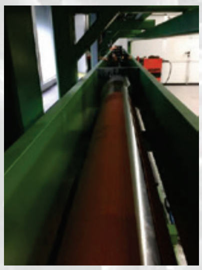




composition of a pilot plant – hydraulic systems

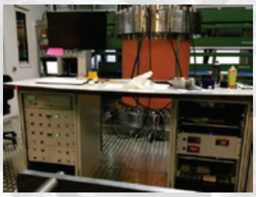


- 4 emc-cylinders with stepless control (s=1,6m, V=15l)
- electrical heating of cylinders
- Fmax = 28MN
- axial cylinder stroke s = ± 30cm
- refill system



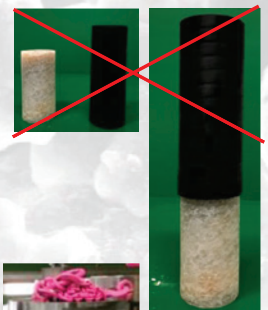
composition of a pilot plant – electrical & electronically systems

uninterrupted power supply (60kVA)
amplifier cards, control cards
sensors – pressure, force, temperature, displacement



preliminary tests to calibrate and check functionality

sample covering ?

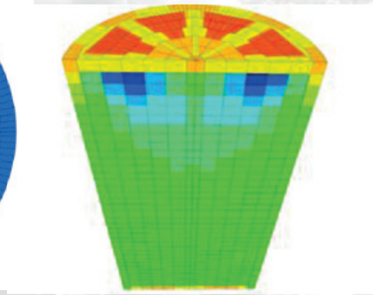


no success in case of glueing → success after ordering an expert for vulcanizing belt conveyer for lignite coal

preliminary tests to calibrate and check functionality

steel dummy needed to calibrate pilot plant
→ hollow cylinder; reinforcement by radius arms
(plain cylinder = 0,66m^3 x 7t/m^3 = 4,6t)

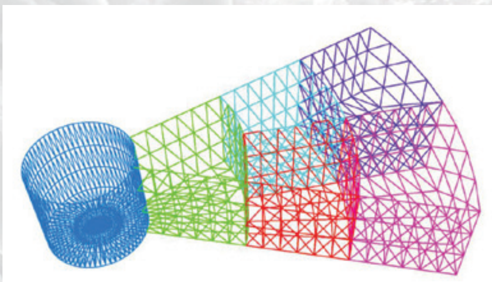
preliminary calculations regarding deformability / stability



construction of a sealing system

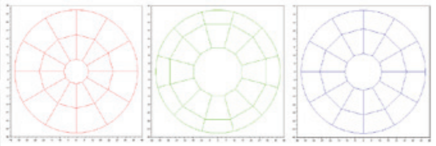
→ size of individual bricks ↔ availability of basic raw material
→ number of bricks ↔ scale factor between pilot plant and reality
→ shape of bricks ↔ avoid continuous gaps

development of a software, able to configure sealing systems different in number, size and shape of individual salt bricks

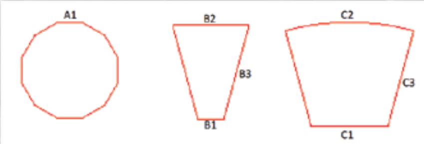


construction of a sealing system

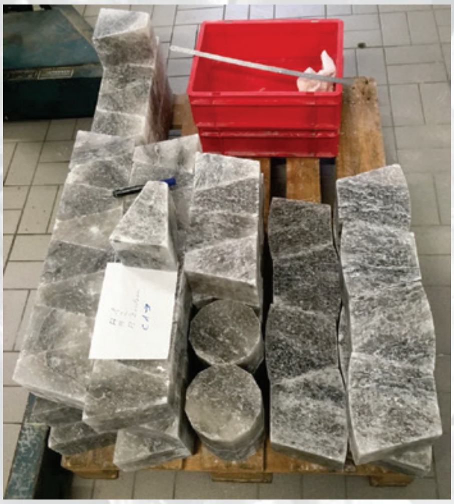
→ size of individual bricks ↔ availability of basic raw material
→ number of bricks ↔ scale factor between pilot plant and reality
→ shape of bricks ↔ avoid continuous gaps / reduce number of different shaped salt bricks



25 salt bricks per slice → 15 slices → 375 bricks
3 types of bricks per slice → 9 different types of bricks



	Volumen (cm^3)	Benötigte Stückzahl	Gesamtvolumen (cm^3)
Zentralstück (A)	1687,5	5	8437,5
Trapez Typ 1 (A)	1125,0	60 (5 x 12)	67500
Trapez Typ 2 (A)	2415,9289	60 (5 x 12)	144955,73
Zentralstück (B)	6750,0	5	33750
Trapez Typ 1 (B)	1687,5	60 (5 x 12)	101250
Trapez Typ 2 (B)	1431,5539	60 (5 x 12)	85893,234
Zentralstück (C)	3796,875	5	18984,375
Trapez Typ 1 (C)	1406,25	60 (5 x 12)	84375
Trapez Typ 2 (C)	1958,8976	60 (5 x 12)	117533,86
		375	662679,7



preparation of bricks

→ milling machine required to prepare 3D-shaped salt bricks

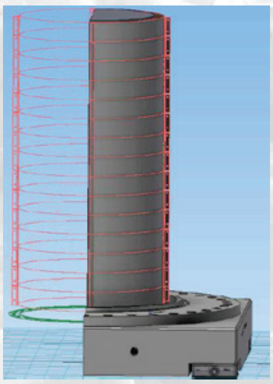
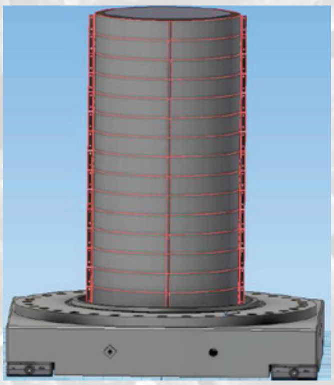
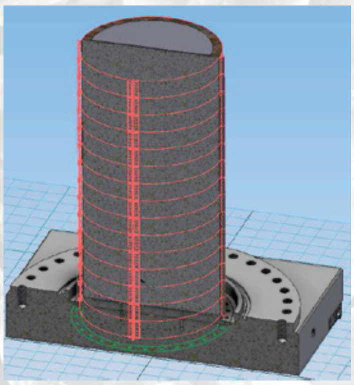
preparation of bricks

- 12t basic raw material → 0,66m³ / 1,5t sealing element
- ≈ 6t crushed salt
- ≈ 4,5t offcuts
- ≈ 7 salt bricks per week → ≈ 1a per sample!



preparation of bricks combined with gaps filled by crushed salt

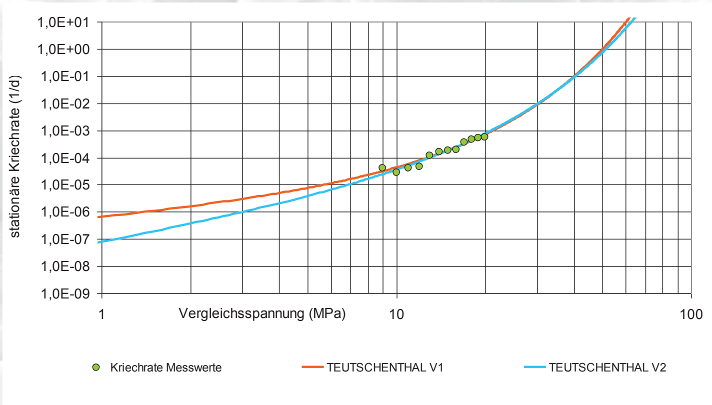
- casing construction to create sealing systems based on salt bricks and gaps filled with crushed salt
- two half rings connected to each other by screws; ring height similar to height of bricks plus thickness of gap
- filling vertical gaps by crushed salt first; followed by drawing off horizontal gap at level of upper edge of each ring

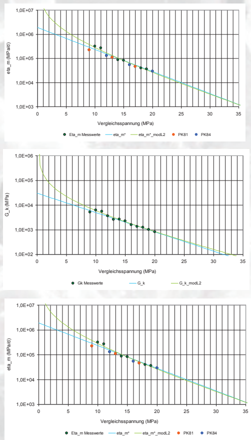




numerical investigations – creep behavior of bricks

lab tests to determine failure strength, dilation strength, creep behaviour of rock salt used for bricks

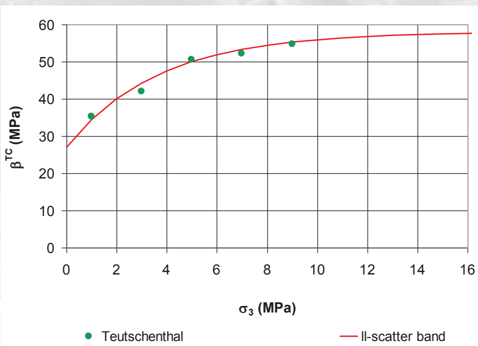
$$\dot{\varepsilon}_1^v = \dot{\varepsilon}_1^{tr} + \dot{\varepsilon}_1^{st} = \left[\frac{\sigma_v}{\overline{\eta}_{k(\sigma)}} \cdot \left\{1 - \frac{\varepsilon_1^{v,t} \cdot \overline{G}_{k(\sigma)}}{\sigma_v}\right\}\right] \cdot \left[\frac{\sigma_v}{\sigma^*}\right]^b + \left[\frac{\sigma_v}{\overline{\eta}_{M(\sigma,T)}} \cdot \left(\frac{\sigma_v}{\sigma^*}\right)^a\right]$$

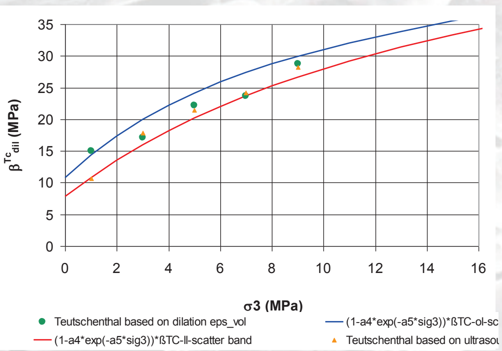




numerical investigations – failure and dilation strength of bricks

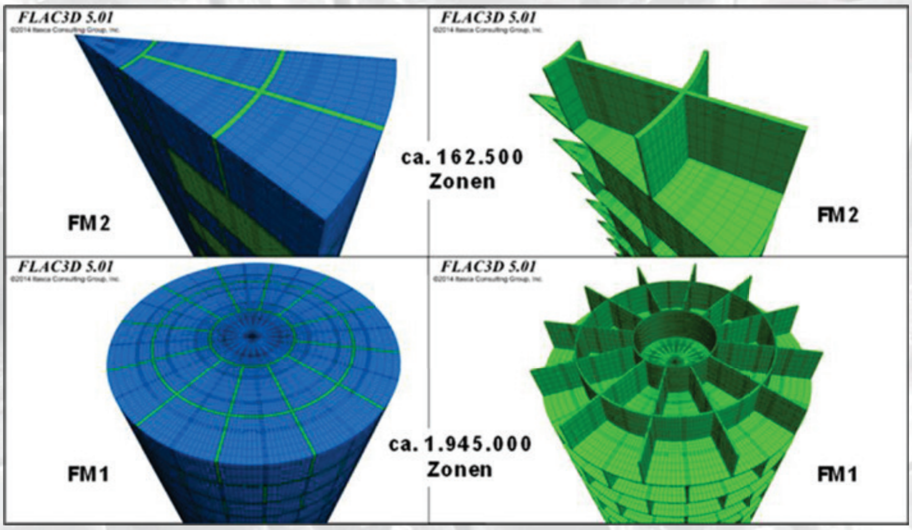
lab tests to determine failure strength, dilation strength, creep behaviour of rock salt used for salt bricks





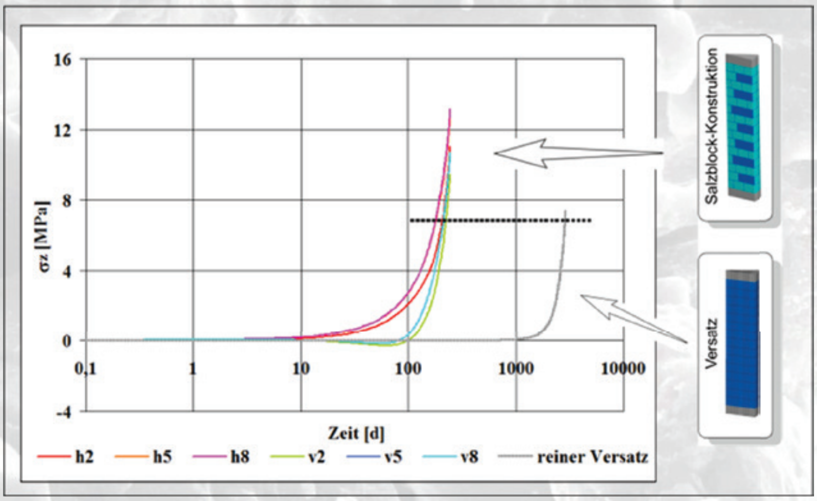
numerical investigations – meshing of bricks and gaps

calculation models → meshing, imaging bricks and gap filling, boundary conditions



numerical investigations – load bearing behavior

preliminary investigations regarding the mechanical load bearing behaviour of a sealing system made by salt bricks with gap filling by crushed salt



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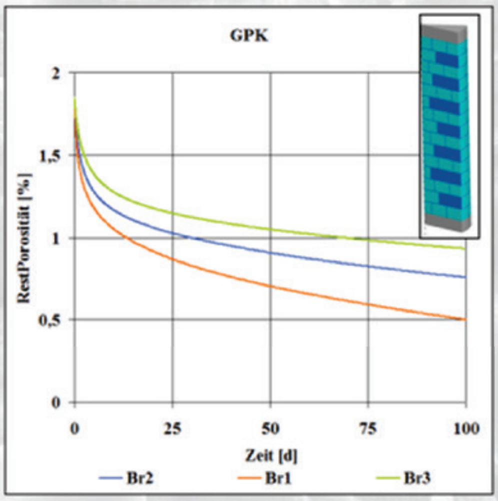

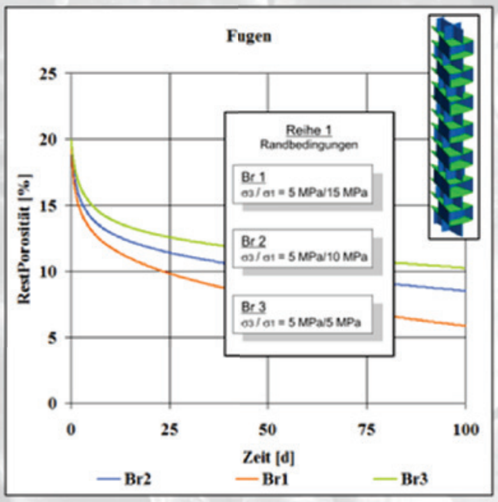

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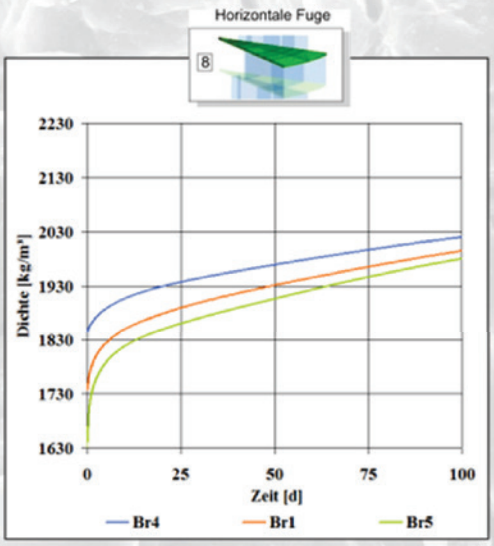

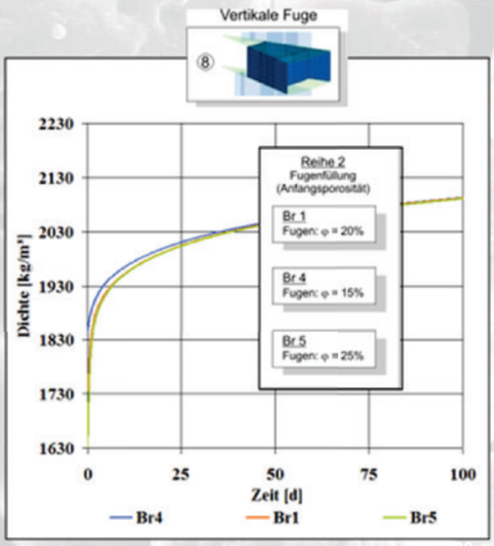

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(1) funding a big challenge

(2) acceptance to continue research work in 2018 – 2021

Thanks to scientific team

(1) scientific assistants Dr.-Ing. Lerche; Dr.-Ing. Dyogdyev; Dipl.-Math. Feierabend

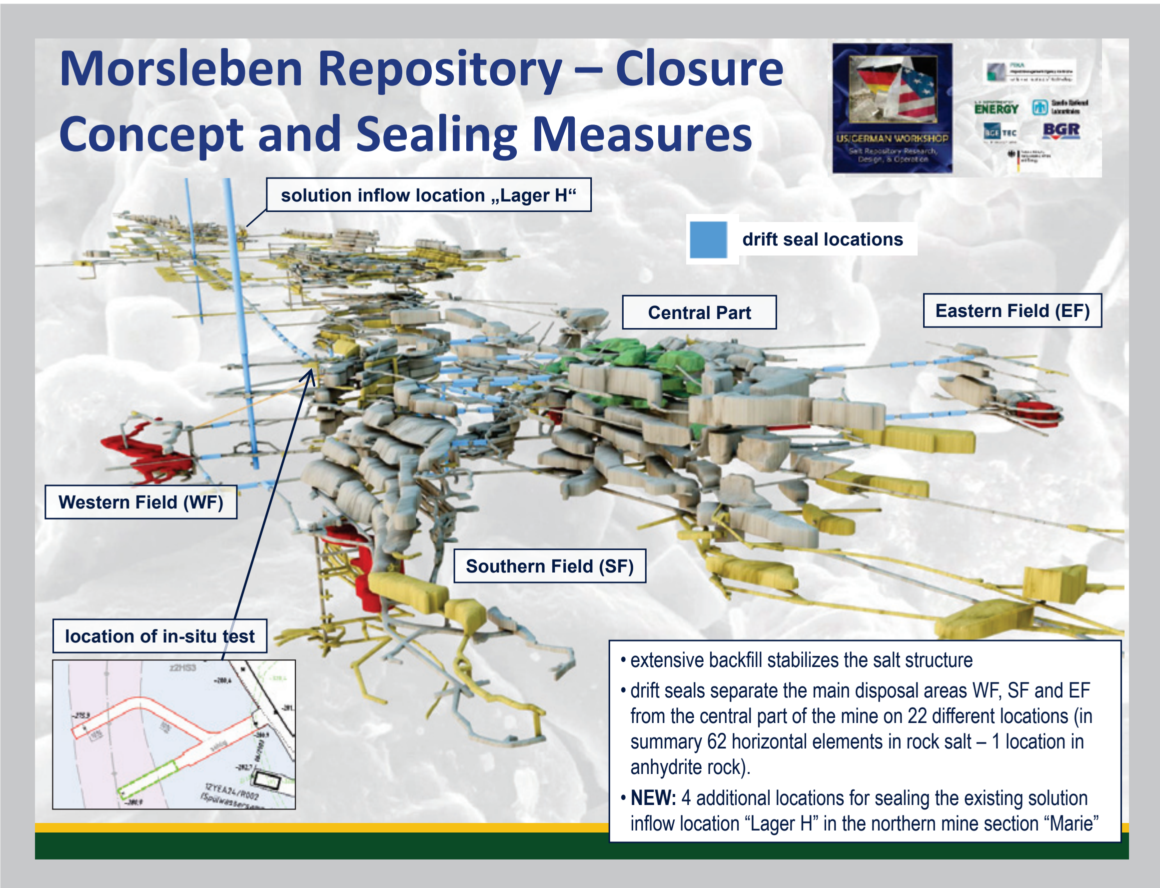
(2) technical assistants Niens, Lohrengel, Belo, Joachim

Final report available after approval by PTKA

Funded by Federal Ministry for Economic Affairs and Energy

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

J. Wollrath, R. Mauke, M. Kreienmeyer, A. Carstensen



In-Situ Test – Construction Design and Geotechnical Measurements

Measurements on in-situ test

requirements of concrete technology (e. g. temperatures, stresses, displacements strength, Young's modulus, porosity, permeability)

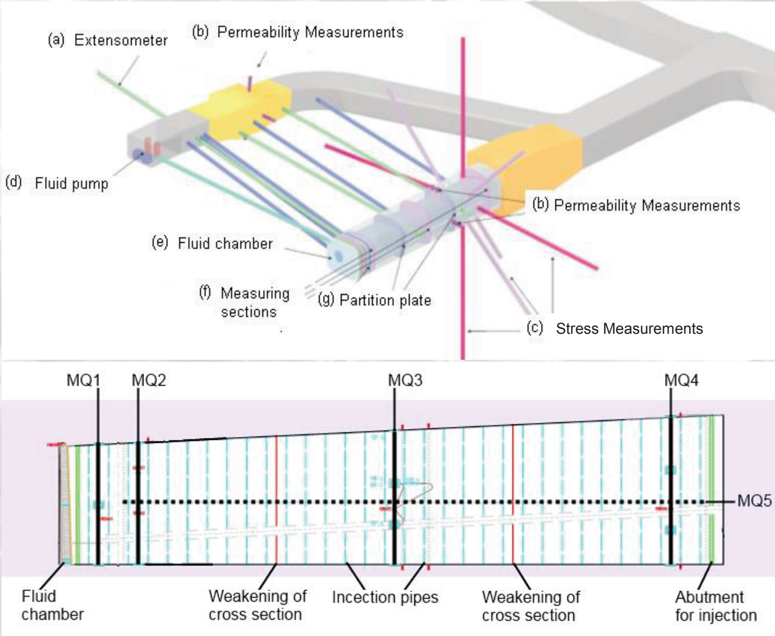
connection of concrete to the rock salt (e. g. cores from the contact zone)

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

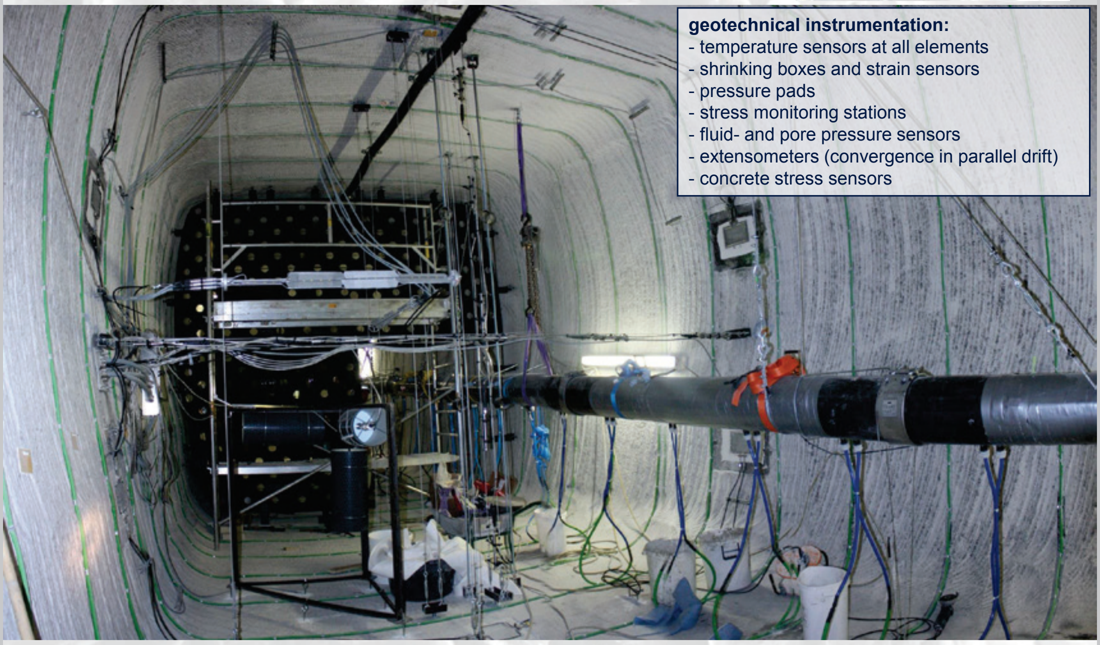
injectability of the contact zone

mechanical stability of location

prediction of stresses and deformations with calibrated numerical analysis



In-Situ Test – Construction Design and Geotechnical Measurements



geotechnical instrumentation:
- temperature sensors at all elements
- shrinking boxes and strain sensors
- pressure pads
- stress monitoring stations
- fluid- and pore pressure sensors
- extensometers (convergence in parallel drift)
- concrete stress sensors

In-Situ Test – View of the Construction

dimension of the construction: height: 3.7 m to 5.0 m, width: 4.6 m, length: 25 m
(this real full scale experiment represent a typical drift seal profile.)

aspects reported on 4th US/German workshop in Berlin (09/2013)

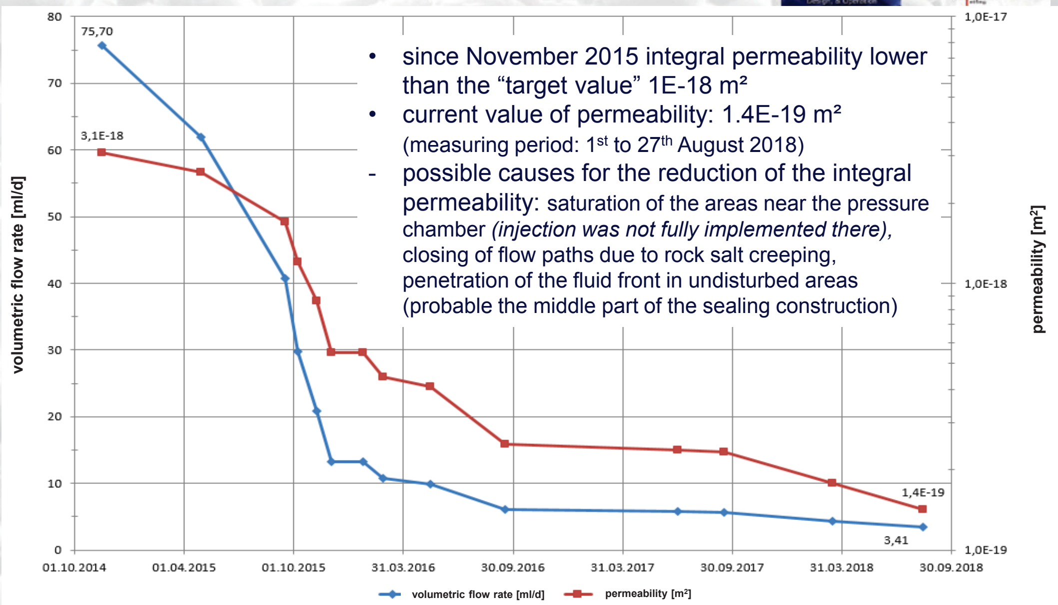
- continuation of the geotechnical measurements
- micro-section or thin section analyses of core samples
- investigation program on core samples (permeability)
- hydraulic main test (1st and 2nd period)
- first results of numerical calculations to estimate the integral permeability
- new findings (e.g. obviously unfavorable corrosion properties of the salt concrete, unexplained crack propagation)

main statements: low level of integral permeability give strong evidence for assumed functionality, but other necessary improvements were identified.

Further Investigations – since last Presentation at 4th Workshop

- **Continuation of the geotechnical measurements** – ongoing (partial failure of sensors)
- **Continuation of the hydraulic main test (cp 0.7 MPa from March 2013 up to now)** – will continue as long as useful (very low permeability level of less than 2E-19 m² in March 2018)
- **Additionally investigation program on core sample and in bore holes from the working face** (repetition of hydrofrac and permeability measurements, crack detection) – non-destructive crack detection from the working face is mostly completed, additional hydrofracing and more exploration drilling is ongoing
- **Execution of additional computations to evaluate the overall functional tests** (successive (best fit)-estimation of the integral permeability) – largely completed
- **Completion of the detailed planning phase (site specific exploration of all 22 + 4 new locations, transmission of (standard-)verifications and construction planning)** – completed for the present – but revision planned (e.g. for other sealing materials depending on the expected magnesium content of the solution)
- **Examination for evidence of crack limitation for drift seals in rock salt from salt concrete** (check of various technical measures concerning its effects on the reduction of the risk of cracking to serve as a basis for further planning) – completed for the present – but review planned by external experts

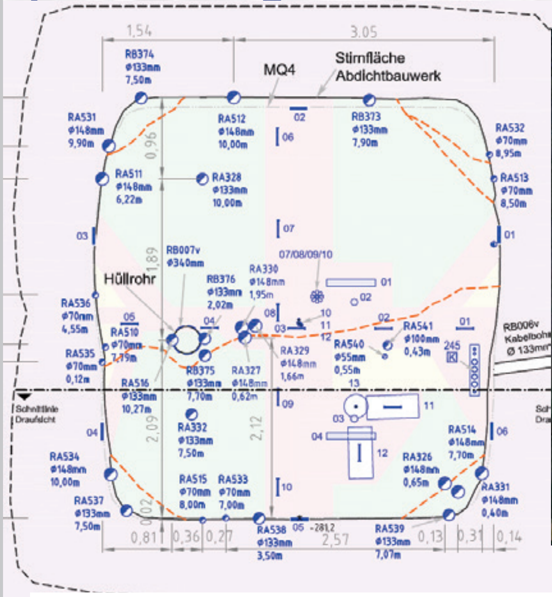
In-situ Experiment - Volumetric Flow Rate and Integral Permeability

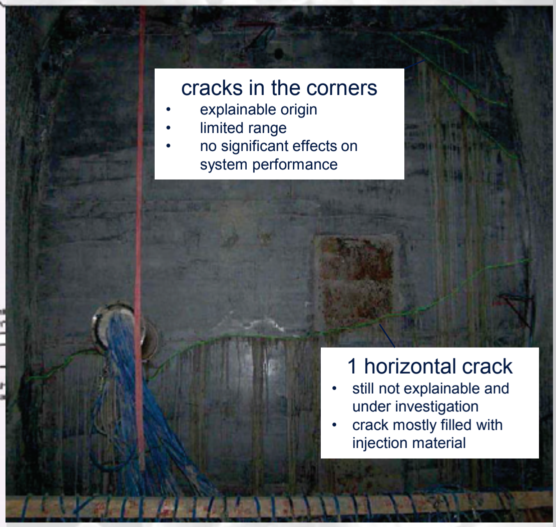


- since November 2015 integral permeability lower than the "target value" 1E-18 m²
- current value of permeability: 1.4E-19 m² (measuring period: 1st to 27th August 2018)
- possible causes for the reduction of the integral permeability: saturation of the areas near the pressure chamber *(injection was not fully implemented there)*, closing of flow paths due to rock salt creeping, penetration of the fluid front in undisturbed areas (probable the middle part of the sealing construction)

for more results see: R. Mauke et al. In situ-Versuch für ein Abdichtbauwerk im Steinsalz im ERAM - aktuelle Ergebnisse und Erkenntnisgewinn Fachgespräch "Verschlusssysteme – Konzepte, Baustoffe, Simulation, Demonstration und Anwendung", Freiberg, 03./04.05.2017

Additional Investigation Program (i.e. Drilling for Crack Detection)





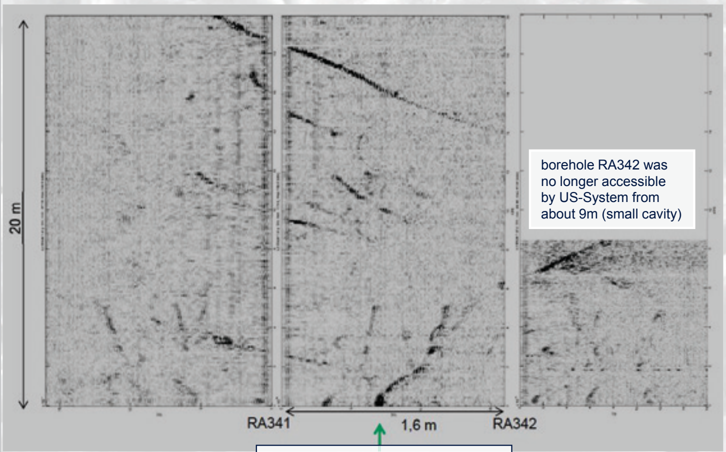
Crack investigation by boreholes and ultrasonic measurements are ongoing. More boreholes are planned to proof the assumption that the horizontal crack extends at most until the first partition plate (approx. 8m).

Non-destructive (Ultrasonic) Investigation for Crack Detection

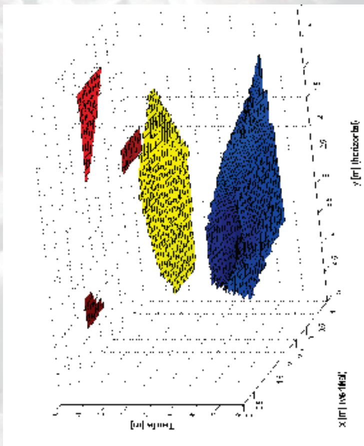
- reflection measurement from boreholes and transmission measurement between boreholes with new developed ultrasonic device for boreholes (here: 6 transmitting and 6 receiving point dry contact transducers)
- LAUS-System (Large Aperture Ultrasonic System – 12 units, each hosting 32 shear wave transducers) for testing of thick concrete structures from the working face (penetration depth up to 6 m - tested at backfilled mining room)

objective: Non-destructive proof of the integrity of a sealing structure including the contact zone

Non-destructive (Ultrasonic) Investigation for Crack Detection



visible crack at backfilling face



left: reflection image around and between two boreholes based on ultrasonic echo measurements

right: example of an actual result of LAUS measurement at the in-situ test site of a drift seal system in rock salt *(3d-illustration of reflectors parallel to the working face – “blue”: near the first partition plate, “yellow”: at about 3m - partially verified by core drilling, “red”: near the airside or working face)*

In-Situ Test – Lessons Learned and Future Investigations

Successful production of the in-situ test structure proofs its principal technical feasibility (see also proceedings at 2nd, 3rd, 4th and 6th Workshop). Any technical "lessons learned" were reported to consider them in the future.

The presented results of the fluid pressure tests show that an integral permeability of lower than 1.0E-18 m^2 is achievable.

Local pathways (cracks) are observed, although the in situ-test plan (due to salt concrete technology) **has been fulfilled.**

Technical measures are available to limit the risk of cracks (e.g. more partitioning plates, cooling of concrete, construction of blocks, …). A review is planned by external experts.

Nevertheless, the aspect of corrosion has to be investigated further (a lower pore-diffusion-coefficient of the salt concrete leads to changes in corrosion properties - this leads to calculated significantly shorter corrosion times particularly taking into account micro cracking of salt concrete)**. Therefore, currently different corrosion investigations are carried out.**

The pressure test will continue as long as the testing device is functioning (possibly with higher pressures).

Among other things, the middle segment will be examined with ultrasonic measurements in boreholes in the next year.

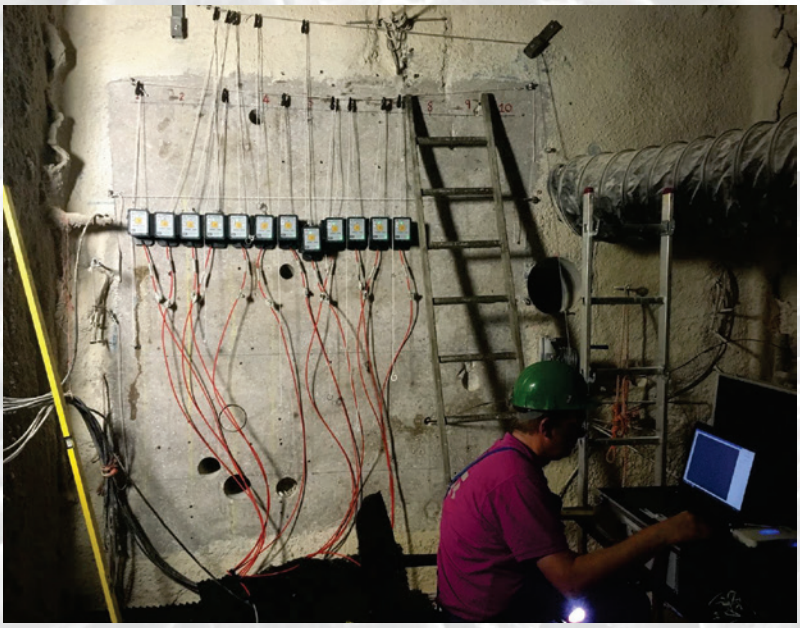
Drift Seal Systems – New Working Program of BGE

Especially there is (currently) no clear proof of crack limitation available, corrosive solutions could penetrate the sealing structure in the long term.

BGE started a new working program following these main issues:

- **Evaluation of the chemistry of the solutions as accurate as possible (especially in terms of Mg content) -** location-specific investigations are are currently taking place
- **Evaluation of different designs and sealing materials** (salt-concrete and MgO-concrete-systems also as shotcrete to limit the high setting temperature), if necessary other materials like bitumen, etc.)
    - salt concrete (verification of corrosion behavior, adaptation of building design, etc.)
    - MgO-concrete (adaption of "Asse"-seals experience, s. next presentation "Industrial Planning and Construction of Drift Seals in the Asse Mine")
    - MgO-shotcrete (comparable to the large-scale test GV2 in the mine of Teutschenthal - R&D-project "MgO-SEAL") - at present, LAUS measurements are taking place
- **Replication of in-situ experiments** (if necessary with less internal measuring instruments)
- **Re-run of the long term safety assessments incl. detailed planning** (with the real reachable hydraulic and geochemical properties of the drift seals)

LAUS Measurements at the MgO-Shotcrete Dam in Teutschenthal



recent measurements by BAM on 27./28.08.2018:

- measurements showed penetration depth of several meters
- this result leads to the expect that it is possible to demonstrate the integrity of a seal made of MgO-shotcrete with this method, too

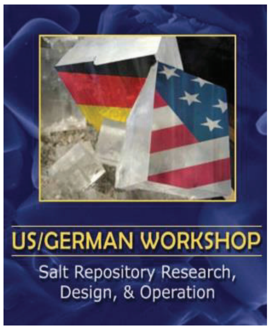
Thank You for Your Attention !

M. Heydorn, J. Adelt, N. Müller-Hoeppe, A. Hofschlag, T. Meyer, L. v. Borstel

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

9th US/German Workshop "Salt Repository Research, Design, and Operation"

Industrial Planning and Construction of Drift Seals in the Asse Mine



September 10th, 2018

Matthias Heydorn, Joachim Adelt, BGE

Dr. Nina Müller-Hoeppe, Astrid Hofschlag, Thomas Meyer, Dr. Liselotte v. Borstel, BGE TECHNOLOGY GmbH

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1

STRUCTURE

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Contents

1. Overview (location mine, history, and key data)
2. Characteristics Asse mine
3. Basic concept regarding flow barriers
4. Overview pilot constructions and routine operations
5. Process description (planning - construction and construction supervision)
6. State of implementation / outlook

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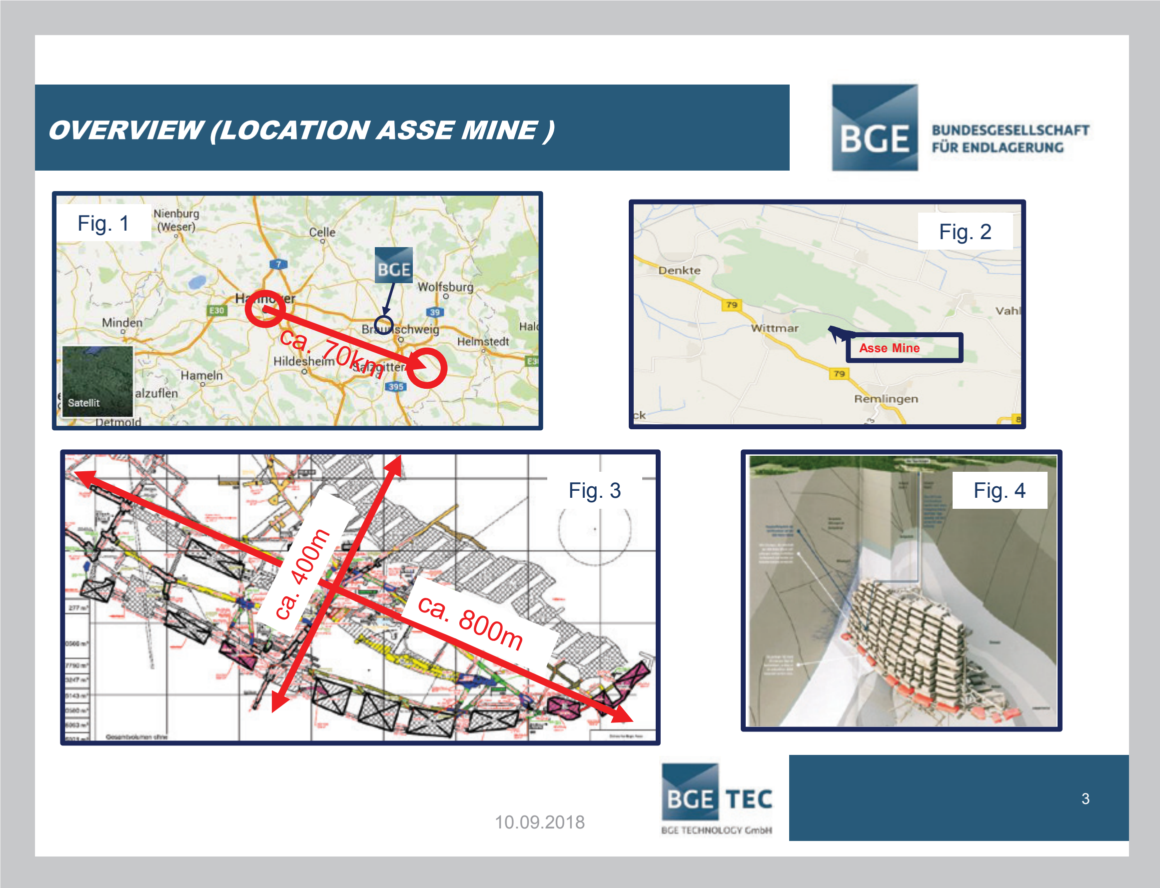
OVERVIEW (LOCATION ASSE MINE)
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
Fig. 1
Nienburg (Weser)
Celle
Wolfsburg
Minden
Braunschweig
Helmstedt
Hildesheim
Hameln
Detmold
Satellit
ca. 70km
Fig. 2
Denkte
Wittmar
Asse Mine
Remlingen
Fig. 3
ca. 400m
ca. 800m
Fig. 4
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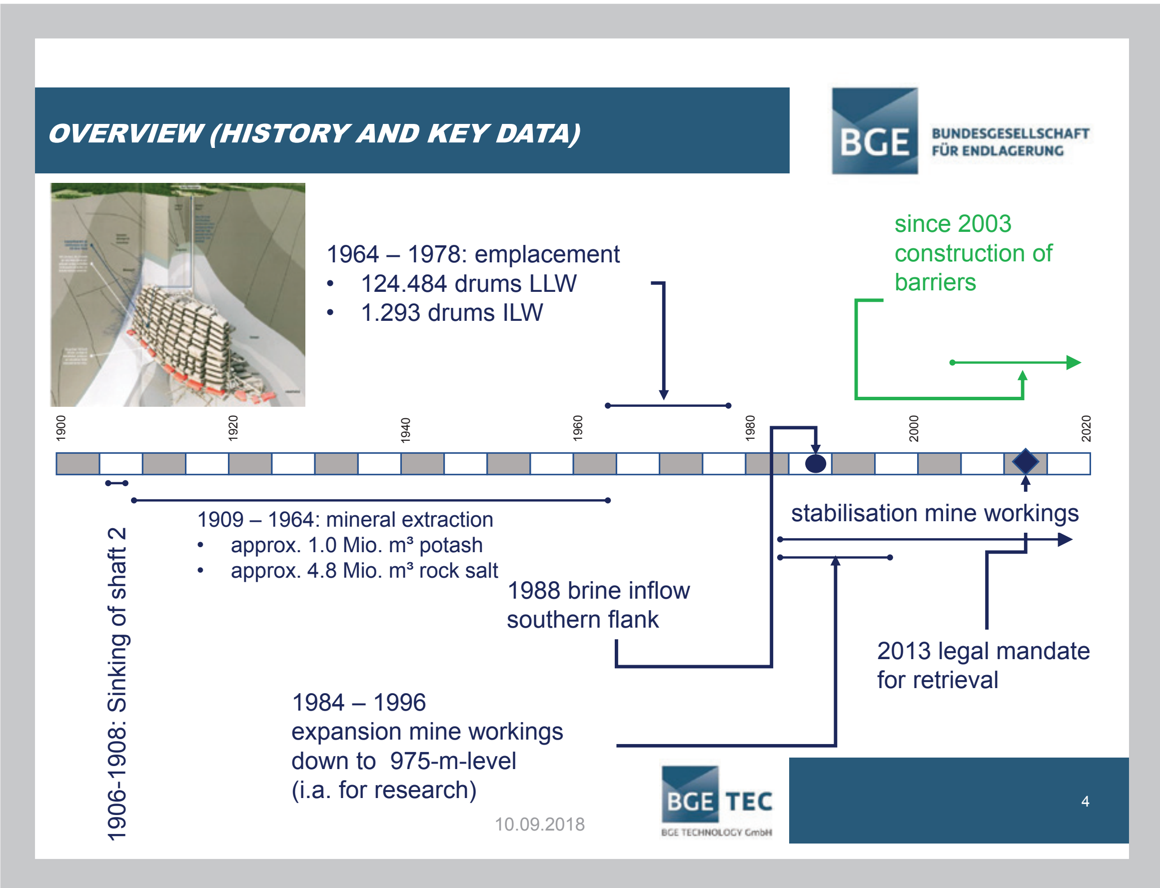
OVERVIEW (HISTORY AND KEY DATA)
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
1964 – 1978: emplacement
• 124.484 drums LLW
• 1.293 drums ILW
since 2003 construction of barriers
1900
1920
1940
1960
1980
2000
2020
1906-1908: Sinking of shaft 2
1909 – 1964: mineral extraction
• approx. 1.0 Mio. m³ potash
• approx. 4.8 Mio. m³ rock salt
1988 brine inflow southern flank
stabilisation mine workings
2013 legal mandate for retrieval
1984 – 1996 expansion mine workings down to 975-m-level (i.a. for research)
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Characteristics Asse Mine

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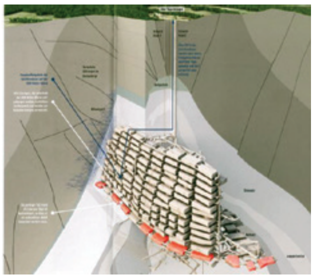
- high excavation level
- open carnallitite areas
- to some extent, damaged rock areas
- radioactive waste emplaced
- brine inflow



Emergency plan to minimise the consequences of excessive brine inflow

i.a. preventive measures
- to stabilise the mine workings
- to protect the emplacement chambers

Installation of geotechnical structures (e.g. flow barriers)

Material ?

Technique ?

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5

BASIC CONCEPT - MATERIAL SELECTION -

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- mechanical and chemical long-term resistance in salinary environment against saturated $MgCl_2$ solution (to maintain effectiveness of the structures)
- compatibility with the host rock (saliniferous formation)
- low permeability
- sufficient stability and stiffness
- at least volume constancy (no diminution, shrinkage) or volume expansion (swelling)
- as easy to handle as possible with little technical effort

Magnesia binder

- 100 a experience in salt mining

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BASIC CONCEPT - CONSTRUCTION PRINCIPLE -

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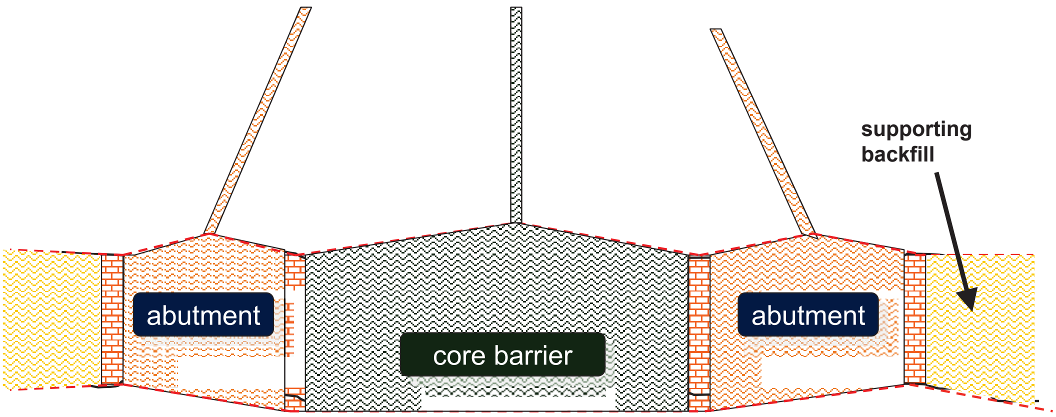
Finish: Concreting of the core barrier (complete)



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OVERVIEW PILOT CONSTRUCTIONS AND ROUTINE OPERATIONS

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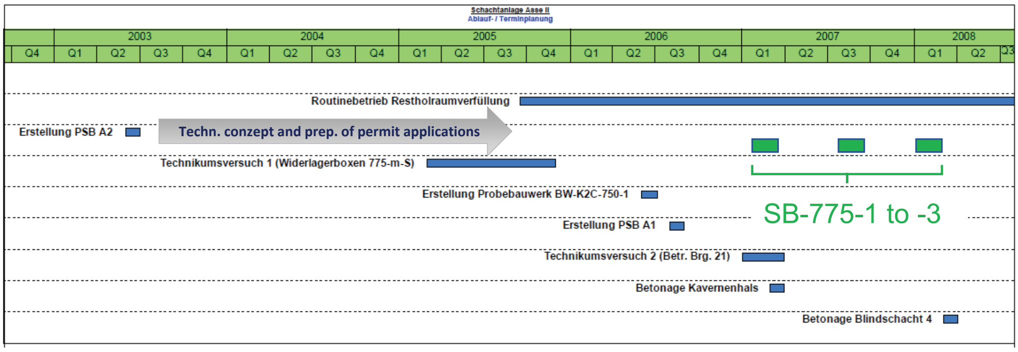

Amount of sorel concrete placed so far: ~ 342,000 m³

thereof flow barrier: ~ 14,700 m³
thereof abutment: ~ 33,400 m³
thereof supporting backfill: ~ 61,900 m³

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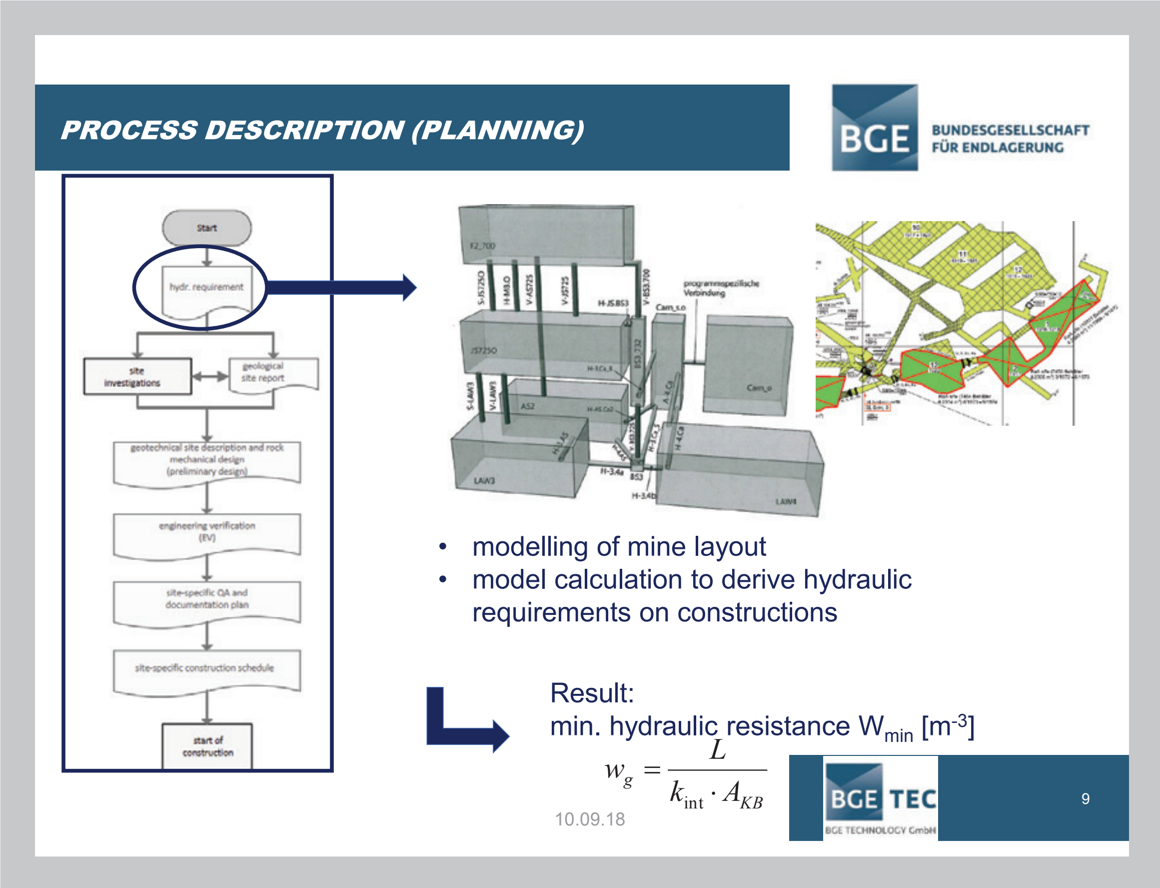
PROCESS DESCRIPTION (PLANNING)
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
Start
hydr. requirement
site investigations
geological site report
geotechnical site description and rock mechanical design (preliminary design)
engineering verification (EV)
site-specific QA and documentation plan
site-specific construction schedule
start of construction
• modelling of mine layout
• model calculation to derive hydraulic requirements on constructions
Result:
min. hydraulic resistance W_{min} [m^{-3}]
$w_g = \frac{L}{k_{int} \cdot A_{KB}}$
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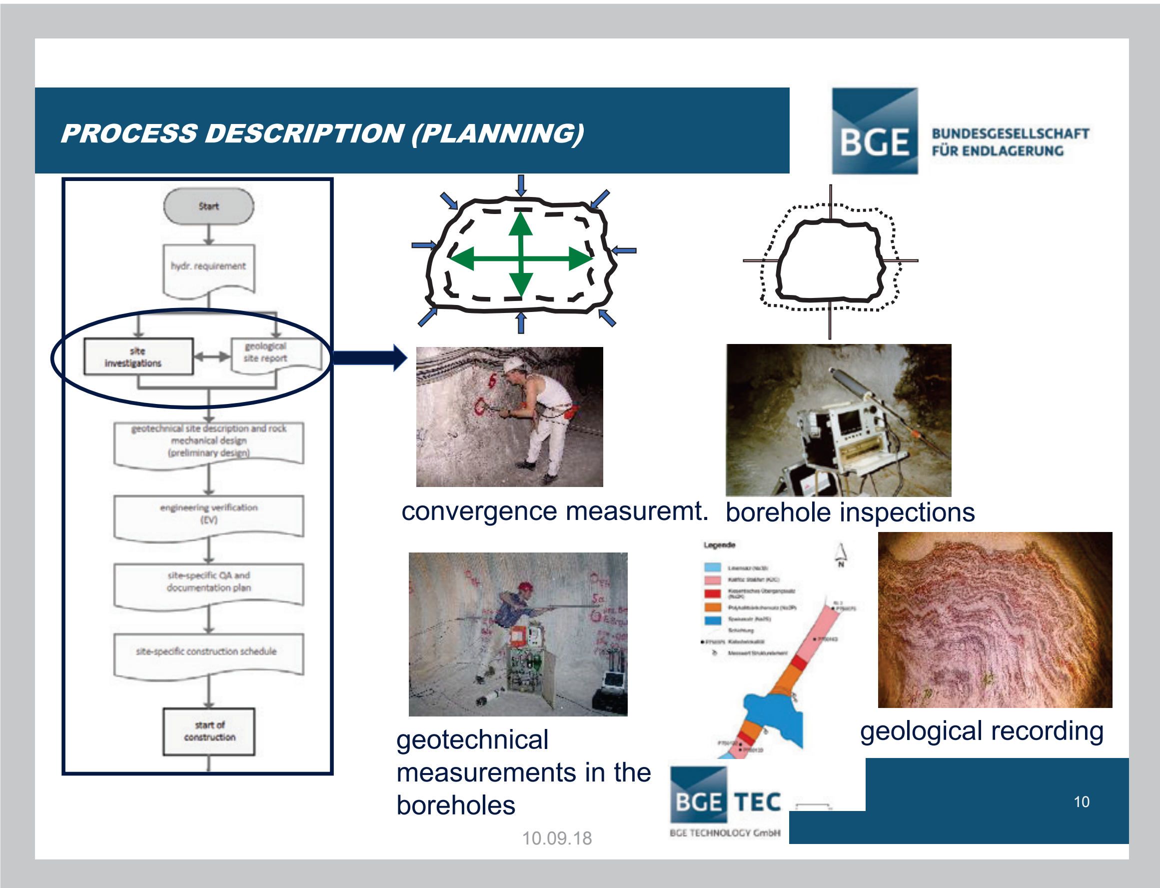
PROCESS DESCRIPTION (PLANNING)
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
Start
hydr. requirement
site investigations
geological site report
geotechnical site description and rock mechanical design (preliminary design)
engineering verification (EV)
site-specific QA and documentation plan
site-specific construction schedule
start of construction
convergence measuremt.
borehole inspections
geotechnical measurements in the boreholes
geological recording
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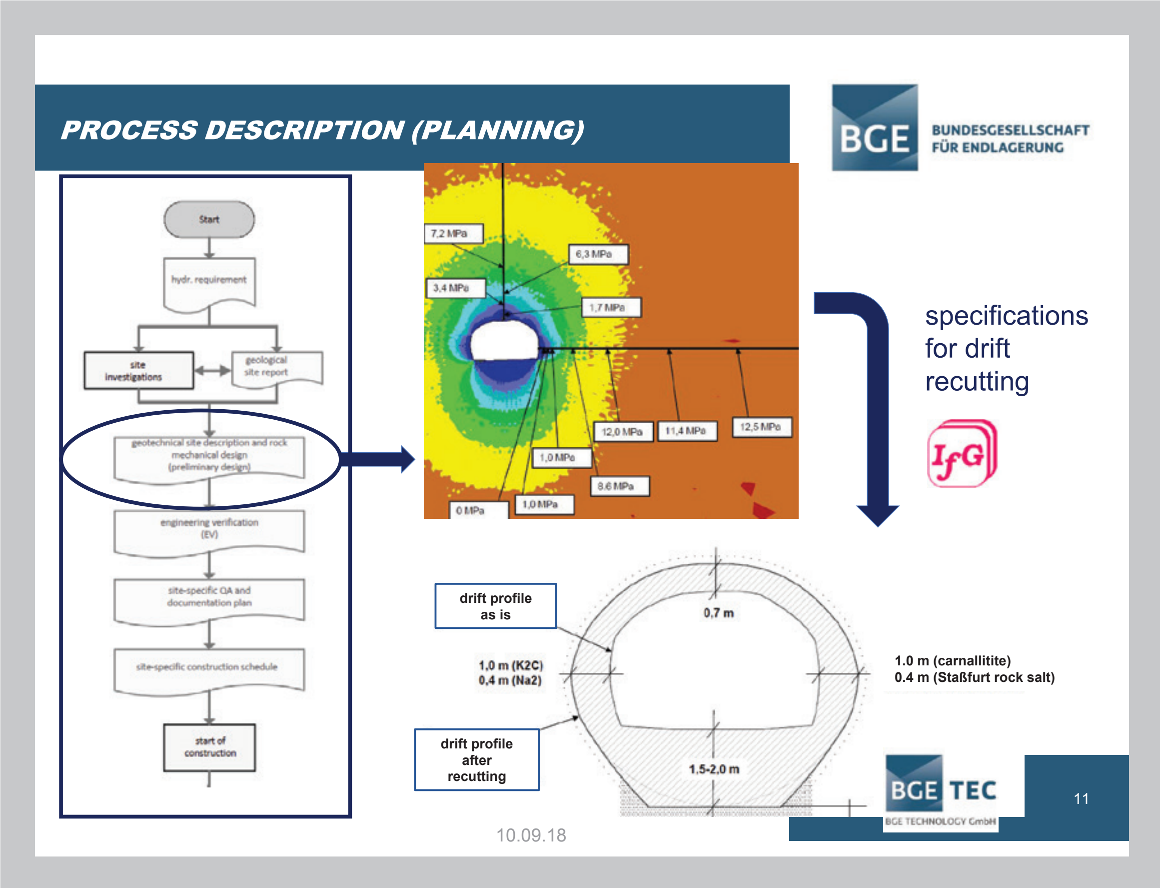
PROCESS DESCRIPTION (PLANNING)
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
Start
hydr. requirement
site investigations
geological site report
geotechnical site description and rock mechanical design (preliminary design)
engineering verification (EV)
site-specific QA and documentation plan
site-specific construction schedule
start of construction
7,2 MPa
6,3 MPa
3,4 MPa
1,7 MPa
12,0 MPa
11,4 MPa
12,5 MPa
1,0 MPa
8,6 MPa
0 MPa
1,0 MPa
specifications for drift recutting
IfG
drift profile as is
0,7 m
1,0 m (K2C)
0,4 m (Na2)
1.0 m (carnallitite)
0.4 m (Staßfurt rock salt)
drift profile after recutting
1,5-2,0 m
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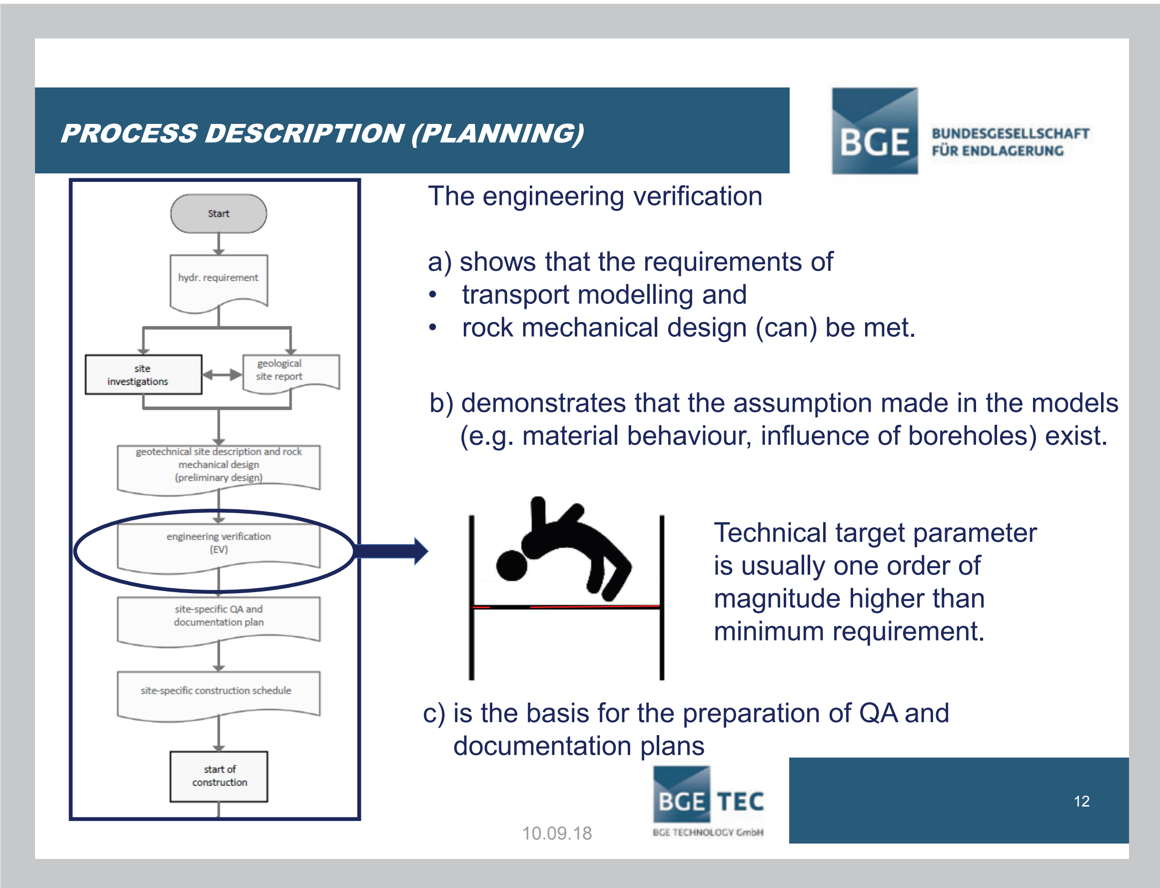
PROCESS DESCRIPTION (PLANNING)
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
Start
hydr. requirement
site investigations
geological site report
geotechnical site description and rock mechanical design (preliminary design)
engineering verification (EV)
site-specific QA and documentation plan
site-specific construction schedule
start of construction
The engineering verification
a) shows that the requirements of
• transport modelling and
• rock mechanical design (can) be met.
b) demonstrates that the assumption made in the models (e.g. material behaviour, influence of boreholes) exist.
Technical target parameter is usually one order of magnitude higher than minimum requirement.
c) is the basis for the preparation of QA and documentation plans
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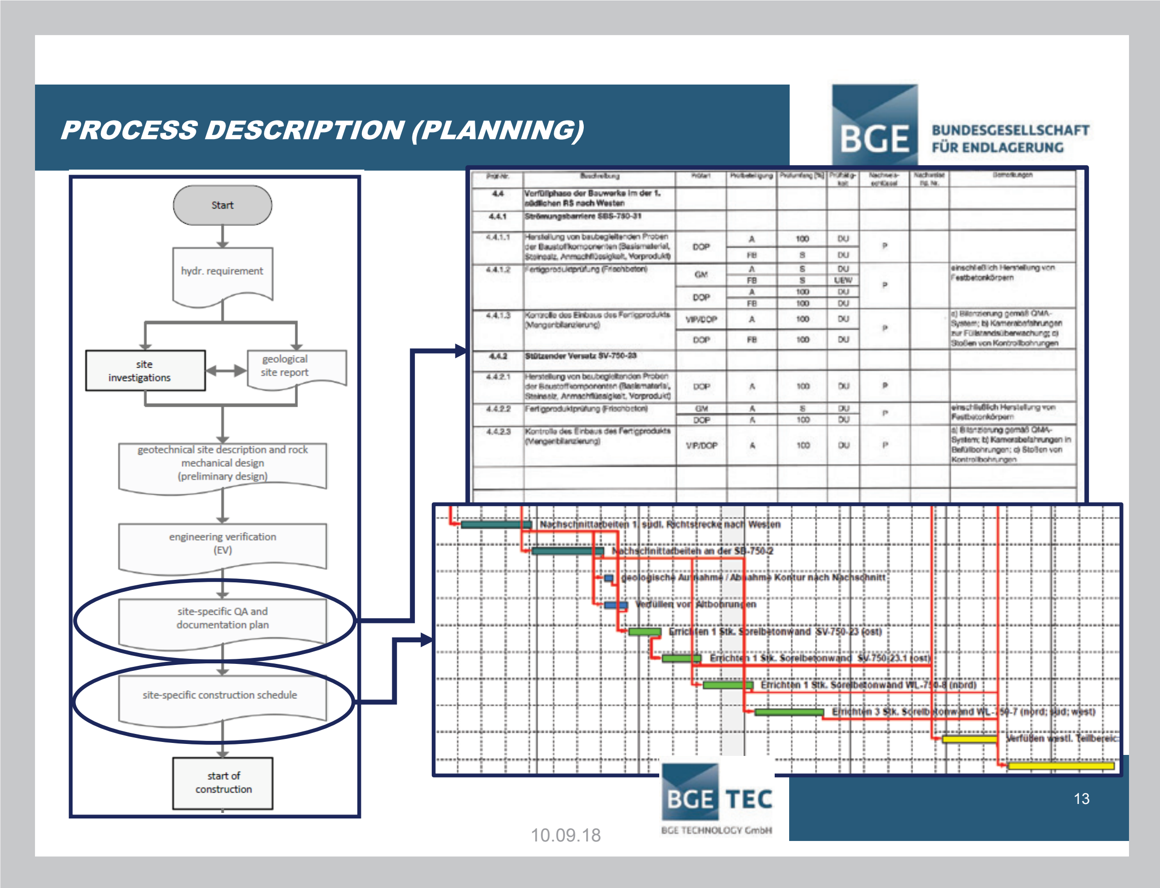

PROCESS DESCRIPTION (PLANNING)
BGE
BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
Start
hydr. requirement
site investigations
geological site report
geotechnical site description and rock mechanical design (preliminary design)
engineering verification (EV)
site-specific QA and documentation plan
site-specific construction schedule
start of construction
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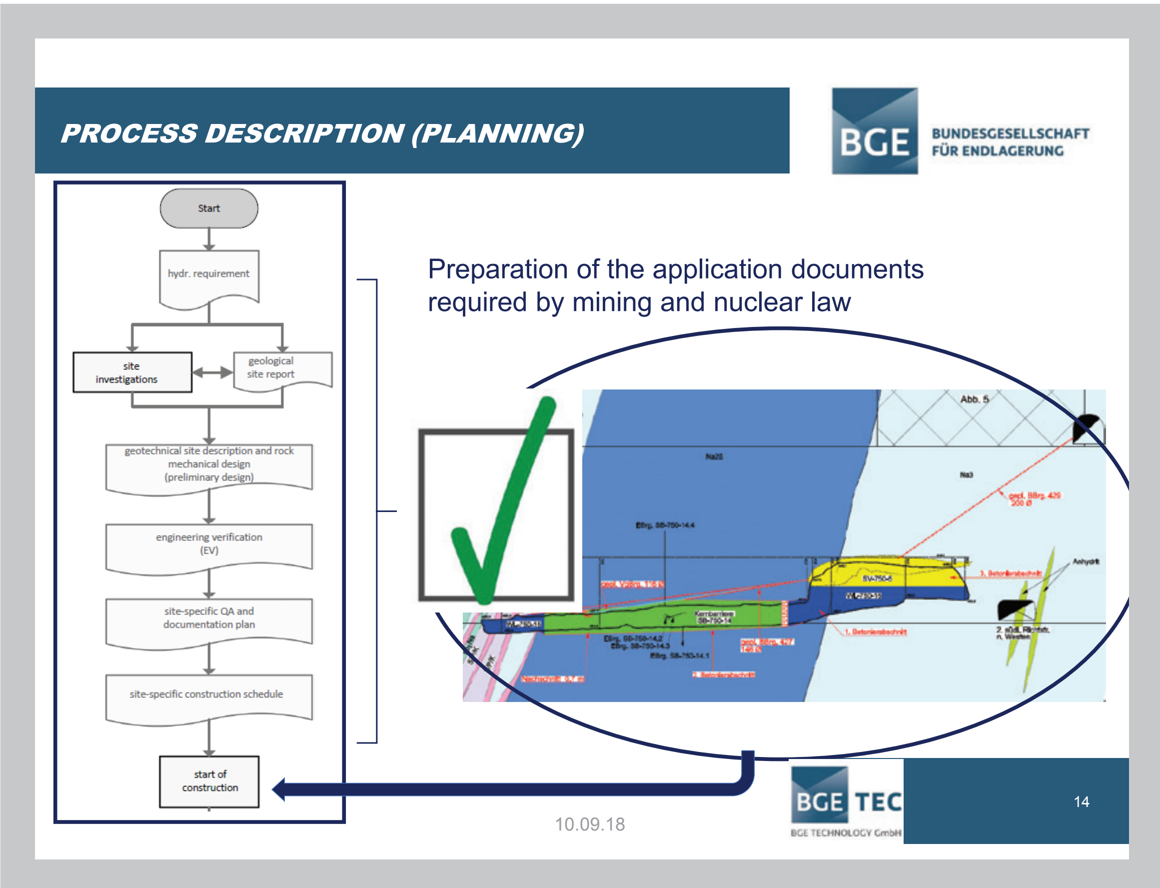
13



PROCESS DESCRIPTION (PLANNING)
BGE
BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
Start
hydr. requirement
site investigations
geological site report
geotechnical site description and rock mechanical design (preliminary design)
engineering verification (EV)
site-specific QA and documentation plan
site-specific construction schedule
start of construction
Preparation of the application documents
required by mining and nuclear law
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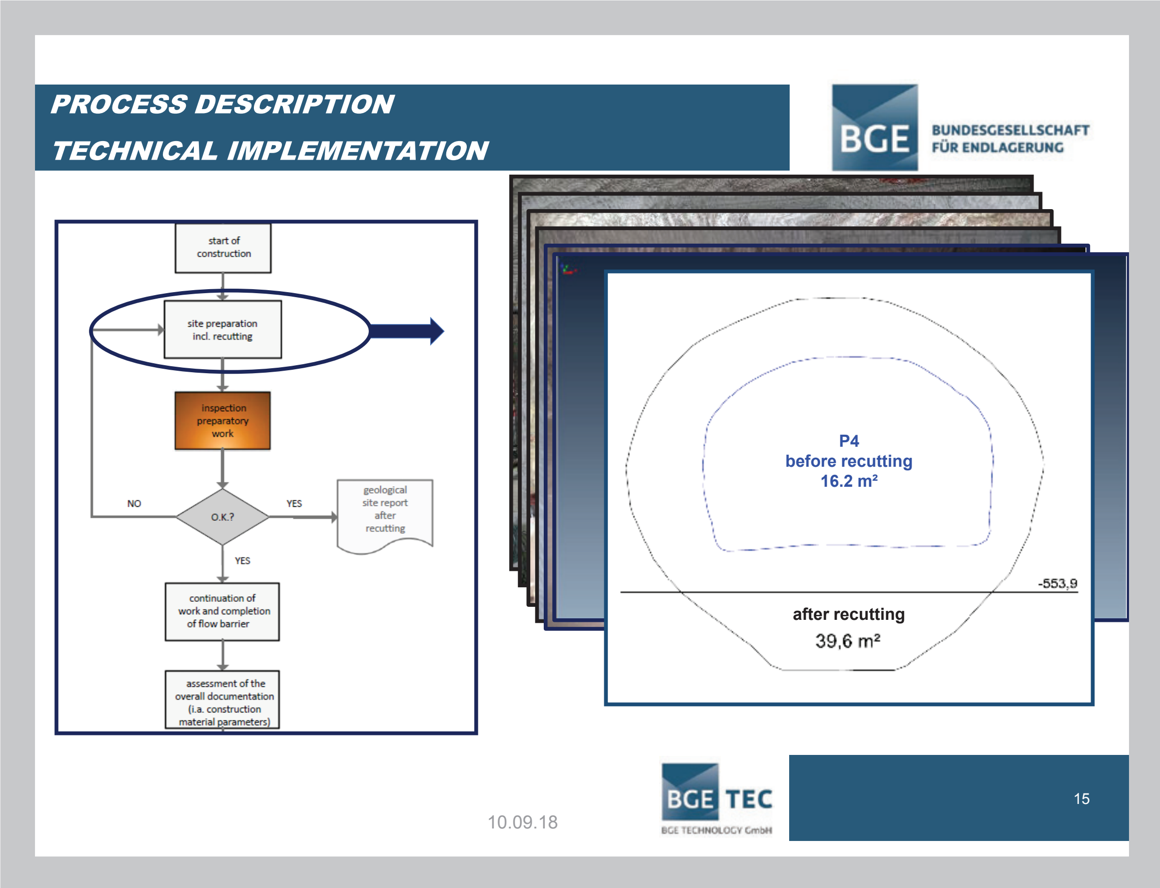
14


PROCESS DESCRIPTION
TECHNICAL IMPLEMENTATION
BGE
BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
start of construction
site preparation incl. recutting
inspection preparatory work
NO
O.K.?
YES
geological site report after recutting
YES
continuation of work and completion of flow barrier
assessment of the overall documentation (i.a. construction material parameters)
P4
before recutting
16.2 m²
-553,9
after recutting
39,6 m²
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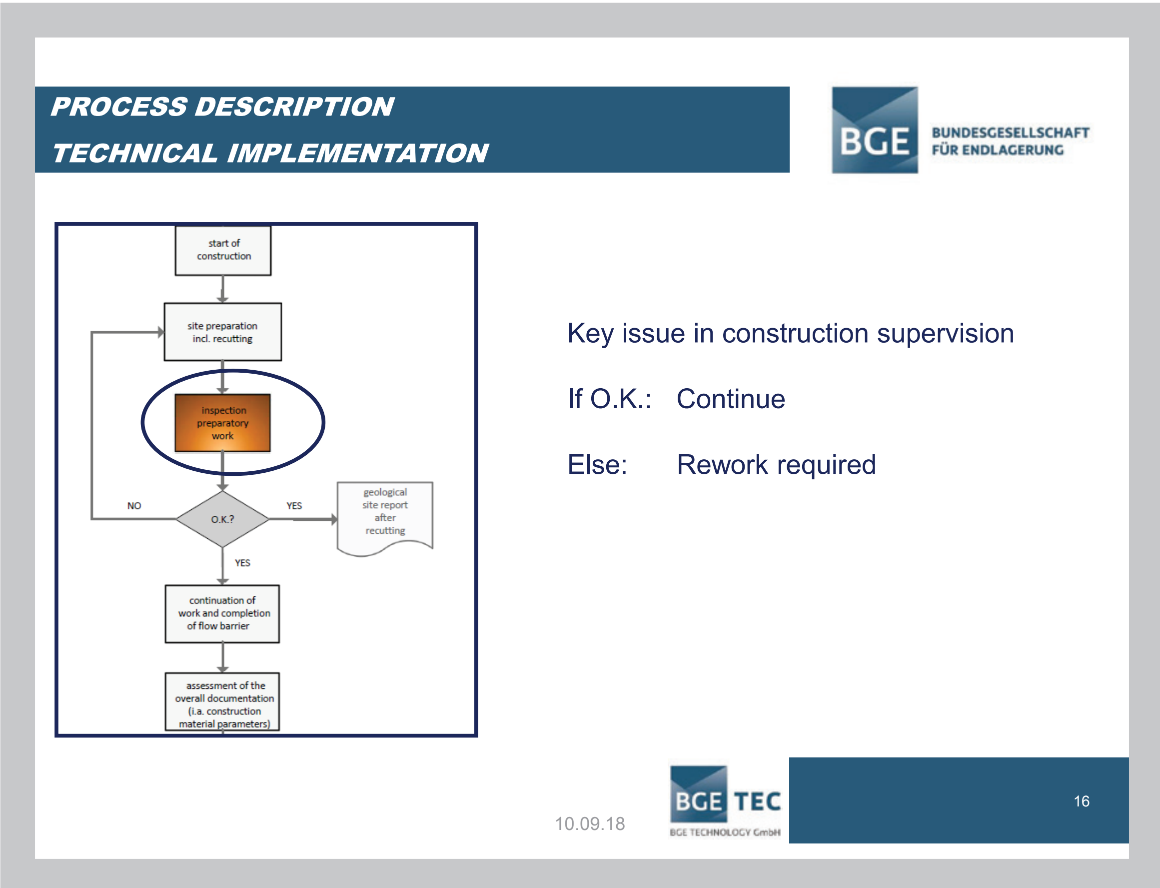
15


PROCESS DESCRIPTION
TECHNICAL IMPLEMENTATION
BGE
BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
start of construction
site preparation incl. recutting
inspection preparatory work
NO
O.K.?
YES
geological site report after recutting
YES
continuation of work and completion of flow barrier
assessment of the overall documentation (i.a. construction material parameters)
Key issue in construction supervision
If O.K.: Continue
Else: Rework required
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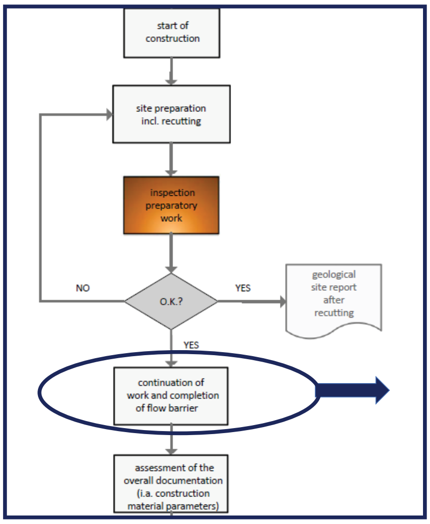
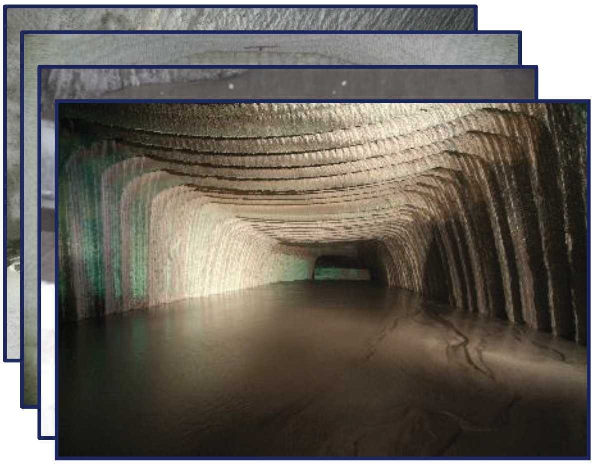
PROCESS DESCRIPTION
TECHNICAL IMPLEMENTATION

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG





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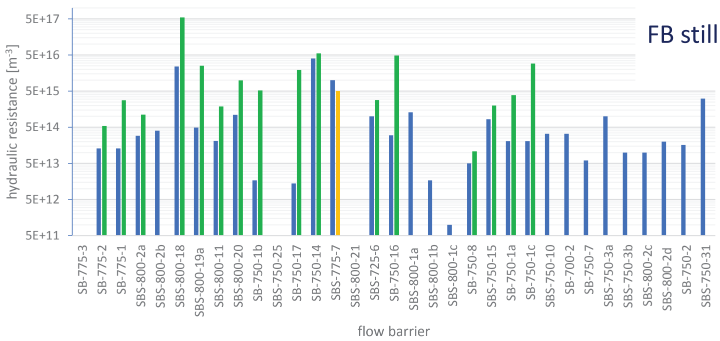
17

STATE OF IMPLEMENTATION AND OUTLOOK

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

No. of concreted FB:	32
Techn. D. carried out:	16
Compatibility requests:	1
FB still planned:	21



There was no specific hydraulic requirement for SB-775-3; it was constructed as a ‘prototype‘.

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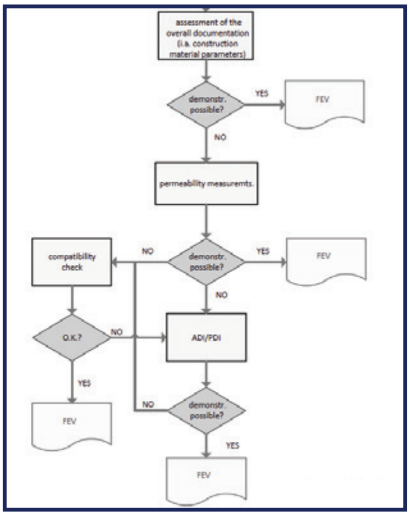
OUTLOOK

PROCESS DESCRIPTION (TECHNIC. DEMONSTR.)

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

The completion of a flow barrier is followed by a technical demonstration process. If necessary, the barrier is improved by mean of injections.



Thank you for your attention and 'Glück auf'!

10.09.18

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19

S. Dunagan


Operational Safety at WIPP and Its Impact
Sean Dunagan
Sandia National Laboratories
Hanover, Germany
September 10-11, 2018
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
PTKA
ENERGY
Sandia National Laboratories
BGE TEC
BGR
Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy. SAND2018-9539C


Overview
▪ WIPP Operational Safety Update
▪ Impact on Operations
▪ Impact Performance Assessment
▪ Impact on Design
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Salt Repository Research, Design, & Operation
ENERGY
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150
2

Safety Update

- Still Operating with limited ventilation
- Bolting still a priority
- Panel 7 Room 6
- Limited mining has resumed

3

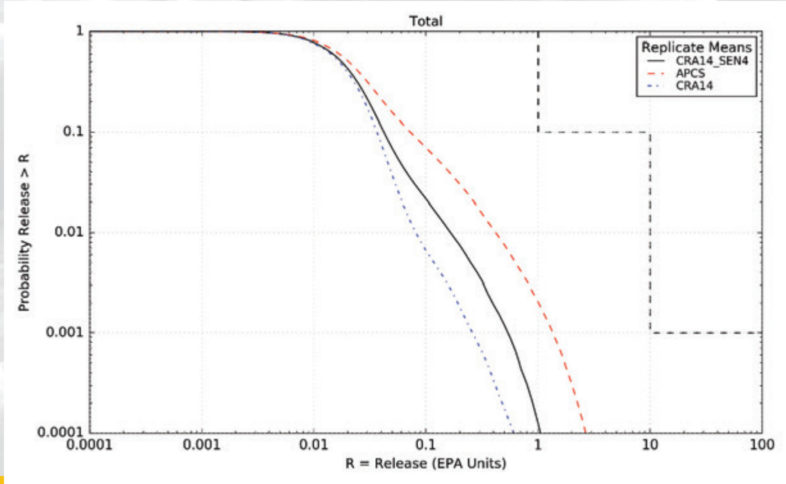
Operation Impacts

- Limited operations remain. Cannot emplace waste, mine, and perform bolting at the same time.
- Ventilation restrictions have impacted mining more than expected.
- Limited bolting shifts

4

Performance Assessment Impacts

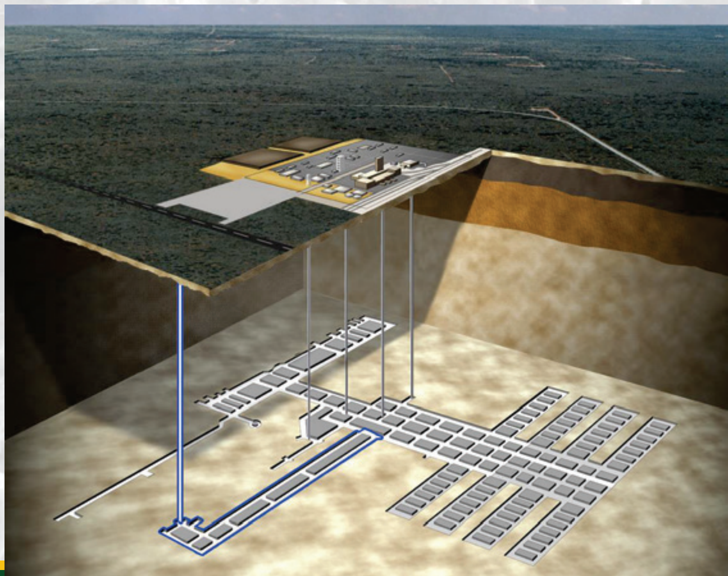
- Withdrawal from south end of mine due to ground control issues impacts PA.
  - No waste in planned panel 9
  - No Run-of-Mine salt closures in panels 3, 4, 5, and 6.



5

Design Impacts

- Ground safety has elevated the importance of the design for the new drifts to the new shaft to the West.



6

Operational Safety Summary

- Safety continues to impact various aspects of operations.
- Operational safety has impacted long-term performance.
- Future designs are desired that will limit ground control necessary to maintain core areas for extended periods of time.
- Ventilation restrictions continue to influence even limited operations.

7

QUESTIONS

8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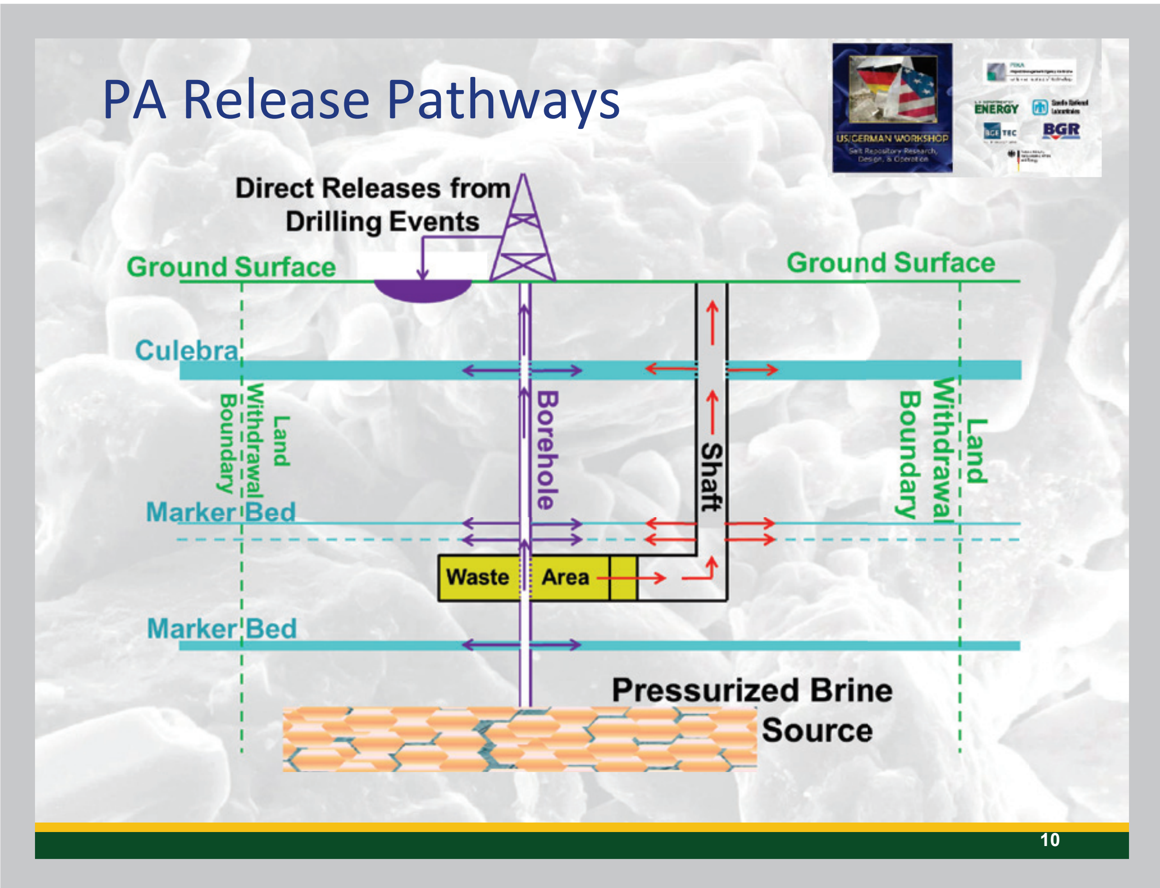
Backup Slides
9


PA Release Pathways
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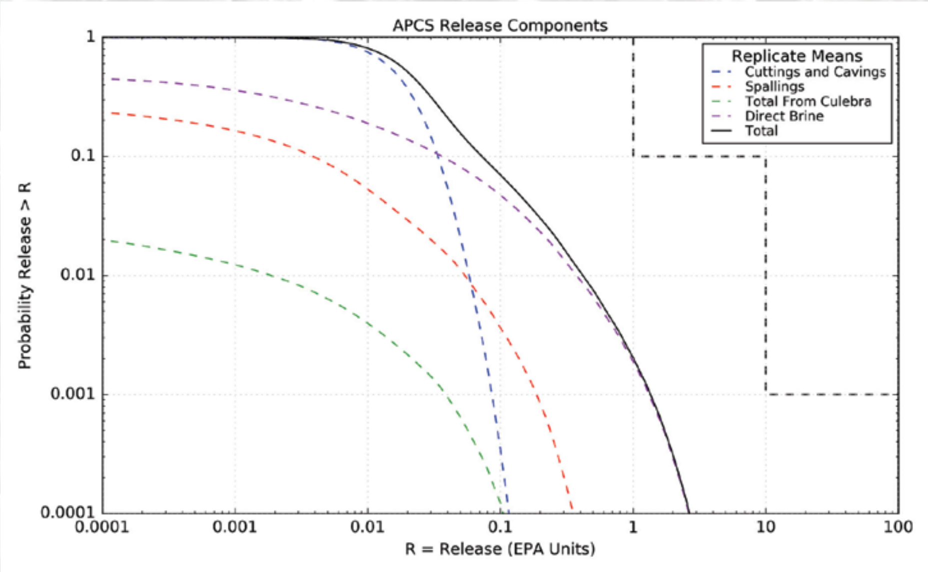
Direct Releases from
Drilling Events
Ground Surface
Ground Surface
Culebra
Land
Withdrawal
Boundary
Borehole
Shaft
Land
Withdrawal
Boundary
Marker Bed
Waste
Area
Marker Bed
Pressurized Brine
Source
10

APCS Release Components



11

APCS Conclusions

- The APCS analysis incorporates a conservative representation of the repository that addresses no panel closures in Panels 3, 4, 5, and 6 and no waste in Panel 9 (that could be located in a new panel to the north)
- The APCS analysis results demonstrate with a reasonable expectation that a modified design of the repository would continue to ensure compliance with all release limits

12

M. Altmaier, J. Mönig, L. Wissmeier

Geochemistry in support of potential emergency measures for Schachtanlage Asse II

PTKA

ENERGY

Sandia National Laboratories

BGE TEC

BGR

GRS, CSD, KIT-INE

Hanover, Germany

September 10-11, 2018

1

GRS CSDENGINEERS+ KIT

Geochemistry in support of potential emergency measures for Schachtanlage Asse II

1. Introduction (KIT-INE)
2. Conceptualization of Radionuclide Source Term (GRS)
3. Modeling the Geochemical Evolution and Gas Formation in Disposal Chambers of the ASSE II (CSD)
4. Radionuclide source terms, solubility and retention processes (KIT-INE)

2

M. Altmaier, J. Mönig, L. Wissmeier,

Geochemistry in support of potential emergency measures for Schachtanlage Asse II

1. Introduction

US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation

Hanover, Germany
September 10-11, 2018

3

Key data

Source: BGE

Asse II Mine

- Waste emplacement: 1967-78
- Low and Intermediate Level Waste
- Inflow of saline solution from the overburden since 1988
- Retrieval (2013 task by law)

4

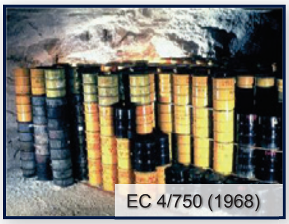
History

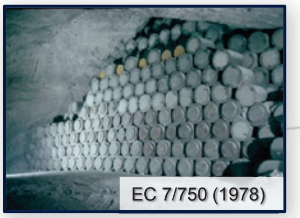
- 1909 – 1964 Mine for potash and rock salt in Lower Saxony.
- 1965 Federation buys the mine for exploration of disposal of radioactive waste (operators responsible: GSF – HMGU*).
- 1967 – 1978 disposal of Low and Intermediate Level Waste (ca. 47000 m^3).
- since 1988 Inflow of saline solution from overburden (daily ca. 11.5 m^3).
- 2009 – 2017 operator responsible BfS**.
- 2013 Implementation of “Lex-Asse” (§ 57 b AtG). The new law creates an important legal basis for the retrieval of radioactive waste.
- since 25.05.2017 responsible operator: BGE***.

** GSF - Gesellschaft für Strahlen- und Umweltforschung (Society for Radiation Research) _ 2008 HMGU- Helmholz Zentrum München*
*** BfS – Bundesamt für Strahlenschutz (Federal Office for Radiation Protection)*
**** BGE - Bundesgesellschaft für Endlagerung mbH (Federal Company for Radioactive Waste Disposal)*

5

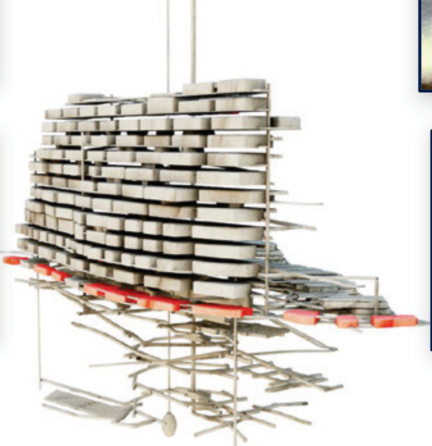
Emplacement of radioactive waste


EC 4/750 (1968)

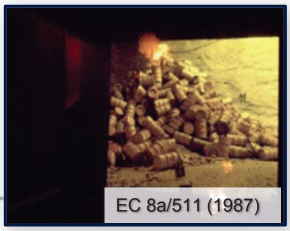

EC 7/750 (1978)

Volume

125787 waste packages / ca. 47.000 cubic meters




EC 8/750 (1975)


EC 8a/511 (1987)

Source: BGE

6

Facts of an old salt mine

GRS CSDENGINEERS+ INGENIOUS BY NATURE KIT Karlsruhe Institute of Technology

Inflow of saline solution and stability problems

The Mine has to be closed, but the proof of long-term safety is not possible in the state of knowledge, that's why

➔ Retrieval of Radioactive Waste = Implementation of "Lex-Asse" (§ 57 b AtG) April 2013, and

➔ Emergency preparedness according to mining law & nuclear law in the case of disposition of radioactive waste in the Asse mine (e.g. in the case of an *Auslegungsüberschreitendes Ereignis)*:

- measures to reduce the probability of occurrence and
- measures to minimize the consequences of an uncontrollable inflow of saline solution

7

Analysis of consequences

GRS CSDENGINEERS+ INGENIOUS BY NATURE KIT Karlsruhe Institute of Technology

Identification of long-term effects of complete or partial disposition of radioactive waste in the Asse II mine:

- Calculations and development of forecasts to be able to better evaluate the emergency measures.
- On the basis of calculations it can be estimated what radiological and chemo-toxic consequences would have to be expected in case of an uncontrollable inflow.
- The analysis also helps to evaluate what measures will have the greatest effect in order to keep the consequences as low as possible.

8

GRS CSDENGINEERS+ INGENIOUS BY NATURE KIT Karlsruhe Institute of Technology

Acknowledgement:

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

The work leading to the following presentations by GRS, CSD and KIT-INE were performed under contract to BGE

9

J. Mönig, B. Förster, D. Buhmann

Geochemistry in support of potential emergency measures for Schachtanlage Asse II

2. Conceptualization of Radionuclide Source Term

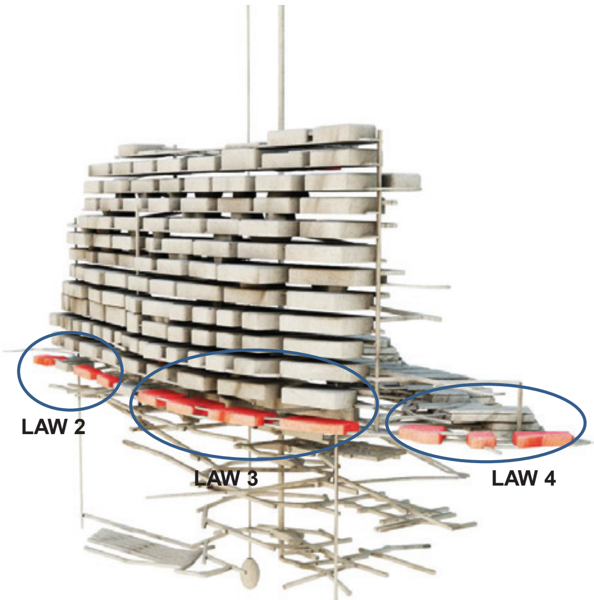
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation

J. Mönig, B. Förster, D. Buhmann
GRS

Hanover, Germany
September 10-11, 2018

GRS

Current Situation of Waste Emplacement in the Asse Mine

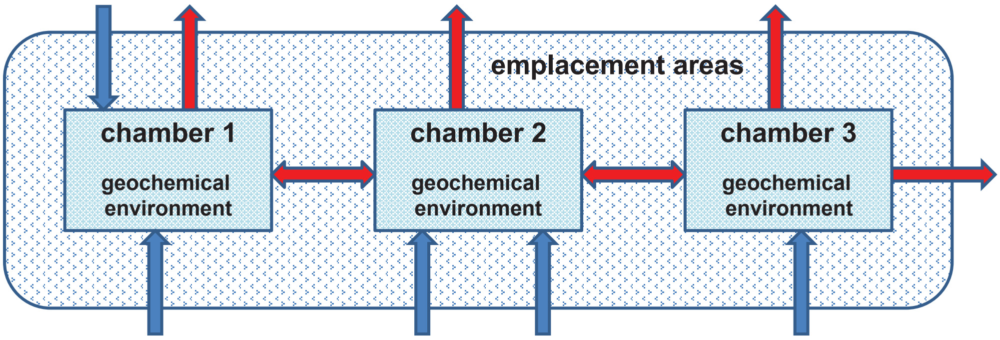


- 12 emplacement chambers with low-level waste
- 4 emplacement areas that are hydraulically separated from each other
  - LAW 1 – 2 chambers (behind LAW 2, not visible)
  - LAW 2 – 3 chambers
  - LAW 3 – 4 chambers
  - LAW 4 – 3 chambers
- (1 chamber with intermediate-level waste at 511 m depth, not visible)

2

GRS

Situation in each emplacement area



- diverse hydraulic connections exist between emplacement chambers
- inflow of uncontaminated solution into each emplacement area via several pathways (via drifts, galleries, pillars)
- outflow of contaminated solution from each emplacement chamber via several pathways
- potential inflow of contaminated solution from neighbouring emplacement chambers and/or emplacement areas

3

GRS

Challenges for radionuclide source term calculation

Radionuclide source terms depend on the geochemical environment (milieu)

The geochemical milieu after inflow of saline solution may change with time

- Geochemical evolution in each emplacement chamber depends on the mass ratio of solid material and solution, the type of inventories, their accessibility and their reactivity (all data exhibit some/considerable uncertainties)
- Geochemical evolution will be different in each emplacement chamber

Different mixtures of waste types in the emplacement chambers

- 200 l thin-walled steel drums, some with concrete
- 200 l thin-walled steel drums embedded in thick concrete hulls

Geochemical evolution may also be affected by inflow from neighbouring emplacement chambers

- Results from quantitative solution exchange calculations between emplacement chambers and the effects on geochemical evolution can only be poorly justified

4

GRS

Methodological approach – current thoughts (1)

For each emplacement chamber

- Thermodynamic equilibrium calculation of initial geochemical milieu (mixing tank) taking into account all inventories except organic carbon
- Assignment of calculated initial geochemical milieu to a solution type, e.g.

highly alkaline $CaCl_2$-solution (pH > 10)

alkaline $CaCl_2$-NaCl-solution (pH ~9)

alkaline $MgCl_2$-solution (pH > 7)

- Estimation of microbial conversion of organic carbon and its implication on geochemical milieu („*potential of acidification of geochemical milieu*“)

alkaline $MgCl_2$-solution (pH > 7) → ? microbial conversion $C_{org} \rightarrow CO_2$ → neutral / acidic $MgCl_2$-solution (pH < 7)

- Qualitative consideration of effect of solution inflow from neighbouring chambers
- Assignment of derived final geochemical milieu to a solution type

5

GRS

Methodological approach – current thoughts (2)

- Assignment of maximum element solubilities to each solution type

alkaline NaCl-solution (pH > 7) →

element	solubility
U	$1{\cdot}10^{-7}$
Am	$1{\cdot}10^{-6}$
Pu	$3{\cdot}10^{-8}$
Th	$5{\cdot}10^{-7}$
Np	$2{\cdot}10^{-7}$

alkaline $MgCl_2$-solution (pH > 7) →

element	solubility
U	$1{\cdot}10^{-7}$
Am	$3{\cdot}10^{-6}$
Pu	$1{\cdot}10^{-8}$
Th	$5{\cdot}10^{-6}$
Np	$1{\cdot}10^{-7}$

Solubility values are arbitrary, just for illustrative purpose

- Consideration of sorption processes only if solubility limits are not reached
- Identification of significant changes in maximum radionuclide solubilities from initial geochemical milieu to final geochemical milieu
  - Determination of relevant changes in the geochemical evolution from initial milieu to final milieu
  - Determination of time domains with „*constant*“ geochemical milieu

6

GRS

Methodological approach – current thoughts (3)

Derivation of radionuclide source terms for emplacement areas

- The highest maximum concentration value in any of the emplacement chambers determines the maximum value in the emplacement area
  - Assessment for each element invidually
- If solubilities are not limiting the element concentrations
  - Lowest sorption coefficient in any of the emplacement chambers is used for the whole emplacement area

	$C_{max, chamber A}$	$C_{max, chamber B}$	$C_{max, chamber C}$	Emplacement area
solution type	highly alkaline $CaCl_2$-solution	alkaline $MgCl_2$-solution	alkaline NaCl-solution	
Am	1E-6	**1E-5**	1E-7	**1E-5**
U	3E-7	**1E-6**	1E-7	**1E-6**
Th	**3E-4**	1E-6	1E-6	**3E-4**

Concentration values are arbitrary, just for illustrative purpose

7

GRS

Methodological approach – discussion

Advantages

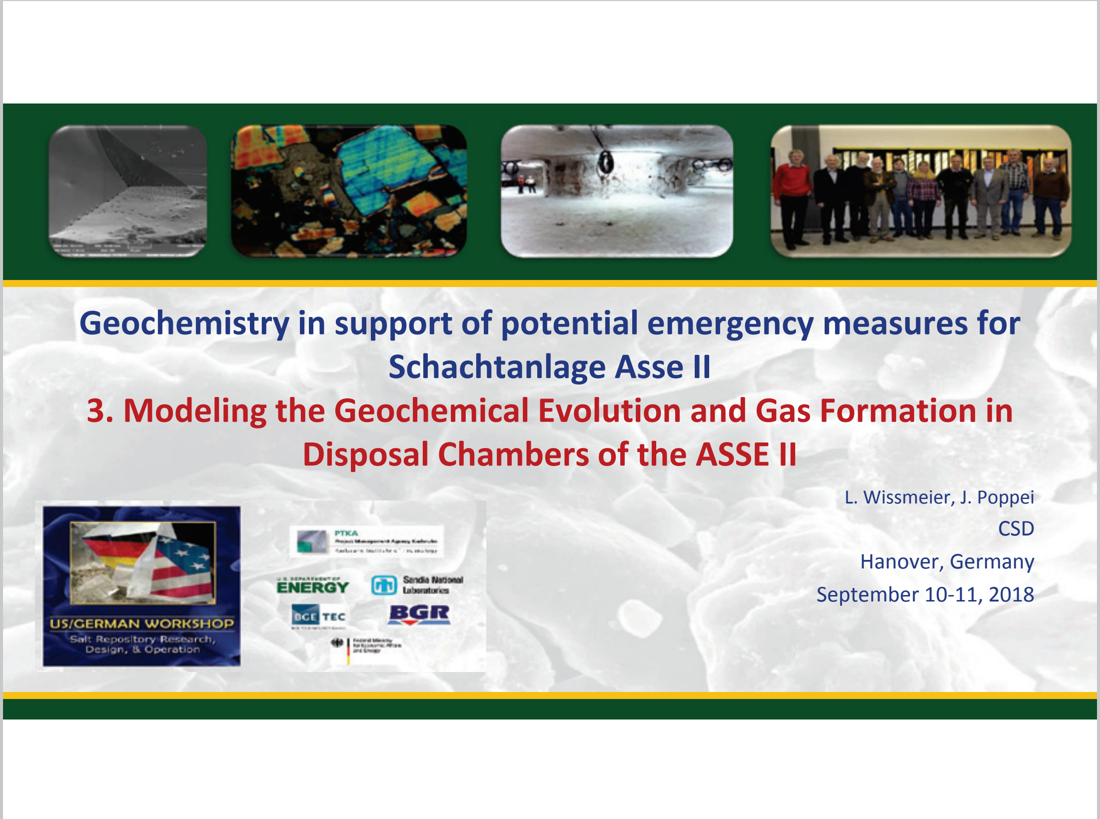
- Fundamentally conservative for each emplacement area
- Evolution of geochemical milieu with time is accounted for
- No need for elaborate calculations of solution exchange between emplacement chambers
- No reliance on hydraulic and geometric input parameters
- Derived radionuclide concentrations are robust against hydraulic variations in the system

Disadvantages

- Collectively, the derived radionuclide source term for an emplacement area does not reflect a specific solution-solids-system, i.e. *the source term is not real*
- Radionuclide source term may overestimate significantly the actual radionuclide source term of the emplacement areas

8

L. Wissmeier, J. Poppei



Introduction

CSDENGINEERS+ INGENIOUS BY NATURE

- What?
  Modeling of the evolution of the geochemical conditions and gas formation in the disposal chambers of the ASSE II
- Why?
  Geochemical conditions: Radionuclide solubility and mobility
  Gas formation: Influence on flow and transport
  Assessment of management strategies: Choice of backfill material
- How?
  Coupled simulations of geochemical processes using equilibrium speciation and kinetic formulations in PHREEQC
- The catch?
  Spatial representation of disposal chambers

3

Reactive Inventories and Associated Geochemical Processes

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Salt host rock:	Mineral dissolution and alteration
R-solution and initial solutions:	Solution speciation
Cement (Portlandite):	Cement corrosion/degradation
Mg-Depot (Brucite mortar):	Dissolution and alteration
Organic waste compounds:	Degradation and gas formation (e.g., CO_2)
Metal compounds:	Corrosion and gas formation (e.g., H_2)
Gas phase compounds:	Dissolution and degassing

4

Modeling Strategy

- Separation of equilibrium reactions and kinetic (time-dependent) reactions

Equilibrium reactions: Host rock, backfill salts, cement, Mg-depot, solution

Kinetic reactions: Metal compounds, organic compounds

- Representation of equilibrium reactions according to (activity corrected) mass action equations with geochemical formulas of reacting components
- Representation of kinetic reactions with their effects and dependencies on solution speciation, mineral alteration and gas formation according to effective stoichiometries and *knowledge-based* rate equations

5

Reactions

Solution speciation
- THEREDA database
- Pitzer activity model

Gas phase
- CO_2
- CH_4
- H_2
- O_2
- N_2

Host rock and backfill salts
- Halite
- Polyhalite

Brucite mortar (backfill material)
- $Mg(OH)_2$
- $MgCl_2$
- $MgSO_4$
- NaCl
- KCl
- $CaSO_4$
- H_2O

Portland cement
- CaO
- SiO_2
- Al_2O_3
- MgO
- SO_3
- H_2O

Mineral model
- Anhydrite
- Artinite
- Brucite
- Calcite
- Carnallite
- Ca-Oxychloride
- Chlorartinite
- CSH(1.1)
- CSH(1.8)
- Friedelssalt
- Gibbsite
- Halite
- Hydromagnesite
- Kainite
- Mg-Oxychloride
- Polyhalite
- Sepiolite
- Sylvite
- Syngenite

Kinetic reactions for metal corrosion and organics degradation

- Cellulose oxidation by molecular oxygen
- Cellulose oxidation by nitrate
- Cellulose oxidation by ferric iron reduction
- Cellulose oxidation by sulfate reduction
- Methane generation from cellulose

- Plastics oxidation by molecular oxygen
- Plastics oxidation by nitrate
- Plastics oxidation by ferric iron reduction
- Plastics oxidation by sulfate reduction
- Methane generation from plastics

- Methane generation from hydrogen oxidation
- Hydrogen oxidation via iron reduction
- Hydrogen oxidation via sulfate reduction

- Aerobe corrosion of C-steel
- Anaerobe corrosion of C-steel
- Anaerobe corrosion of C-steel with CO_2

- Aerobe corrosion of stainless steel
- Anaerobe corrosion of stainless steel
- Anaerobe corrosion of stainless steel with CO_2

- Anaerobe conversion of FeOOH
- Iron sulfide precipitation

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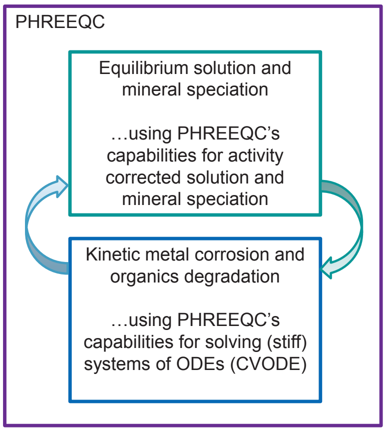
Implementation in Geochemical Modelling Framework PHREEQC

- Kinetic reactions according to first order rates with respect to primary educts (organic compounds, metals)
- Additional rate dependencies (secondary educt limiters, pH_m, O_2-saturation, chaotropicity, etc.)
- Feedback between equilibrium and kinetic reactions
  - Effect of solid phase buffering of CO_2 on pH_m
  - Effect of sulfate reduction on mineral speciation
  - Dependence of metal corrosion on pH_m and Cl^-
  - Dependence of organic degradation on activity of water and chaotropicity
  - Calculation of degassing according to Henry's law



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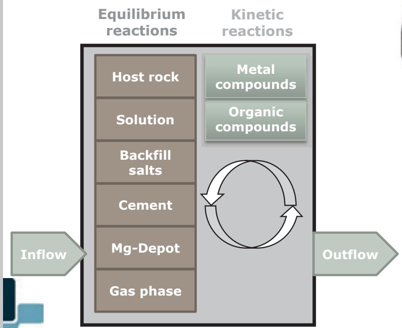
Spatial Differentiation and Discretization Limiting Cases

Case 1:
Batch reactor for disposal chambers
(perfect mixing of inventories)



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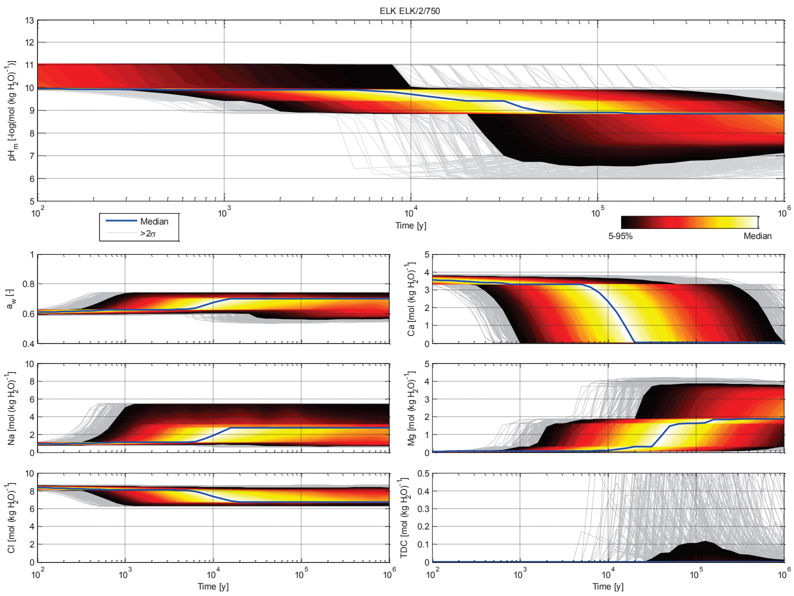

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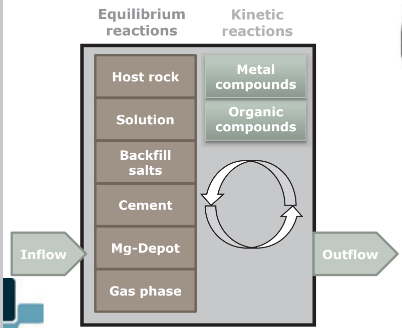
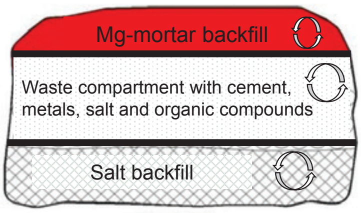
Spatial Differentiation and Discretization Limiting Cases

Case 1:
Batch reactor for disposal chambers
(perfect mixing within disposal chamber)



Limited but important amount of mixing between material compartments!

Case 2:
Batch reactors for material compartments
(perfect mixing within material compartments; no exchange between material compartments)



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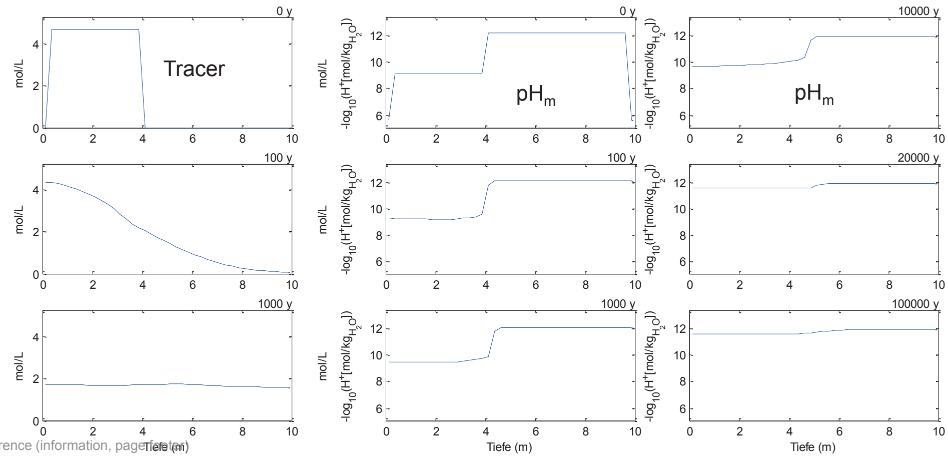
Persistence of Geochemical Conditions in Mg-Depot and Cement Compartments



Reference (information, page, date)

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Spatial Differentiation and Discretization
=> Vertical Transect with Solute Transport in and between Material Compartments

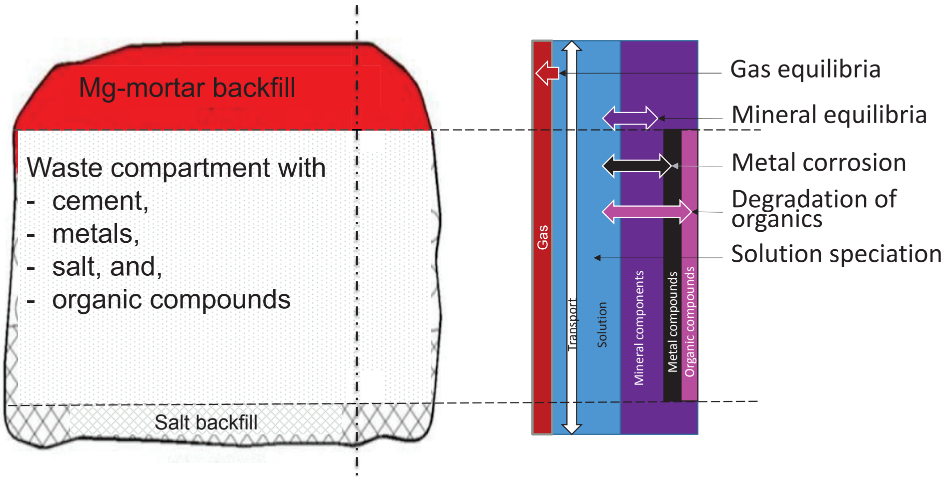

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Tableau Form of Kinetic Reactions

	Cellulose $C_6H_{12}O_6$	Polymer C_2H_4	Hydrogen H_2	Carbon steel Fe^0	Stainless steel Fe^0	Ferric iron FeO(OH)	Ferrous iron Fe_3O_4	Nitrate NO_3^-	Sulfate SO_4^{2-}	Methane CH_4	Nitrogen N_2	H_2S	H_2O	CO_2	O_2	H^+	Siderite $FeCO_3$	FeS
Cellulose oxidation by molecular oxygen	-1												6	6	-6			
Cellulose oxidation by nitrate	-1							-4.8			2.4		8.4	6		-4.8		
Cellulose oxidation by ferric iron reduction	-1					-24	24						-6	6		24		
Cellulose oxidation by sulfate reduction	-1								-3			3	6	6		-6		
Methane generation from cellulose	-1		4							2			-2	4				
Plastics oxidation by molecular oxygen		-1											2	2	-3			
Plastics oxidation by nitrate		-1						-2.4			1.2		3.2	2		-2.4		
Plastics oxidation by ferric iron reduction		-1				-12	12						-4	2		12		
Plastics oxidation by sulfate reduction		-1							-1.5			1.5	2	2		-3		
Methane generation from plastics		-1	3.33							0.67			-2.67	1.33				
Methane generation from hydrogen oxidation			-4							1			2	-1				
Hydrogen oxidation via iron reduction			-1			-2	2									2		
Hydrogen oxidation via sulfate reduction			-4						-1			1	4			-2		
Aerobe corrosion of C-steel				-4		4							-2		-3			
Anaerobe corrosion of C-steel			4	-3			1						-4					
Anaerobe corrosion of C-steel with CO_2			1	-1									-1	-1			1	
Aerobe corrosion of stainless steel					-4	4							-2		-3			
Anaerobe corrosion of stainless steel			4		-3		1						-4					
Anaerobe corrosion of stainless steel with CO_2			1		-1								-1	-1			1	
Anaerobe conversion of FeOOH			1	-1		-2	1											
Iron sulfide precipitation							-1					-1	2					1

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Probabilistic Uncertainty Analysis

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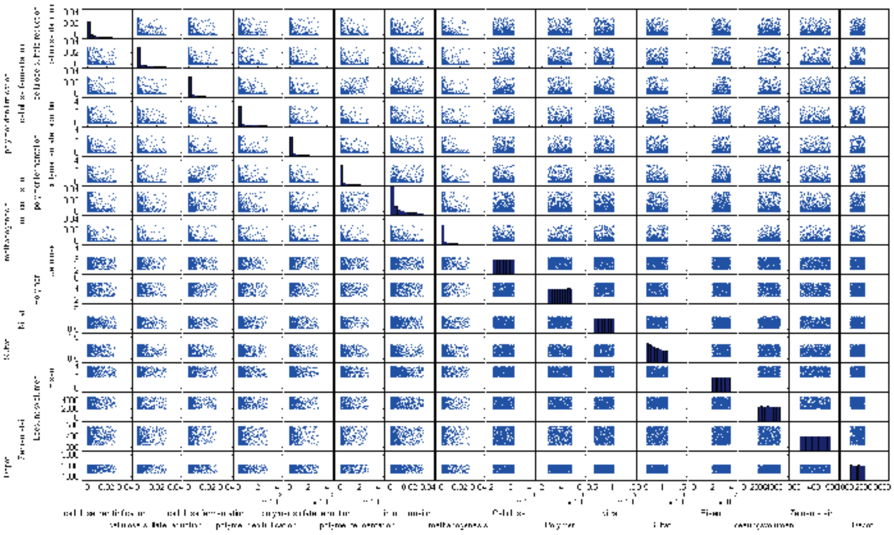

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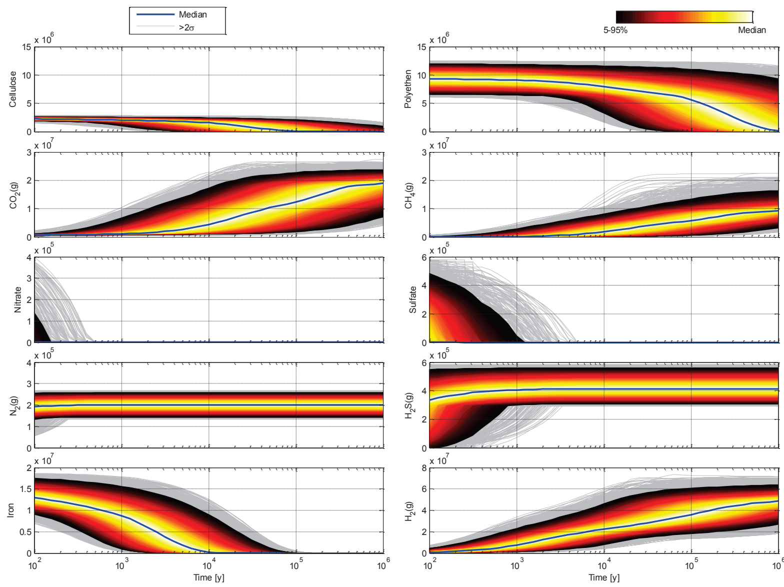

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M. Altmaier, D. Fellhauer, V. Metz

Geochemistry in support of potential emergency measures for Schachtanlage Asse II

4. Radionuclide source terms, solubility and retention processes

M. Altmaier, D. Fellhauer, V. Metz
KIT-INE
Hanover, Germany
September 10-11, 2018

Karlsruhe Institute of Technology

Geochemistry in support of potential emergency measures for Schachtanlage Asse II
4. Radionuclide source terms, solubility and retention processes

Karlsruhe Institute of Technology – Institute for Nuclear Waste Disposal (KIT-INE)

M. Altmaier, D. Fellhauer, V. Metz

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Aim

- **Realistic description of radionuclide behavior relevant for Asse II !**
- Realistic and scientifically justified description of radionuclide behavior in saline systems. Focus on RN solubility, sorption and geochemistry.
- **Scientific basis (KIT-INE)**
  - Comprehensive and systematic RD&D on radionuclide behavior in saline systems performed at KIT-INE within Helmholtz.
  - Studies on radionuclide solubility and sorption related to Asse II performed under contract to BGE (BfS).
  - (Collaborative) research projects funded by BMWi, BMBF.
  - International networking:
    - NEA-TDB, NEA Salt Club, ABC-Salt Workshop Series, …
    - exchange around WIPP, => US-DOE, LANL, SNL.

3

Methodology

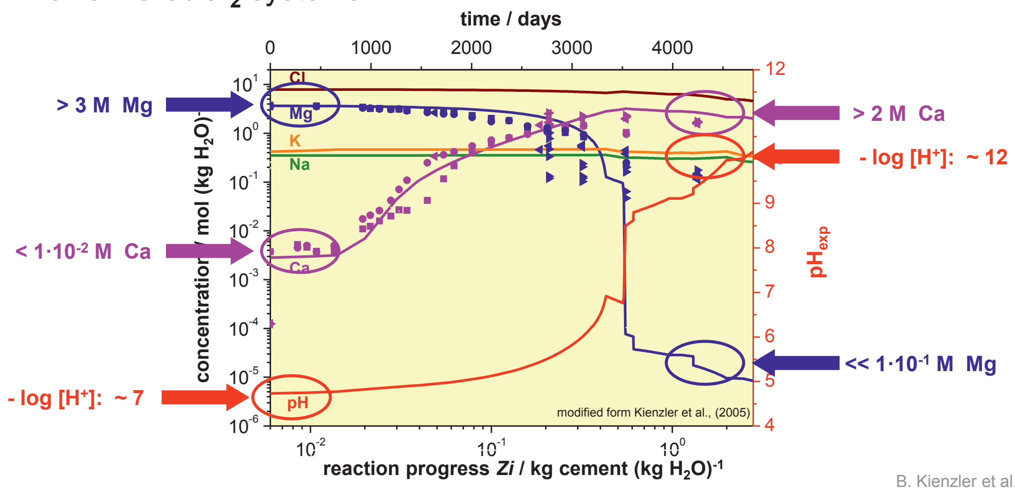
- **Radionuclide retention** is strongly depending on geochemical conditions and is treated as function of **(i) RN solubility limits**, and **(ii) RN sorption on relevant solid phase surfaces**.
- **Radionuclide solubility limits** derived from
  - **systematic experimental studies**, supported by geochemical modeling.
  - geochemical calculations **validated** against experimental evidence.
- Models for predicting RN solubility usually valid over large range of pH_m and *I*, thus providing high **robustness**. Strong emphasis on detailed chemical models and **process understanding**.
- **Radionuclide sorption** on **near field** (Fe-corrosion phases, cement alteration phases, Sorel, …) and **far field** materials can provide significant radionuclide retention. => systematic experimental assessment.

4

Matrix systems: NaCl, $MgCl_2$, $CaCl_2$

KIT
Karlsruhe Institute of Technology

- **NaCl** and **$MgCl_2$** are main components to be considered.
- Corrosion of cementitious waste in $MgCl_2$ brines can lead to saline alkaline **$CaCl_2$** systems.



B. Kienzler et al.

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Radionuclide solubility, Np(V) case

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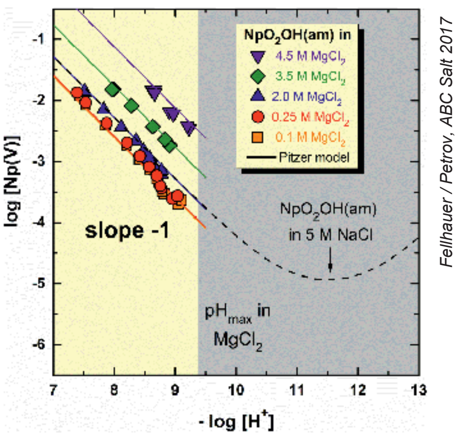

4.5 M $MgCl_2$

- Experimental data partly available for comparable solution conditions:
  - *Fellhauer / Petrov, ABC Salt 2017*
- **pH_m = 6.5:**
  - $NpO_2OH(am) \Leftrightarrow NpO_2Cl_x^{1-x}(aq)$
  - *$\log[Np(V)]_m > -1.0$*
- **pH_m = 8.7:**
  - $NpO_2OH(am) \Leftrightarrow NpO_2Cl_x^{1-x}(aq)$
  - $\log[Np(V)]_m = -1.8$

- Systematic experimental studies required to derive data and process understanding. Direct information and input for developing TDB.
- Information on solid phases, chemical speciation an ion-interaction.

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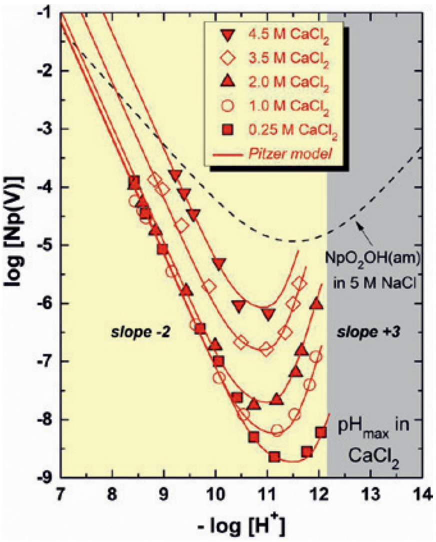
Radionuclide solubility, Np(V) case



Fellhauer (2016)

4.0 M $CaCl_2$

- Experimental data available for comparable solution conditions:
  - *Fellhauer (2016)*
- **pH_m = 8.7:**
  - $Ca_{0.5}NpO_2(OH)_2$(cr,hyd) ⇔ $NpO_2Cl_x^{1-x}$(aq)
  - $\log[Np(V)]_m = -3.2$
- **pH_m = 11.7:**
  - $Ca_{0.5}NpO_2(OH)_2$(cr,hyd) ⇔ $NpO_2OH_x^{1-x}$(aq)
  - $\log[Np(V)]_m = -5.0$

- Np(V) solubility under presence of Ca significantly lower due to solid phase transformation processes.

7

Current KIT-INE study on RN solubility limits

- Orientative solubility limits derived for generic brine solutions. Main components: NaCl, $MgCl_2$, and $CaCl_2$.

- The following **concentrated salt solutions** are considered:
  - **5.0 M NaCl** solution with pH_m = 6.5 and 8.7
  - **4.5 M $MgCl_2$** solution with pH_m = 6.5 and 8.7
  - **4.0 M $CaCl_2$** solution with pH_m = 8.7 and 12.0

8

Current KIT-INE study on RN solubility limits

pH_m conditions:

- **Weakly alkaline (pH_m 8.7)**
  as expected due to pH buffering by $Mg(OH)_2$ or related phases (e.g., due to reaction of cementitious waste with $MgCl_2$-dominated solutions).
- **Slightly acidic (pH_m 6.5)**
  e.g. relevant due to degradation of organic materials and high $CO_2(g)$ production in emplacement rooms with low cement inventory.
- **Strongly alkaline (pH_m 12.0)**
  as expected due to reaction of cementitious waste forms in concentrated $MgCl_2$ solutions (emplacement rooms with large cement inventory).

Effect of carbonate on RN solubility is treated separately.

Effect of organic complexing ligands will be considered in a subsequent project.

9

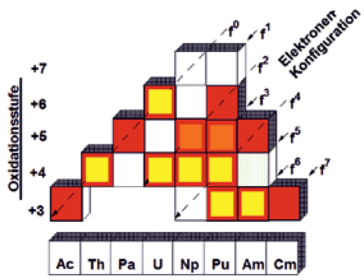
Current KIT-INE study on RN solubility limits

Radionuclides

- Th(IV)
- U(IV), U(VI)
- Pu(III), Pu(IV), Pu(V), Pu(VI)
- Am(III)
- Cm(III)
- Np(IV), Np(V)
- Pb(II)
- Pa(IV), Pa(V)
- Ra(II)

For two ILW emplacement rooms:

- Sr(II)
- Cs(I)



Redox conditions

- All potentially relevant RN oxidation states of radionuclides considered, forming under oxidizing to strongly reducing conditions - spanning from "in contact with air" to "in contact with corroding iron" .

10

Results: maximum concentrations for selected *actinides*
in carbonate free solutions

	5.0 M NaCl		4,5 M $MgCl_2$		4,0 M $CaCl_2$		Assignment of radionuclide oxidation states to qualitative redox conditions
	pH_m 6,5	pH_m 8,7	pH_m 6,5	pH_m 8,7	pH_m 8,7	pH_m 12,0	
	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	
Th(IV)	−6,0 ± 1	−6,0 ± 0,5	−6,0 ± 1,5	−6,0 ± 1	−6,0 ± 1	−2,5 ± 0,4	all redox conditions
U(IV)	−7,0 ± 0,5	−7,0 ± 0,5	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	Strongly reducing conditions
U(VI)	−5,0 ± 0,5	−6,7 ± 0,3	−2,4 ± 0,5	−5,2 ± 0,5	−7,3 ± 0,3	−5,5 ± 0,5	Weakly reducing to strongly oxidizing
Np(IV)	<−8,0 ±0,1	<−8,0 ±0,1	−7,0 ± 1	−8,0 ± 1	−8,0 ± 1	−5,8 ± 0,4	Strongly reducing to redox-neutral
Np(V)	−2,2 ± 0,3	−3,3 ± 0,3	> −1,0	−1,8 ± 0,3	−3,2 ± 0,3	−4,1 ± 0,3	redox-neutral to oxidizing
Pu(III) (1)	−2,7 ± 0,7	−7,8 ± 0,7	−2,2 ± 1	−7,3 ± 0,5	−7,5 ± 0,7	−9,0±0,7(3)	(strongly) reducing
Pu(IV)	<−7,7 ±0,1	<−7,7 ±0,1	−7,7 ± 1	−7,7 ± 1	−7,7 ± 1	−7,0 ± 0,4	(strongly) reducing to weakly oxidizing
Pu(V) (2)	−7,2 ± 0,7	−9,4±0,7(3)	−6,4 ± 1	−8,6±0,5(3)	−8,6±0,7(3)	−6,7 ± 0,5	Oxidizing
Am(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions
Cm(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions

[1] estimated for (pe+pH) ≈ 2, [2] estimated for (pe+pH) ≈ 19, [3] Under these conditions, the ***concentration of Pu(III) and Pu(V)*** is controlled by a redox equilibrium with solid Pu(IV) and, therefore, directly depends on the redox milieu (pe+pH). Note, that the predominant Pu species in solution is Pu(IV)(aq) with log[Pu(IV)] = −7,5.

Detailed information on data and models will be provided within report of KIT-INE to BGE.

11

Results: maximum concentrations for selected *actinides*
in carbonate free solutions

	5.0 M NaCl		4,5 M $MgCl_2$		4,0 M $CaCl_2$		Assignment of radionuclide oxidation states to qualitative redox conditions
	pH_m 6,5	pH_m 8,7	pH_m 6,5	pH_m 8,7	pH_m 8,7	pH_m 12,0	
	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	
Th(IV)	−6,0 ± 1	−6,0 ± 0,5	−6,0 ± 1,5	−6,0 ± 1	−6,0 ± 1	−2,5 ± 0,4	all redox conditions
U(IV)	−7,0 ± 0,5	−7,0 ± 0,5	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	Strongly reducing conditions
U(VI)	−5,0 ± 0,5	−6,7 ± 0,3	−2,4 ± 0,5	−5,2 ± 0,5	−7,3 ± 0,3	−5,5 ± 0,5	Weakly reducing to strongly oxidizing
Np(IV)	<−8,0 ±0,1	<−8,0 ±0,1	−7,0 ± 1	−8,0 ± 1	−8,0 ± 1	−5,8 ± 0,4	Strongly reducing to redox-neutral
Np(V)	−2,2 ± 0,3	−3,3 ± 0,3	> −1,0	−1,8 ± 0,3	−3,2 ± 0,3	−4,1 ± 0,3	redox-neutral to oxidizing
Pu(III) (1)	−2,7 ± 0,7	−7,8 ± 0,7	−2,2 ± 1	−7,3 ± 0,5	−7,5 ± 0,7	−9,0±0,7(3)	(strongly) reducing
Pu(IV)	<−7,7 ±0,1	<−7,7 ±0,1	−7,7 ± 1	−7,7 ± 1	−7,7 ± 1	−7,0 ± 0,4	(strongly) reducing to weakly oxidizing
Pu(V) (2)	−7,2 ± 0,7	−9,4±0,7(3)	−6,4 ± 1	−8,6±0,5(3)	−8,6±0,7(3)	−6,7 ± 0,5	Oxidizing
Am(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions
Cm(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions

- An(III) solubility strongly increased at pH_m = 6.5 relative to pH_m = 8.7.

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Results: maximum concentrations for selected *actinides*
in carbonate free solutions

	5.0 M NaCl		4,5 M $MgCl_2$		4,0 M $CaCl_2$		Assignment of radionuclide oxidation states to qualitative redox conditions
	pH_m 6,5	pH_m 8,7	pH_m 6,5	pH_m 8,7	pH_m 8,7	pH_m 12,0	
	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	
Th(IV)	−6,0 ± 1	−6,0 ± 0,5	−6,0 ± 1,5	−6,0 ± 1	−6,0 ± 1	−2,5 ± 0,4	all redox conditions
U(IV)	−7,0 ± 0,5	−7,0 ± 0,5	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	Strongly reducing conditions
U(VI)	−5,0 ± 0,5	−6,7 ± 0,3	−2,4 ± 0,5	−5,2 ± 0,5	−7,3 ± 0,3	−5,5 ± 0,5	Weakly reducing to strongly oxidizing
Np(IV)	<−8,0 ±0,1	<−8,0 ±0,1	−7,0 ± 1	−8,0 ± 1	−8,0 ± 1	−5,8 ± 0,4	Strongly reducing to redox-neutral
Np(V)	−2,2 ± 0,3	−3,3 ± 0,3	> −1,0	−1,8 ± 0,3	−3,2 ± 0,3	−4,1 ± 0,3	redox-neutral to oxidizing
Pu(III) (1)	−2,7 ± 0,7	−7,8 ± 0,7	−2,2 ± 1	−7,3 ± 0,5	−7,5 ± 0,7	−9,0±0,7(3)	(strongly) reducing
Pu(IV)	<−7,7 ±0,1	<−7,7 ±0,1	−7,7 ± 1	−7,7 ± 1	−7,7 ± 1	−7,0 ± 0,4	(strongly) reducing to weakly oxidizing
Pu(V) (2)	−7,2 ± 0,7	−9,4±0,7(3)	−6,4 ± 1	−8,6±0,5(3)	−8,6±0,7(3)	−6,7 ± 0,5	Oxidizing
Am(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions
Cm(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions

- An(III) solubility strongly increased at pH_m = 6.5 relative to pH_m = 8.7.

13

Results: maximum concentrations for selected *actinides*
in carbonate free solutions

	5.0 M NaCl		4,5 M $MgCl_2$		4,0 M $CaCl_2$		Assignment of radionuclide oxidation states to qualitative redox conditions
	pH_m 6,5	pH_m 8,7	pH_m 6,5	pH_m 8,7	pH_m 8,7	pH_m 12,0	
	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	
Th(IV)	−6,0 ± 1	−6,0 ± 0,5	−6,0 ± 1,5	−6,0 ± 1	−6,0 ± 1	−2,5 ± 0,4	all redox conditions
U(IV)	−7,0 ± 0,5	−7,0 ± 0,5	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	Strongly reducing conditions
U(VI)	−5,0 ± 0,5	−6,7 ± 0,3	−2,4 ± 0,5	−5,2 ± 0,5	−7,3 ± 0,3	−5,5 ± 0,5	Weakly reducing to strongly oxidizing
Np(IV)	<−8,0 ±0,1	<−8,0 ±0,1	−7,0 ± 1	−8,0 ± 1	−8,0 ± 1	−5,8 ± 0,4	Strongly reducing to redox-neutral
Np(V)	−2,2 ± 0,3	−3,3 ± 0,3	> −1,0	−1,8 ± 0,3	−3,2 ± 0,3	−4,1 ± 0,3	redox-neutral to oxidizing
Pu(III) (1)	−2,7 ± 0,7	−7,8 ± 0,7	−2,2 ± 1	−7,3 ± 0,5	−7,5 ± 0,7	−9,0±0,7(3)	(strongly) reducing
Pu(IV)	<−7,7 ±0,1	<−7,7 ±0,1	−7,7 ± 1	−7,7 ± 1	−7,7 ± 1	−7,0 ± 0,4	(strongly) reducing to weakly oxidizing
Pu(V) (2)	−7,2 ± 0,7	−9,4±0,7(3)	−6,4 ± 1	−8,6±0,5(3)	−8,6±0,7(3)	−6,7 ± 0,5	Oxidizing
Am(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions
Cm(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions

- An(III) solubility not increased in concentrated $CaCl_2$ at pH_m = 8.7 relative to pH_m = 12.0.

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Results: maximum concentrations for selected *actinides* *in carbonate free solutions*

	5.0 M NaCl		4,5 M $MgCl_2$		4,0 M $CaCl_2$		Assignment of radionuclide oxidation states to qualitative redox conditions
	pH_m 6,5	pH_m 8,7	pH_m 6,5	pH_m 8,7	pH_m 8,7	pH_m 12,0	
	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	log $[RN]_m$	
Th(IV)	−6,0 ± 1	−6,0 ± 0,5	−6,0 ± 1,5	−6,0 ± 1	−6,0 ± 1	−2,5 ± 0,4	all redox conditions
U(IV)	−7,0 ± 0,5	−7,0 ± 0,5	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	−7,0 ± 1	Strongly reducing conditions
U(VI)	−5,0 ± 0,5	−6,7 ± 0,3	−2,4 ± 0,5	−5,2 ± 0,5	−7,3 ± 0,3	−5,5 ± 0,5	Weakly reducing to strongly oxidizing
Np(IV)	<−8,0 ±0,1	<−8,0 ±0,1	−7,0 ± 1	−8,0 ± 1	−8,0 ± 1	−5,8 ± 0,4	Strongly reducing to redox-neutral
Np(V)	−2,2 ± 0,3	−3,3 ± 0,3	> −1,0	−1,8 ± 0,3	−3,2 ± 0,3	−4,1 ± 0,3	redox-neutral to oxidizing
Pu(III) [1]	−2,7 ± 0,7	−7,8 ± 0,7	−2,2 ± 1	−7,3 ± 0,5	−7,5 ± 0,7	−9,0±0,7(3)	(strongly) reducing
Pu(IV)	<−7,7 ±0,1	<−7,7 ±0,1	−7,7 ± 1	−7,7 ± 1	−7,7 ± 1	−7,0 ± 0,4	(strongly) reducing to weakly oxidizing
Pu(V) [2]	−7,2 ± 0,7	−9,4±0,7(3)	−6,4 ± 1	−8,6±0,5(3)	−8,6±0,7(3)	−6,7 ± 0,5	Oxidizing
Am(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions
Cm(III)	−1,5 ± 0,5	−6,7 ± 0,5	−1,8 ± 0,7	−5,7 ± 0,7	−5,5 ± 0,7	−5,0 ± 0,5	all redox conditions

- An(IV) show low and constant solubility over large pH_m-range. Exception: alkaline $CaCl_2$.

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Conclusions / Outlook

- **Orientative maximum solubility concentrations derived by KIT-INE for 11 radionuclides in 3 generic brine solutions at 3 different pH_m.**
- **Work by KIT-INE on radionuclide behavior is complementary to the work of GRS and CSD. => Good teamwork! Thanks!**
- Future work on solubility limits:
  - *Explicit assessment of organics complexation (under planning).*
  - *Refined treatment of geochemical conditions (specific not generic), and discussion on redox conditions.*
  - *Assessment of influence of “minor components” on RN solubility.*
- Studies on RN sorption retention on relevant near and far field materials required. Solubility limits provide input for targeted sorption studies.

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Thank you for your attention !!!

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david.fellhauer@kit.edu
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17

B. Stanislaw, A. Marta

Internal structure and deformation of clay-salt complexes in salt diapirs: a case study from the Polish Basin area

Burliga Stanislaw, Adamuszek Marta

University of Wroclaw, Poland
Polish Geological Institute – National Research Institute, Poland

Hanover, Germany
September 10-11, 2018

Scope of presentation

Polish Nuclear Power Program (adopted in 2014): nuclear energy ca. 2030; waste repositories beyond 2030
Diapiric salt structures considered as possible sites

- **Clayey salts evaluated based on sample-scale investigations:**
  - **physical properties (permeability, porosity, etc.):** ***variegated***
  - **geomechanical tests:** ***lower strenght and rheological properties than rock salt***
  - **sorption properties:** ***higher than rock salt***
- **What does not the laboratory test show?**

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Petrography of clayey salts

salty clays – clayey salts (zuber) – rock salt

- soluble constituents: halite (silvite, carnallite)
- insoluble constituents:
  - clay minerals: illite, chlorite (smectite)
  - sulphates: anhydrite (gypsum)
  - carbonates: magnesite, dolomite, calcite, siderite
  - other minerals: quartz, hematite, feldspar,

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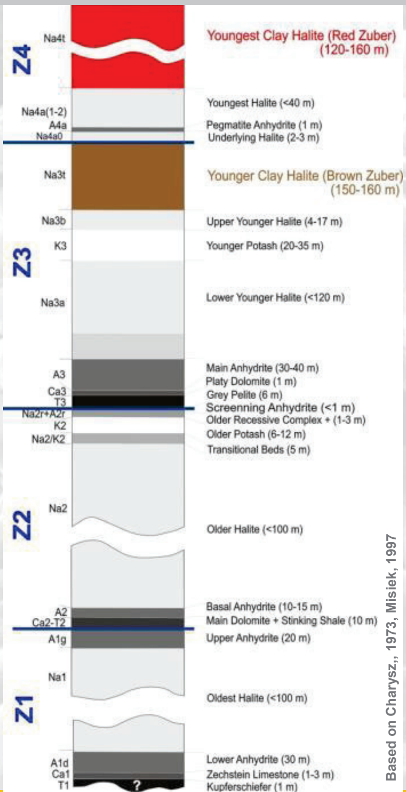
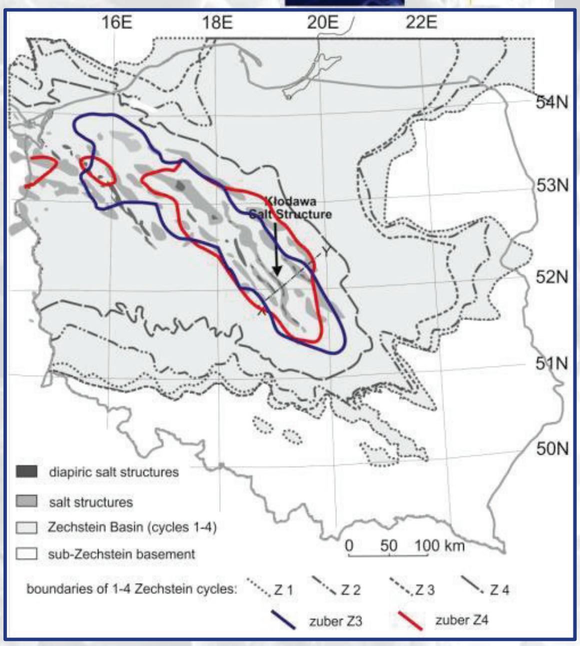


Zechstein clayey salts in Poland



Based on Wagner, 1994; Tomassi-Morawiec & Czapowski, 2006

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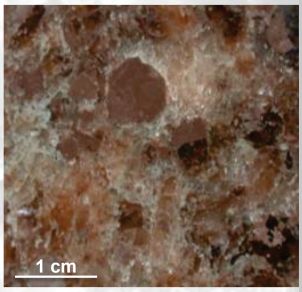
Lithostratigraphy

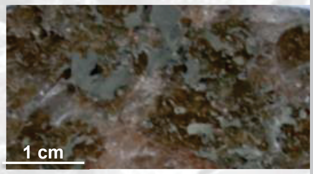
- Youngest Clay Halite (Z4)
  Red Zuber

  hematite-rich,
  redish clays and halite



- Younger Clay Halite (Z3)
  Brown Zuber

  greyish-greenish clays
  + honey-colour halite



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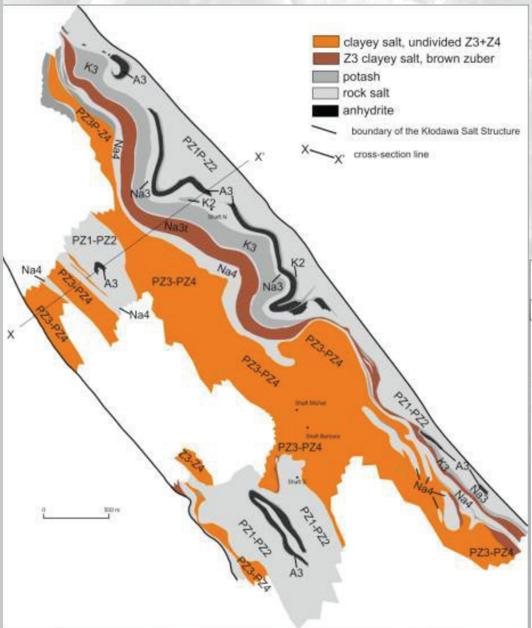
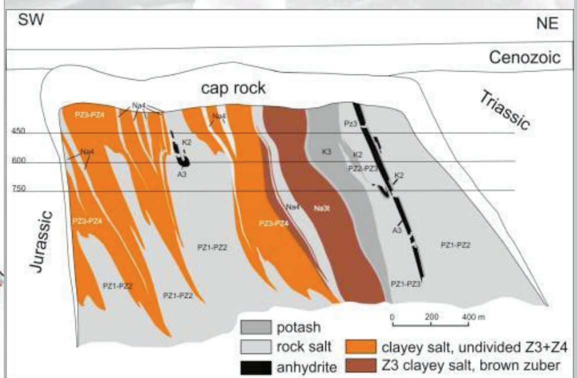
Tectonic position of clayey salts

Kłodawa Salt Structure



- synclinoria inside salt structures
- salt structure margins
- shallow depth
- clay-rich cap rock



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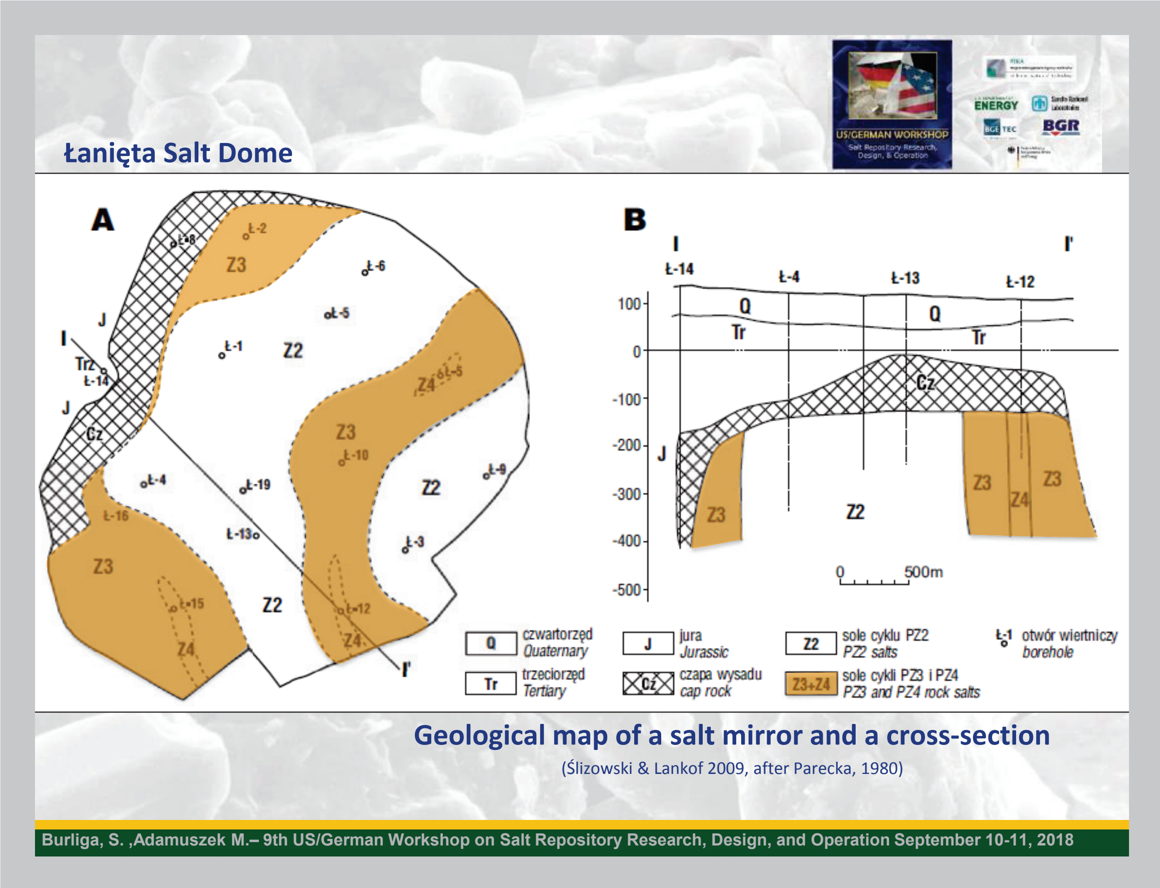
Łanięta Salt Dome
A
B
I
I'
Z2
Z3
Z4
Cz
J
Q
Tr
500m
Q czwartorzęd Quaternary
Tr trzeciorzęd Tertiary
J jura Jurassic
Cz czapa wysadu cap rock
Z2 sole cyklu PZ2 PZ2 salts
Z3+Z4 sole cykli PZ3 i PZ4 PZ3 and PZ4 rock salts
otwór wiertniczy borehole
Geological map of a salt mirror and a cross-section
(Ślizowski & Lankof 2009, after Parecka, 1980)
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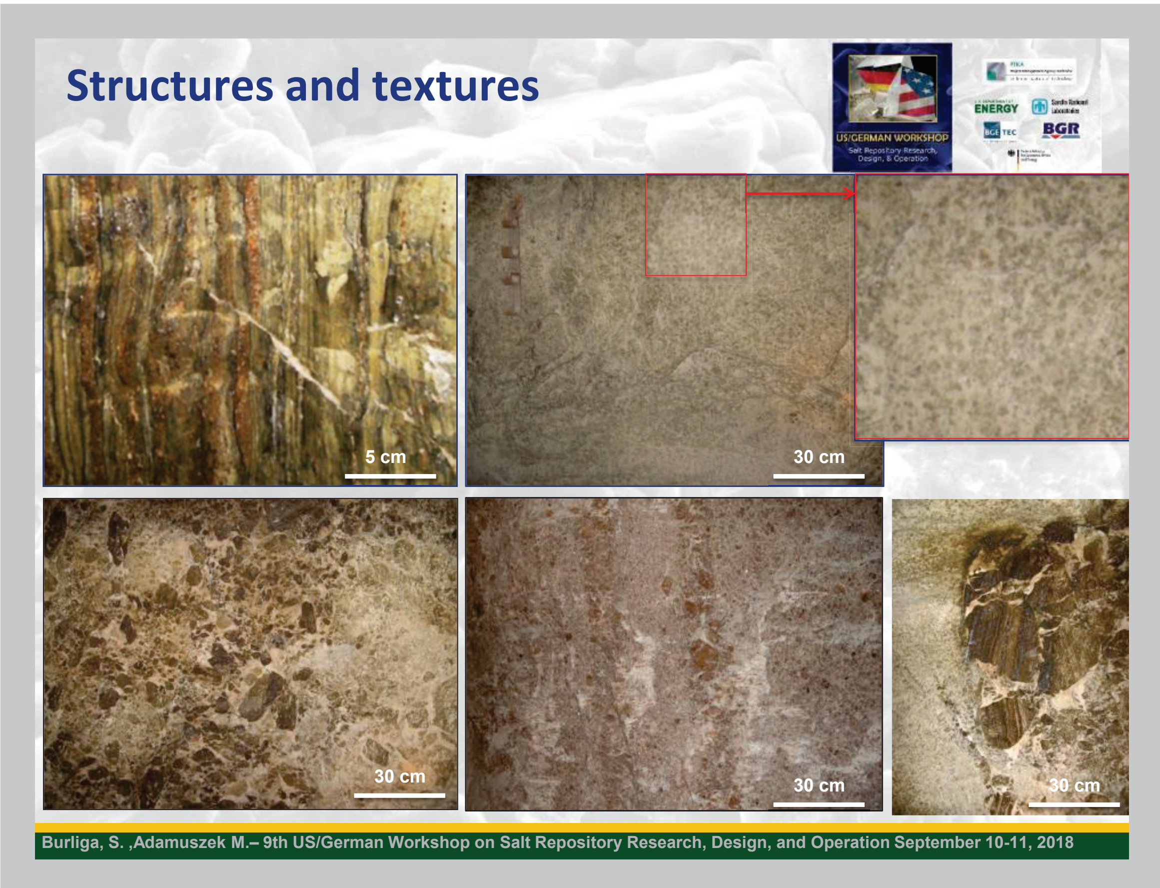
Structures and textures
5 cm
30 cm
30 cm
30 cm
30 cm
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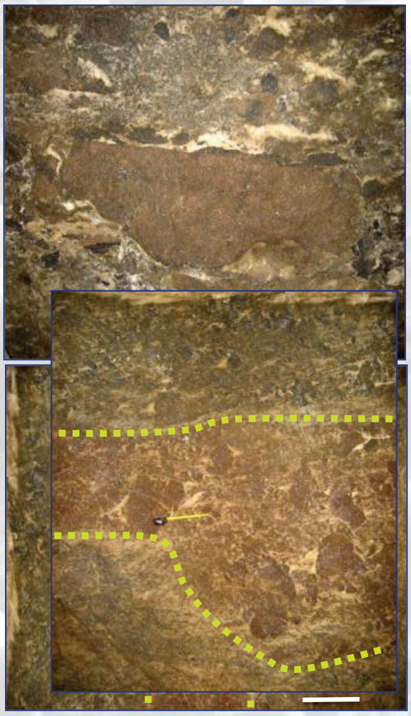
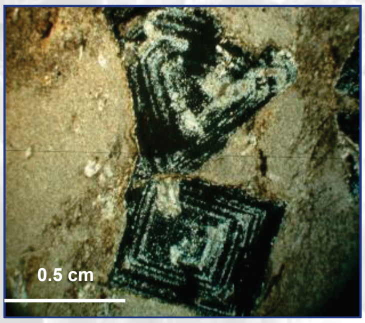
Tectonic or sedimentary origin?



- rounded boulders-to-pebbles
- grain gradation
- channel infills
- relics of primary crystal growth

>> submarine proximal and distal fan + open basin facies

>> superimposed tectonic deformation



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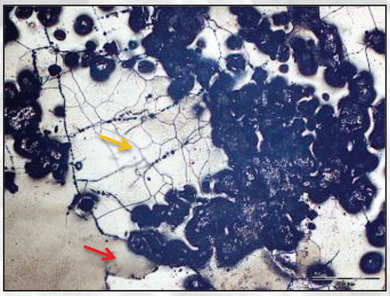
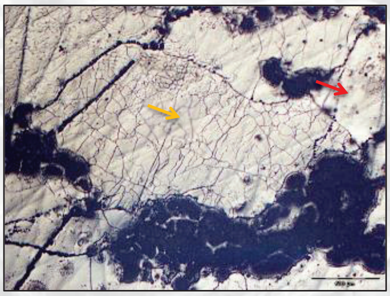
Subgrains in halite – plalaeopiezometry





$$\sigma = 107\ D^{-0.87}$$

- mostly dynamically recrystallized
- dislocation creep
- several generations of subgrains + new grains
- relics of primary structures

Lithostratigraphic unit	*Average grain size D [μm]*	*Differential stress range σ [MPa}*	*Average differential stress σ [MPa}*
Red Clayey Salt Na4t	102.36	1.36-3.76	2.15
Brown Clayey Salt Na3t	90.83	1.71-2.68	2.20

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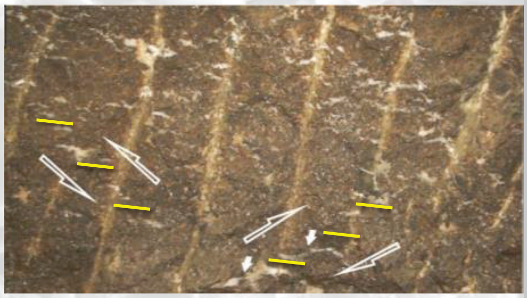
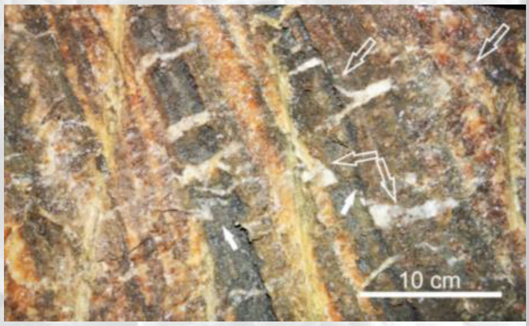
Tectonic deformation – veins

- common in clay-rich layers
- subparallel and diagonal to layering
- variegated length and thickness
- tenshion gashes in massive clayey salt
- seal fractures and interboudin necks





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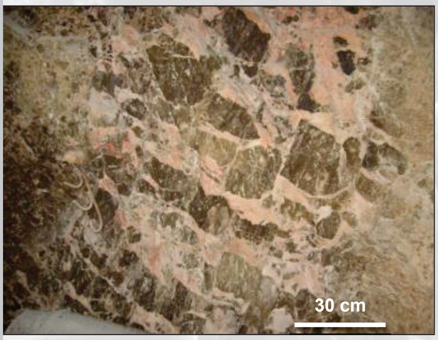
Tectonic deformation – veins

- fibrous and massive halite veins
- primarily halite (+potash)
- several generations of fracture sealing and fluid circulation



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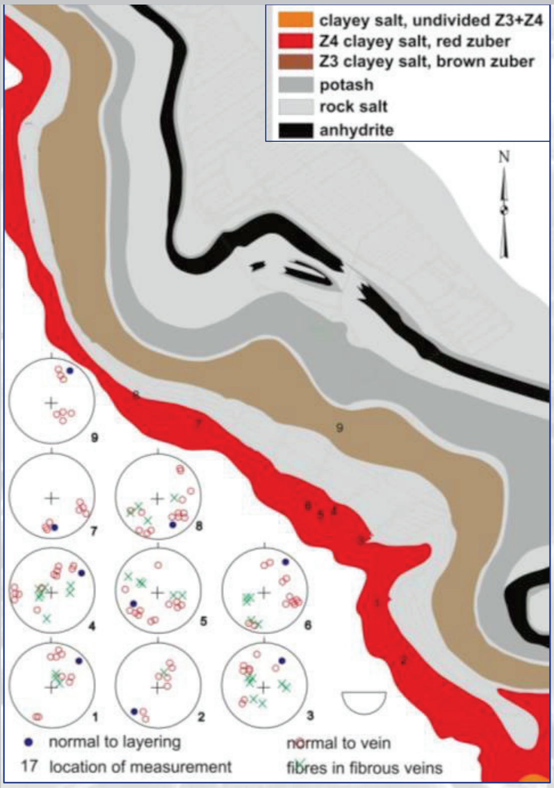

Orientation of veins

- several sets of veins originated during salt structure evolution
- different orientation throughout the strcuture
- arrangement dependent on layering
- fibres parallel and oblique to walls
- „old” vein generations

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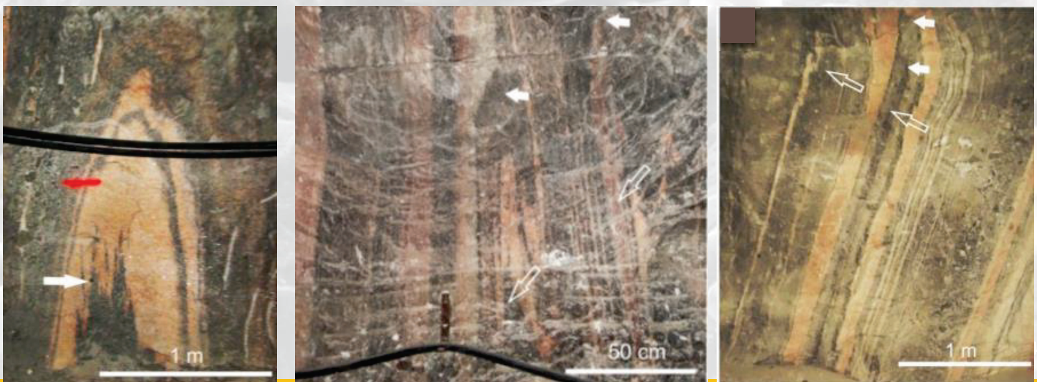
Tectonic deformation – folds

- low degree of deformation in outer and NE domains of the KSS
- large-scale superimposed folding in central domain of the KSS
- layer thickness reduction
- repetetive occurrence of clayey salt Z3 and Z4 layers and Z4 rock salt
  >> thickening of clayey salt complexes



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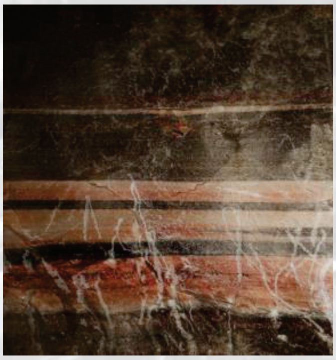
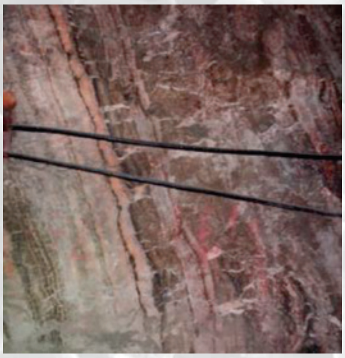
Tectonic deformation

- style of tectonic deformation dependent on structure, texture and mineral composition of clayey salt layers
- brittle deformation characteristic for layers with high clay content, ductile deformation common for halite-rich layers
- variegated deformation throughout the KSS: common large- and small-scale sedimentary structures in clay-rich layers adjacent to dynamically recrystallized halite layers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Conclusions

- Tectonic deformation in the KSS depended on lithology and location in the salt structure: brittle or ductile style of deformation is determined by relative clay and halite content in layers
- Several generations of veins of varying composition indicate that fluids could circulate in clayey salt complexes periodically. Fractures were consequently sealed. No evidence on postdiagenetic solution of the clayey salt complex.
- Clayey salts targeted for repositories should be evaluated individually – vein and fracture systems are specific for lithological types, non-penetrative, being influenced by local tectonics
- Common presence of sedimentary structures indicate that clayey salt complexes have been protected from intensive deformation by rock salt complexes, thus, they seem to be the most suitable for repositories. Clay cap rock on top.
- Laboratory tests on samples are not representative for the bulk clayey salt complex; detailed mapping and structural analysis are essential to built a relible geological model for other tests.

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US/GERMAN WORKSHOP
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S. Dunagan

WIPP: Status and Future Work

Sean Dunagan
Sandia National Laboratories

Hanover, Germany
September 10-11, 2018

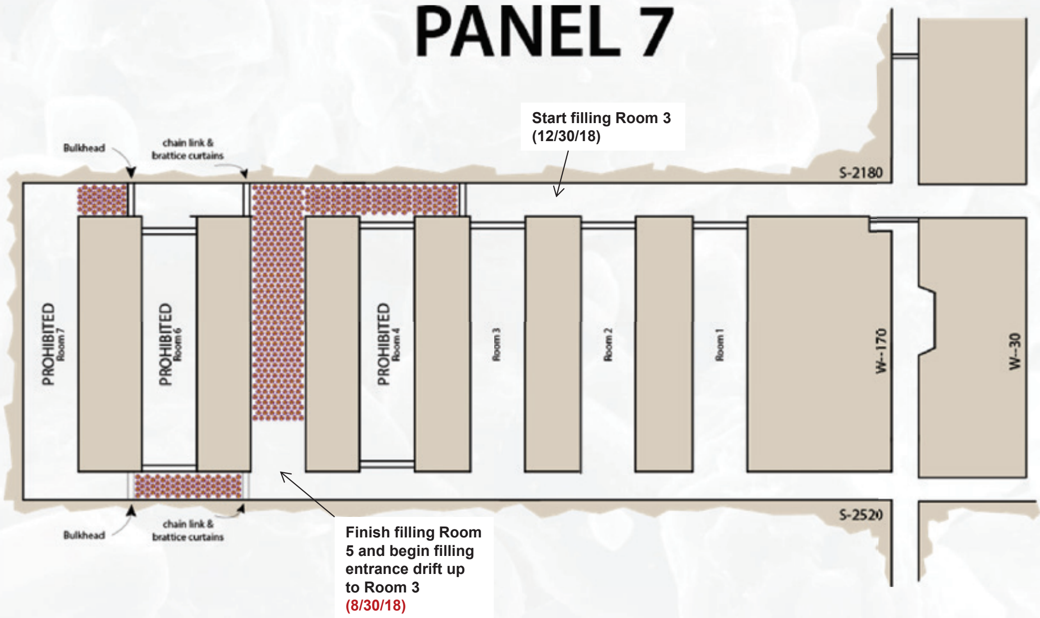
Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy. SAND2018-9568C

Outline

- Waste Emplacement
- Shipping Status and Outlook
- Ventilation Changes
- Mining Update
- Site Construction
- Future Work and Changes

2

Waste Emplacement



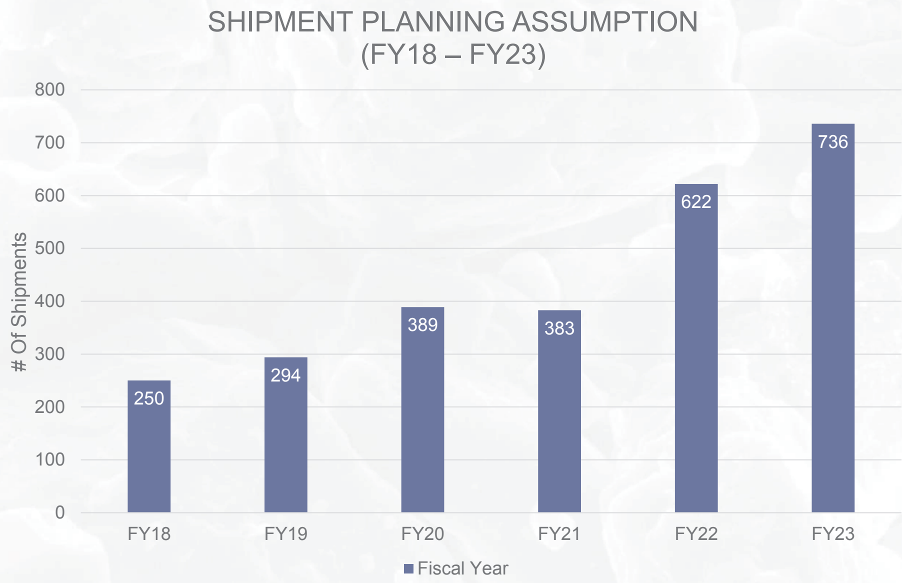
3

Waste Shipments

- Total Shipments received (since 1999) – 12,214
- Shipments since restart – 320
- Averaging 7-8 shipments/week
  - Increasing to 8-10 shipments/week end of August

4

Shipping Outlook



5

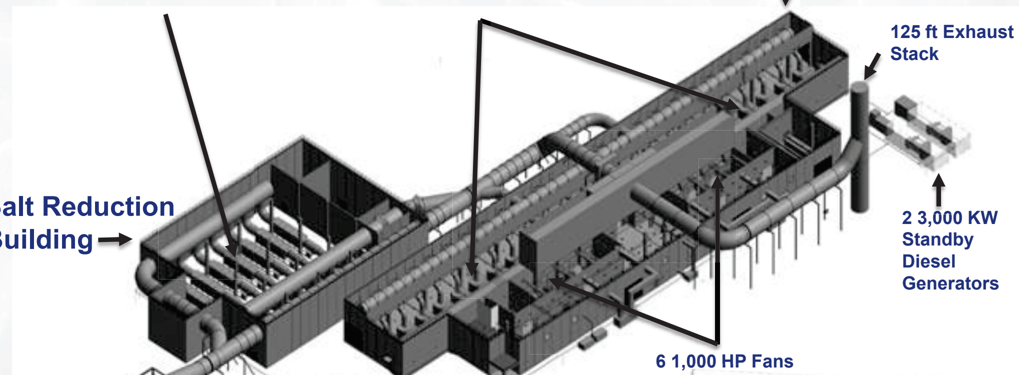
Ventilation Changes

Supplemental Ventilation System (SVS)

- Provides sufficient airflow to support mining and waste emplacement activities
- Designed to provide additional 130,000 CFM of airflow in the WIPP underground

6

Site Ventilation Construction



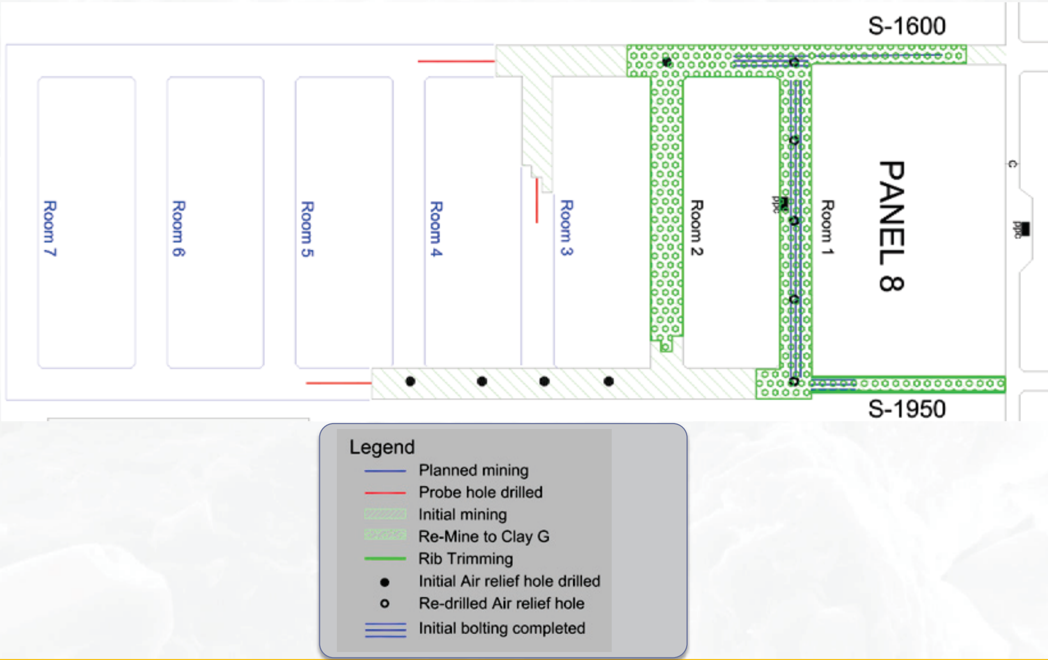
7

Utility Shaft

- Located west of the WIPP parking lot across the existing road
- Geotechnical core drilling completed
- Using top-down drilling method

8

Mining Update



9

Conceptual Vision for WIPP (concept for future)

10

Regulatory Issues

Description

▪ Panel Closure Redesign	NMED/EPA
▪ New Shaft	NMED/EPA
▪ New Filter Building	NMED
▪ Revise Calculation Method for Waste Volume (volume of record)	NMED/EPA
▪ Compliance Recertification Application (CRA) - 2019	EPA
▪ 10 Year Permit Renewal	NMED

11

Future work

- **A potential dilute and dispose approach to surplus plutonium waste disposition has been proposed**
  - WIPP would dispose of transuranic waste similar to waste streams that have previously been accepted and emplaced from several DOE sites
  - National Academy of Science reviewing approach
  - Multi-decade mission
  - No final decisions made

94
Pu
Plutonium
244.064

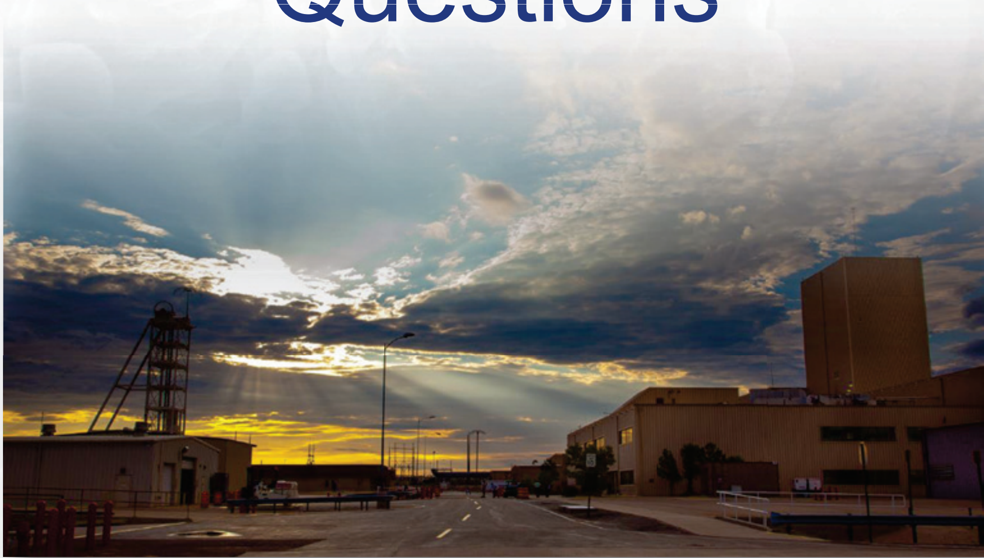
12

Summary

- WIPP is continuing to be challenged with its mission due to low ventilation rates. This is impacting mining, maintenance and emplacement.
- Construction projects are underway to address low ventilation rates and enable WIPP to resume full operations.
- Significant amount of regulatory work ahead.
- WIPP is being considered for additional waste beyond what is in the current inventory.

13

Questions

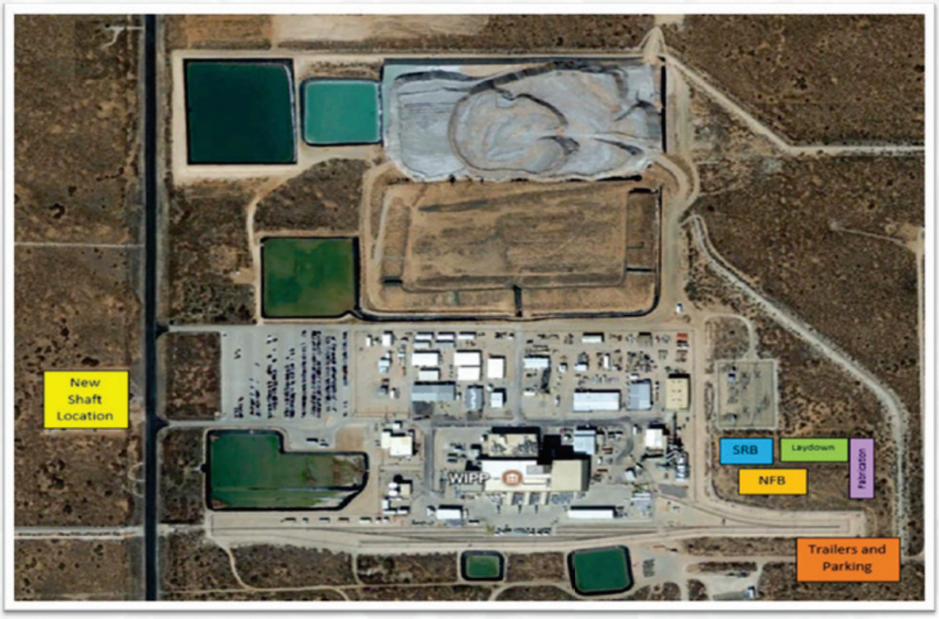


14

Backup Slides

15

New Ventilation System Site Layout



16

J. Mönig

Ex ante vs. ex post planning of radioactive waste retrieval in salt repositories

Jörg Mönig
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH

Hannover, Germany
September 10-11, 2018

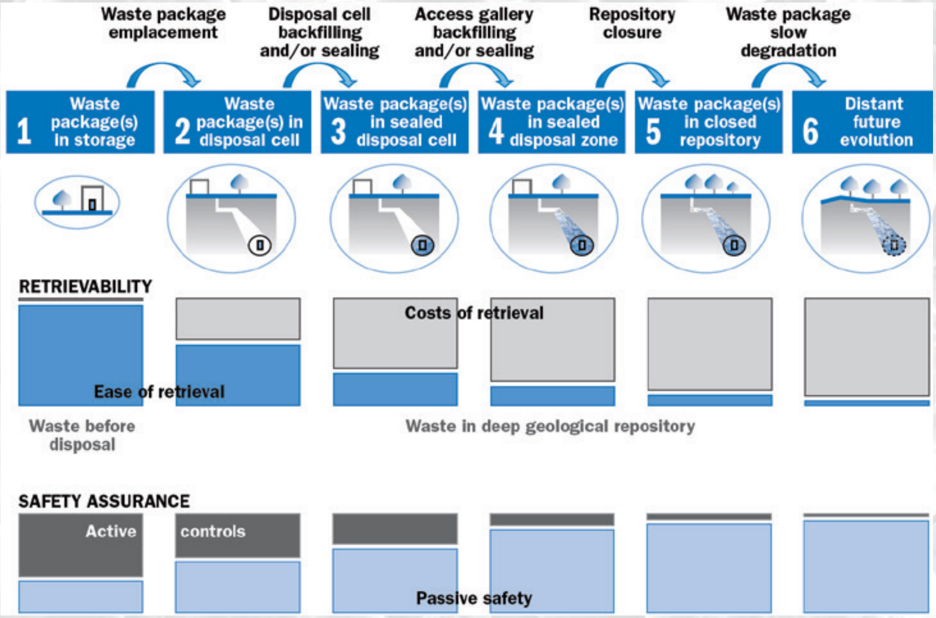
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2018-XXXX.

Important Note

- This presentation has been prepared based on extensive material which was kindly provided by
  - BGE (Mr. Mike Piske)
  - BGE TECHNOLOGY (Mr. Philipp Herold)
- All statements and conclusions are personal views from the presenter and are by no means endorsed by BGE or BGE TECHNOLOGY, respectively!

NEA-Report 7085 (2012)



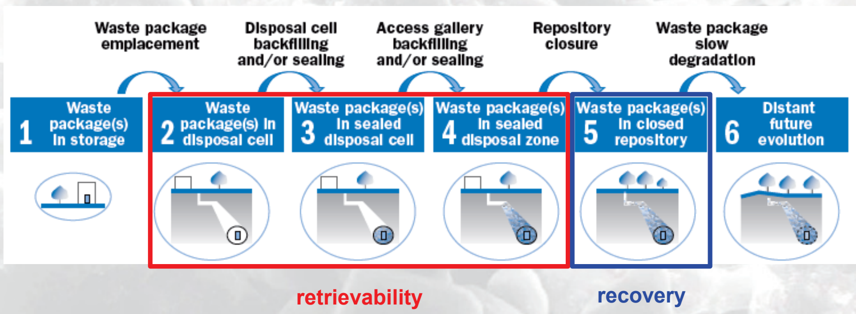
Legal Provisions in Germany

- German Site Selection Act (2017) stipulates that
  - a site for a HLW repository shall be selected which ensures the **best possible safety** for the permanent protection of man and environment against ionizing radiation and other detrimental effects of the waste for a period of 1 million years
  - measures have to be provided for to be able
    - to **retrieve** the emplaced waste from the repository **during the operational phase** and
    - to **recover** the waste within **500 years after closure of the repository**
- Safety Requirements for HLW (BMU 2010)
  - Measures taken to secure the options of recovering or retrieval **must not impair** the passive safety barriers and thus the **long-term safety**

Definitions

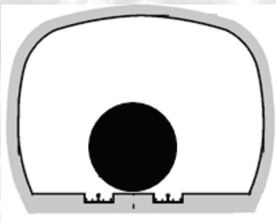
- Definitions
  - Retrievability
    - describes the **planned** technical feasibility to remove all emplaced radioactive waste from the repository during the operational phase
  - Retrieval
    - designates the active doing of removing waste casks from the repository
  - Recovery
    - is the **unplanned** removal of radioactive waste from the repository

Scope of Consideration

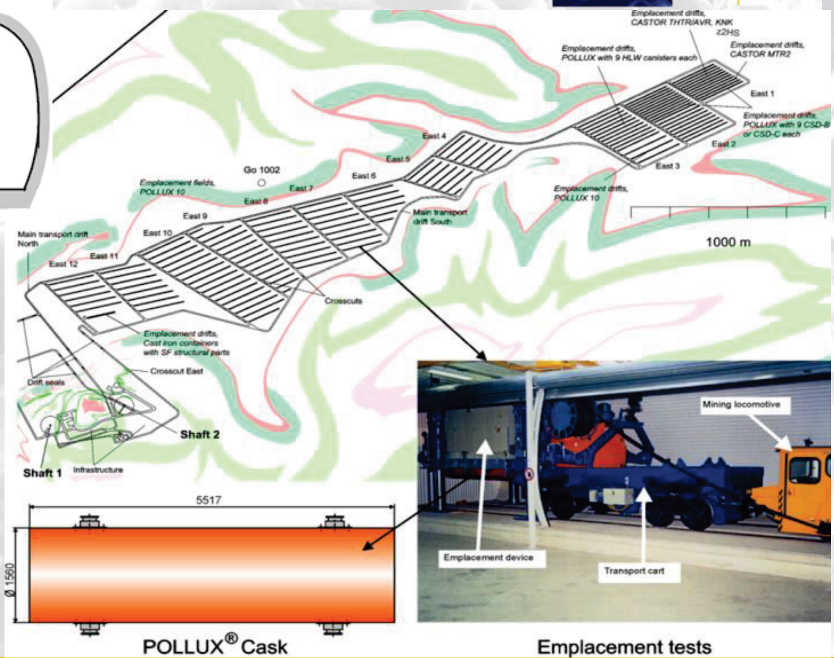


- Retrievability concept based on Re-mining strategy (developed by BGETEC in the ERNESTA project)
  - Emplacement of waste casks with stepwise backfilling of mine openings and closure of emplacement drifts
  - Conceptual and technical adaptations to ease retrieval
  - Ensuring favorable conditions during retrievability period

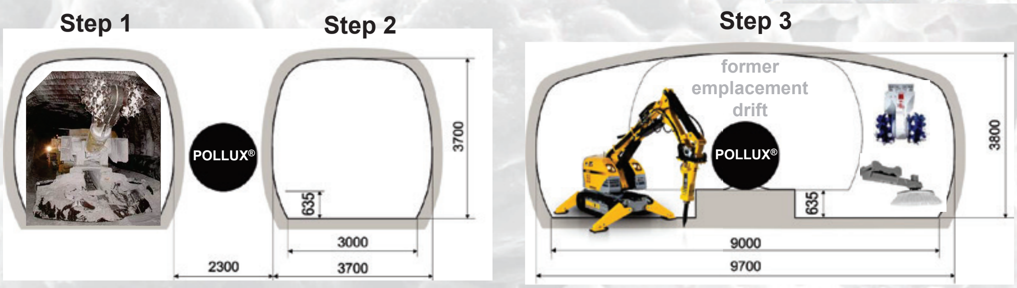
Drift Disposal of HLW



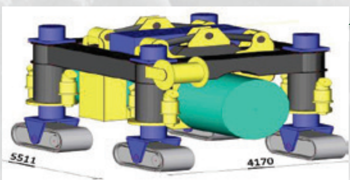
- Casks are emplaced in up to 250 m long blind drifts
- Mine layout taken from the Preliminary Safety Assessment for the Gorleben site



Drift Disposal of HLW



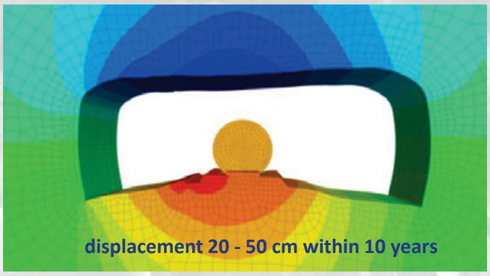
- Retrieval can be realized via stepwise excavation of two drifts
  - parallel to emplaced POLLUX® casks
  - between two cross-cuts

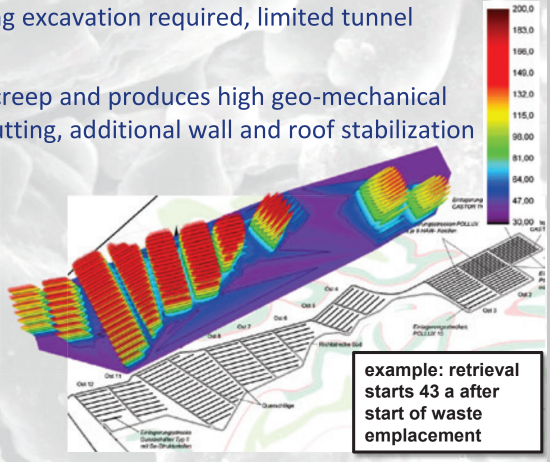


- Removal of remaining pillar
- Alternatingly,
  - uncovering of emplaced casks
  - Lifting with modified emplacement technique
  - and transport to above ground
- Backfilling of empty drift

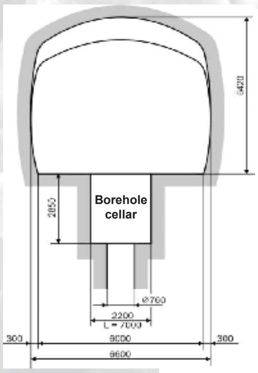
Drift Disposal of HLW

- Challenges for Retrieval
  - Retrieval period coincides in some emplacement fields with temperature maximum
  - Additional cooling equipment during excavation required, limited tunnel length, cooling intervals necessary
  - High temperature accelerates salt creep and produces high geo-mechanical stress (→ floor upheaval, drift re-cutting, additional wall and roof stabilization needed)

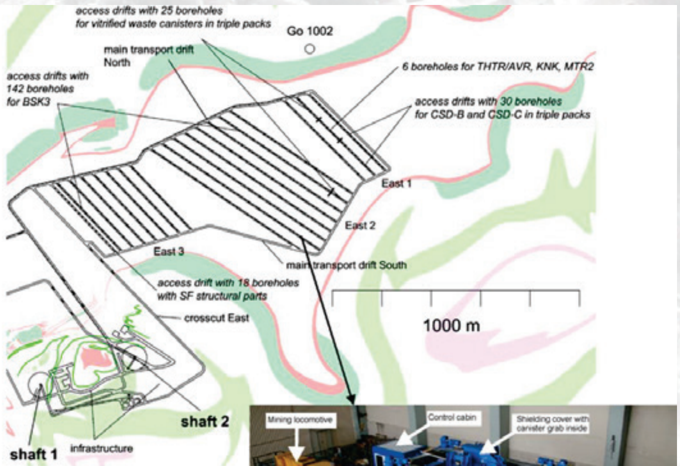


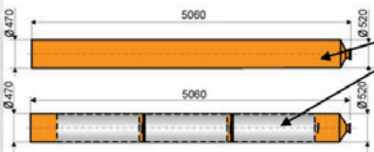


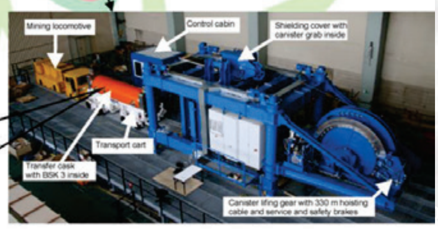
Borehole Disposal of HLW



Unshielded waste canisters are emplaced in boreholes (up to 300 m depth)

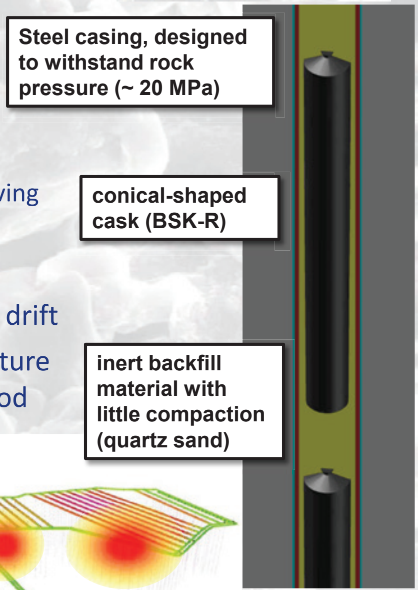


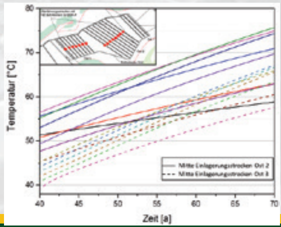


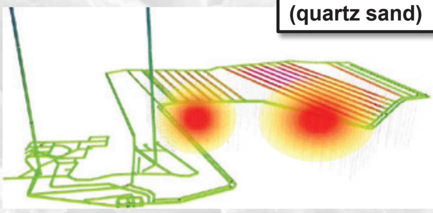


Borehole Disposal of HLW

- Design provisions to ease retrieval:
  - additional casing of the borehole
  - void space within casing filled with sand
  - conical-shaped canister (BSK-R)
- Retrieval is reversal of emplacement process
  - Development of special sucking device for removing the quartz sand from inside the casing
- Steel casing remains in the rock mass
- Heat sources are located beneath emplacement drift
- Temperature maxima are below design temperature und occur significantly beyond the retrieval period



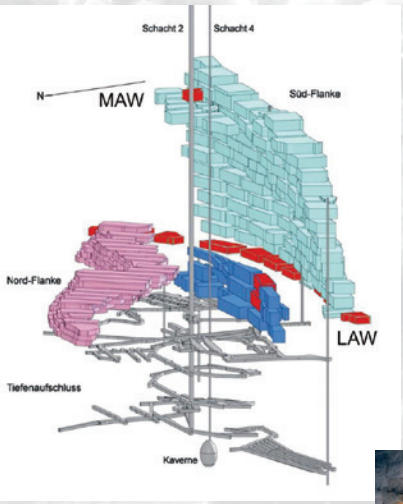




Legal Provisions in Germany

- Lex Asse (2013) stipulates
  - The Asse mine has to be shut down without delay
  - The shut down shall take place when the radioactive waste has been retrieved

Waste Retrieval at Asse Mine



- 12 chambers at 750 m level with LLW, partly with concrete overpack
- 1 chamber at 511 m level with ILW
- Different disposal strategies used throughout time:
  - piling, slope dumping

Chamber 4/750

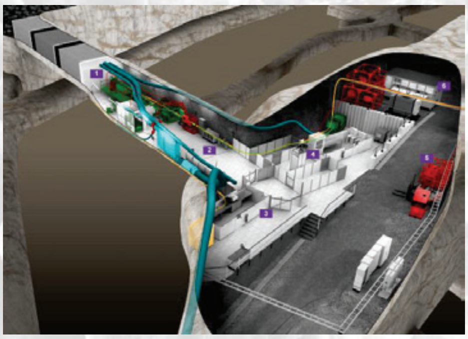
Chamber 8/750

Fact Investigation

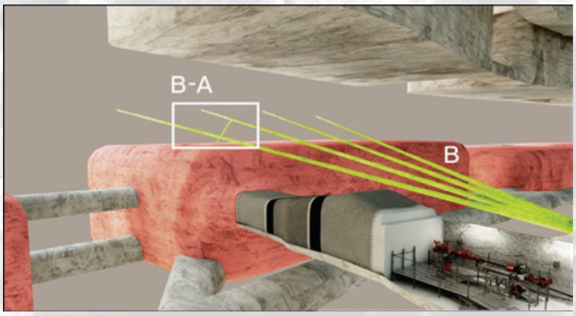
- Objective is to determine relevant boundary conditions for waste retrieval, e.g.
  - atmosphere in chamber
  - status of rock mass

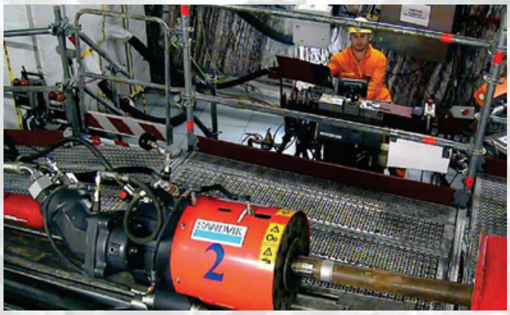
Installation of a facility for handling nuclear material

- boring technique (preventer, scram slide valve, drillings bunker, radiological filter, special ventilation)
- radiation protection measurement instrumentation (radiation protection lab below ground)
- Application and handling license according to § 9 AtG



Results at chamber 7/750

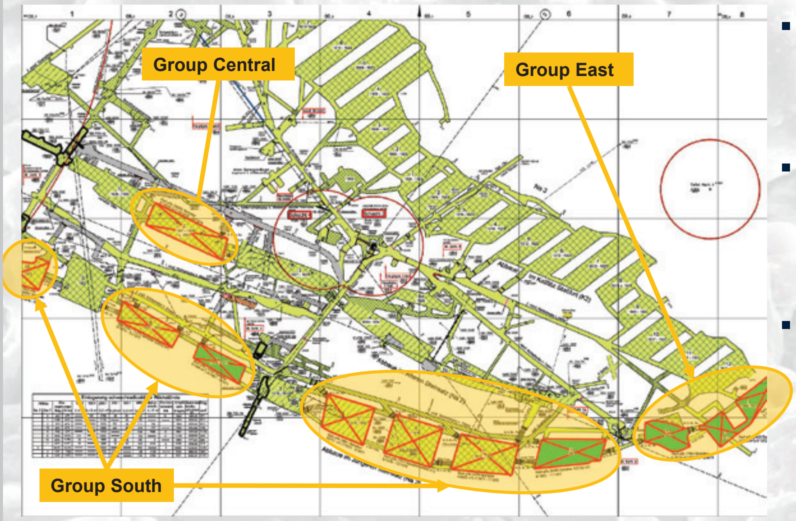




- Chamber roof is damaged
- Extension of chamber determined
- No explosive atmosphere
- Dose rate in the chamber 14,6 µSv/h
- Elevated Rn-concentration 64 kBq/m^3
- Low tritium concentration
  - 0,4 kBq/m^3 in head space
  - 0,7 kBq/m^3 in backfill

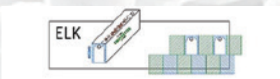
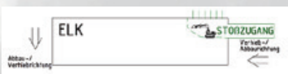
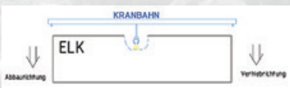
Situation in Chamber 7/750

Retrieval Planning



- East (3 chambers)
  - no backfill
  - no mining above
  - piled waste canisters
- Central (2 chambers)
  - backfilled (partly/completely)
  - No mining above
  - slope-dumped canisters
- South (7 chambers)
  - Not, partly or completely backfilled
  - Low roof thickness, roofs are damaged
  - piled and slope-dumped canisters

Feasible Retrieval Options

Retrieval Option		Chamber group East	Chamber group South	C C
Symbolbild	Bezeichnung			
	consecutive mining of partial areas	√	√	
	construction with horizontal / vertical mining along the strike (access from side wall)	√	X	
	construction with vertical mining using a crane along the strike (access from roof)	√	X	

Personal Conclusions

- Technical solutions to ensure retrievability of HLW have been conceived
  - The measures do not contrast the safety concept for waste disposal
  - Safe retrieval operation seems feasible (remains to be proven)
  - but…
    - The measures affect the technical repository design
    - The retrievability option may result in a repository design which could challenge the notion of the best possible safety
- Retrieval of waste from the Asse Mine requires still a lot of conceptual thinking and preparatory work
  - Special adaptation of procedures for each chamber necessary
  - but … since the system evolves, is there enough time for this?

E. Simo

KOSINA Project Results: Geological Modeling and Technical Repository Concepts in Bedded Salt Formation

Eric Simo
BGE TECHNOLOGY GmbH

Hanover, Germany
September 10-11, 2018

Motivation

- According to the site selection act (StandAG, July 2013): All possible host rocks for a HLW repository must be investigated
- This includes also the bedded salt formations in Germany
- Safety demonstration concept for a HLW repository in salt dome is already available
- Aim of KOSINA: Development of generic repository concepts and safety and safety demonstration concept for bedded salt formation (Type: „flat-bedded salt" und Type „salt pillow")
  - ✓ Funded by BMWi/PTKA
  - ✓ Project Partners: BGR, GRS, IfG, BGE TECHNOLOGY

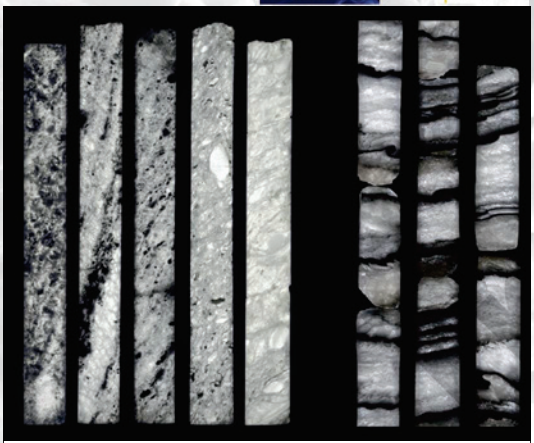
Objectives

1. Derivation of generic geological models and corresponding material parameters
2. Development of a safety and demonstration concept
3. Development of technical repository designs for four different disposal options
4. Analyses of the integrity of the geological barriers as well as analyses of radiological consequences
5. Generation of scientific-technical fundamentals for a safety-related evaluation of repositories in different host rock formations

Geological Modeling

Generic Geological Modeling

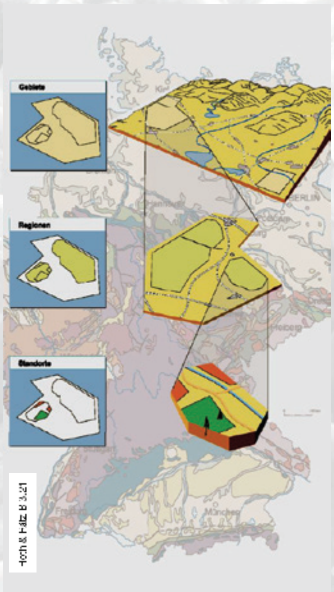
- Based on literature review of bedded salt studies in Germany
- BGR-Report: „Occurrence and Composition of Bedded Rock Salt Formations in Germany “ (2014)
- Caution: No Site Selection!



Staßfurt-Rock Salt Salt Dome Gorleben	Staßfurt-Rock Salt Flat-Bedded Salt Teutschenthal

Comparison of typical cross section of halotectonically deformed rock salt and bedded rock salt
Source: BGR, 2014

Generic Geological Modeling

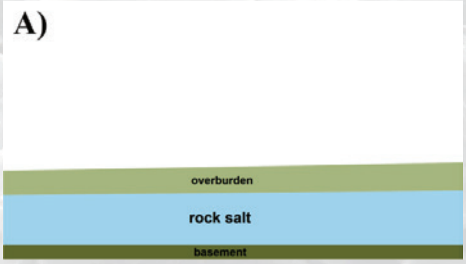


- Geoscientific exclusion criteria
- Minimum requirements for the generic geological model area
  - Permeability $<10^{-10}$ m/s
  - Host Rock Thickness >100 m
  - Depth > 300 m below ground level
  - Sufficiently large area for the design of the repository
  - max disposal depth: 1000 m
  - No risk of rock bursts

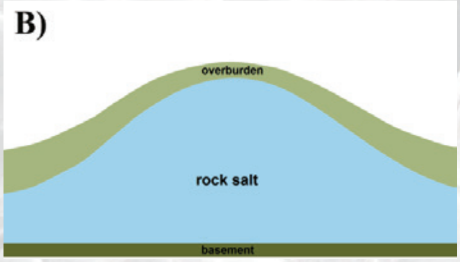
Source: AkEnd (2002) / Komission Lagerung hoch radioaktiver Abfallstoffe (2016)

Types of Bedded Salt Formations

Type „Flat-Bedded Salt“



Type „Salt Pillow“



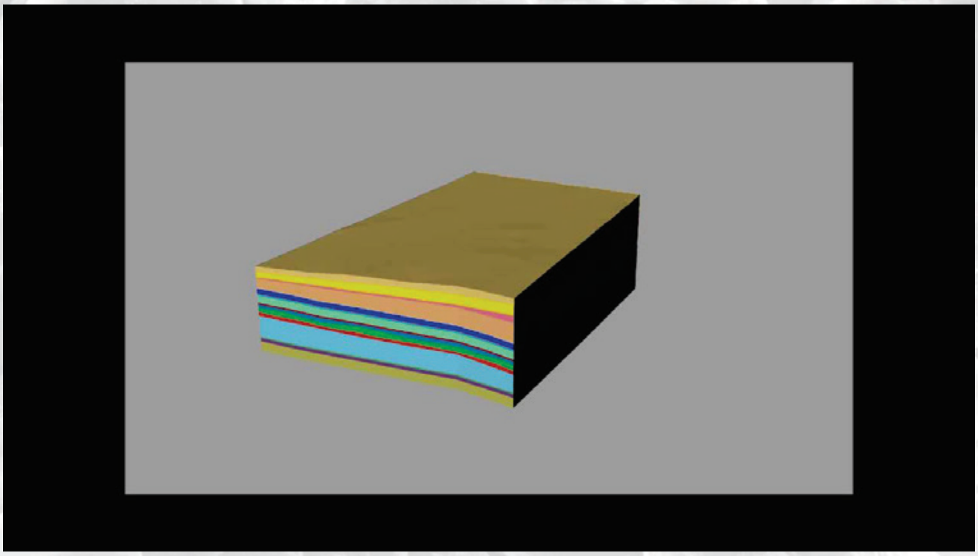
Genesis:

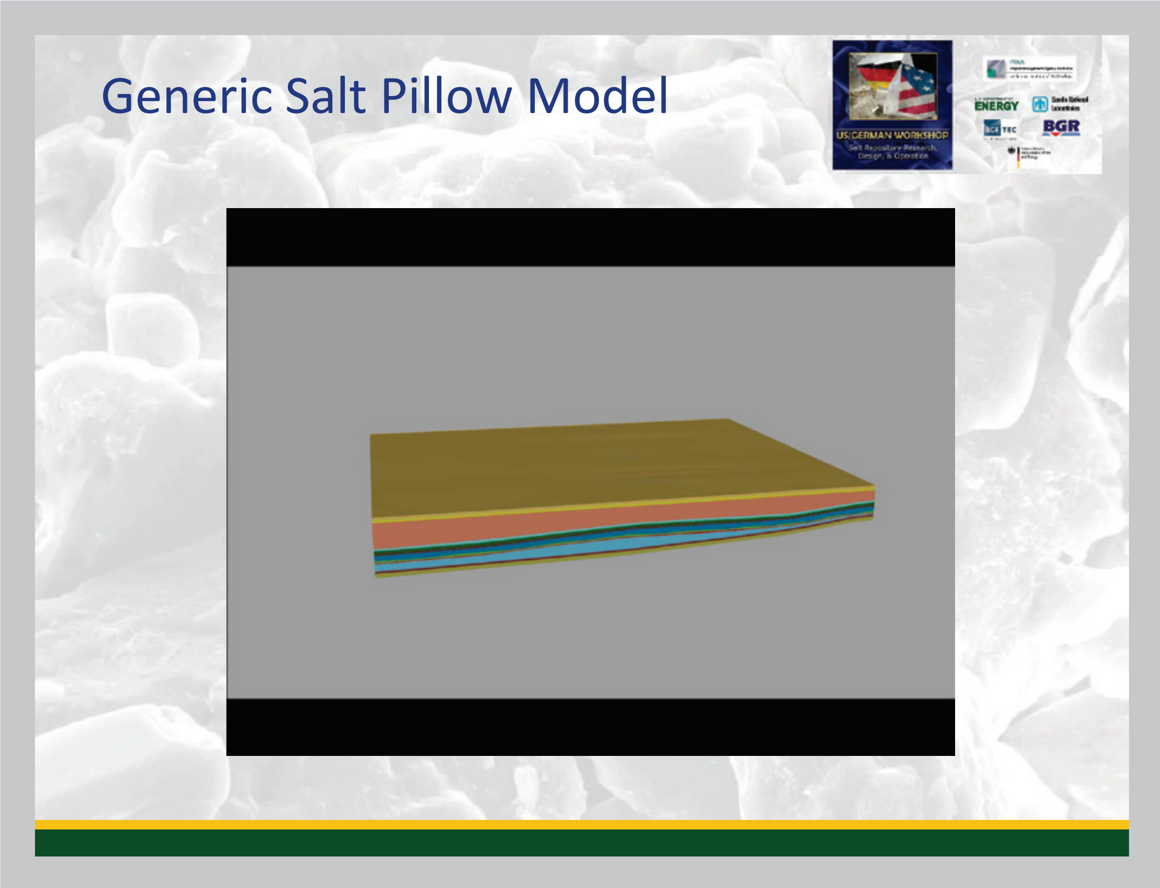
- Almost undisturbed bedding condition

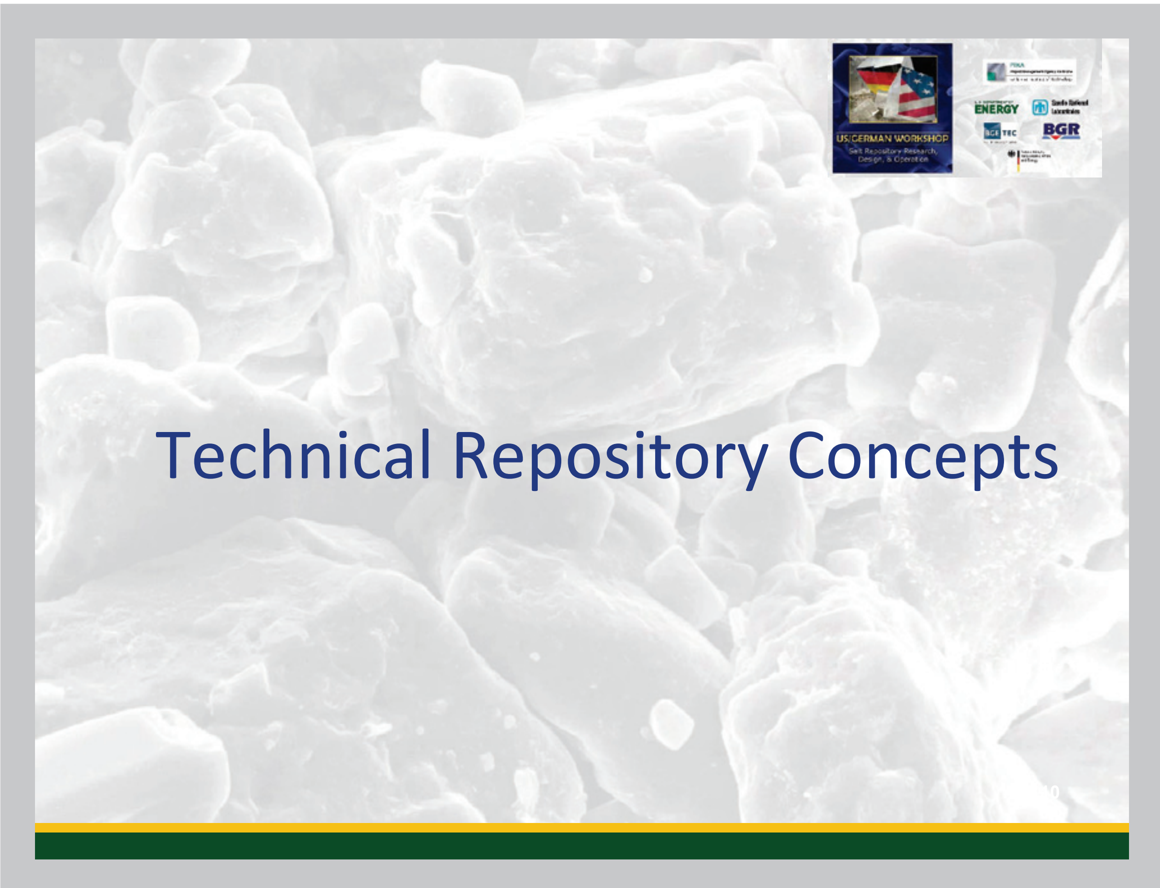
Genesis:

- Salt migration due to difference of densities
- Accumulation of rock salt by lateral inflow due to the mobility of the Staßfurt-Formation

Generic Flat-Bedded Salt Model




Generic Salt Pillow Model


Technical Repository Concepts

Fundamentals of Repository Design

1. **Inventory of radioactive waste and the corresponding waste casks**
2. **Thermal design of HLW Repository in compliance with the temperature criterion**
3. **Conception of the repository mine layout**
4. **Design and Planning of transport and emplacement technology**
5. **Design of geotechnical barriers**

1. Radioactive waste inventory

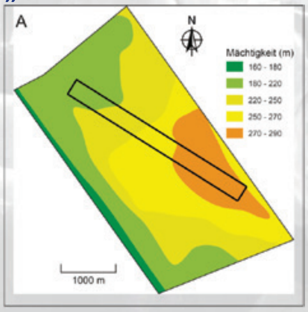
Waste from Nuclear Power Plants	N° of fuel elements - Metric tons of heavy metal
PWR (UO2+MOX)	13,980 – 7180 tons
BWR (UO2+MOX)	15,600 – 2685 tons
WWER (UO2+MOX)	5,050 – 580 tons
Total	34,630 fuel elements – 10445 tons

Waste from research reactors	N° of fuel elements
AVR	288,161 pebbles
THTR 3000	617,606 pebbles
KNK	2,484 rods
Otto-Hahn	52 rods
BER II	120 rods
FRM II	150 rods
FRMZ	89 rods
RFR	950 fuel elements and 1 fuel rod cask with 16 fuel rods

Waste from Reprocessing	N° of casks
CSD-V	3,729 casks
CSD-B	140 casks
CSD-C	4,104 casks
Total	7,973 casks

Disposal Concepts in KOSINA

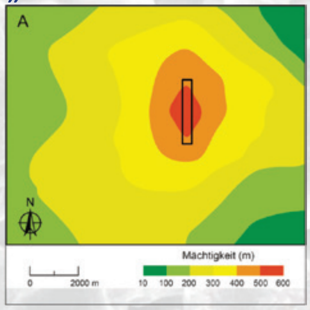
Type „Flat-Bedded Salt“



Disposal Concepts:

1. Drift Disposal Concept
2. Horizontal borehole disposal concept

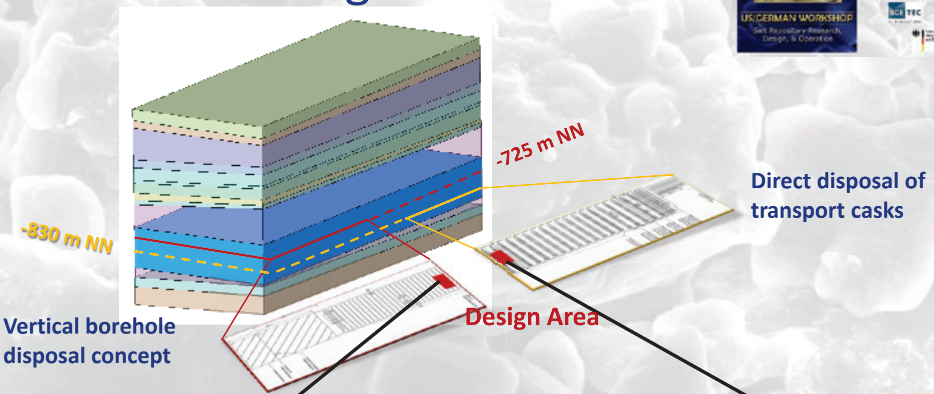
Type „Salt Pillow“

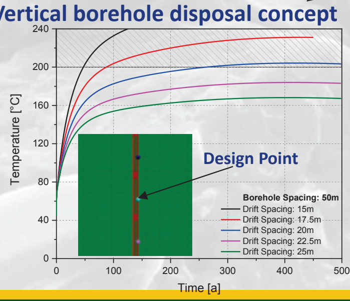


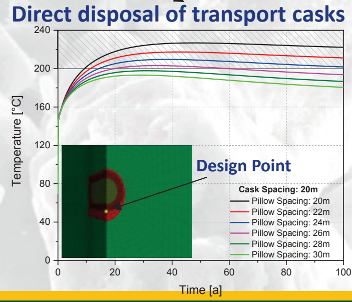
Disposal Concepts:

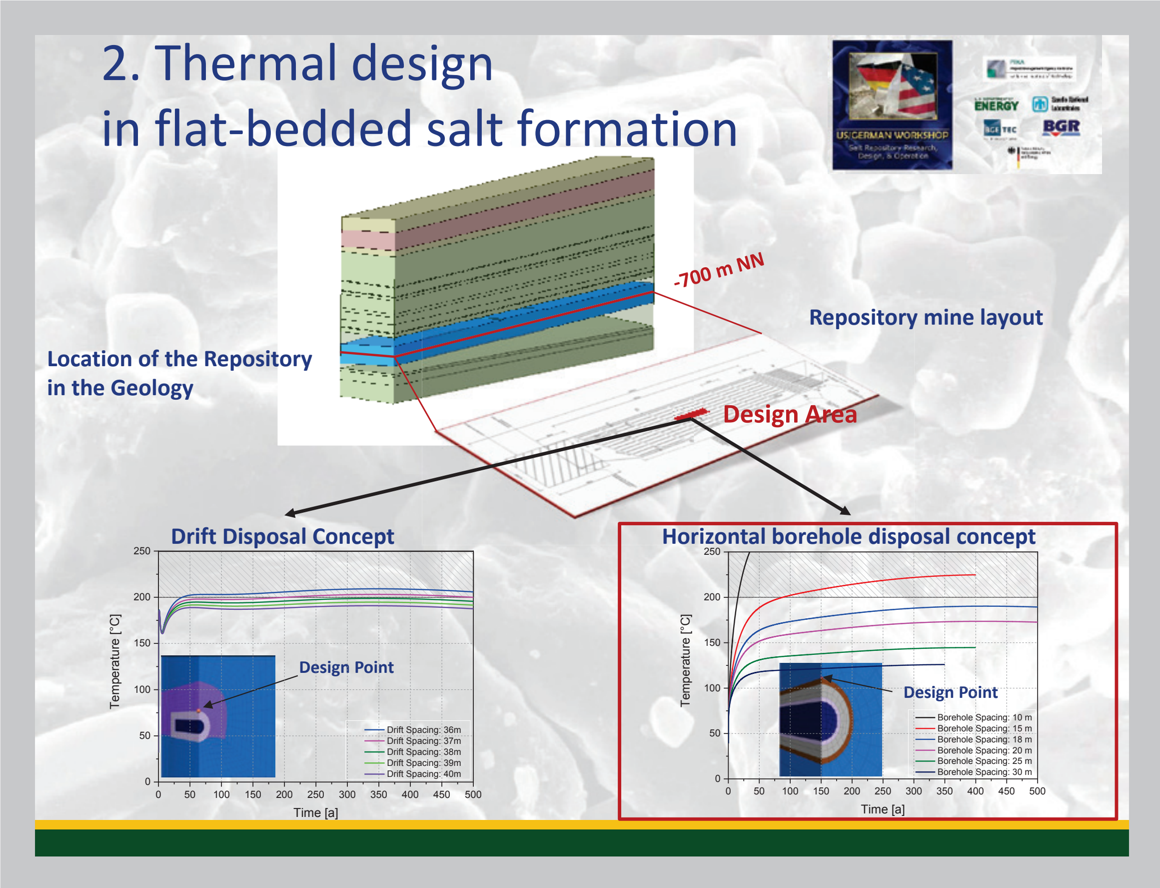
3. Vertical borehole disposal concept
4. Direct disposal of transport casks

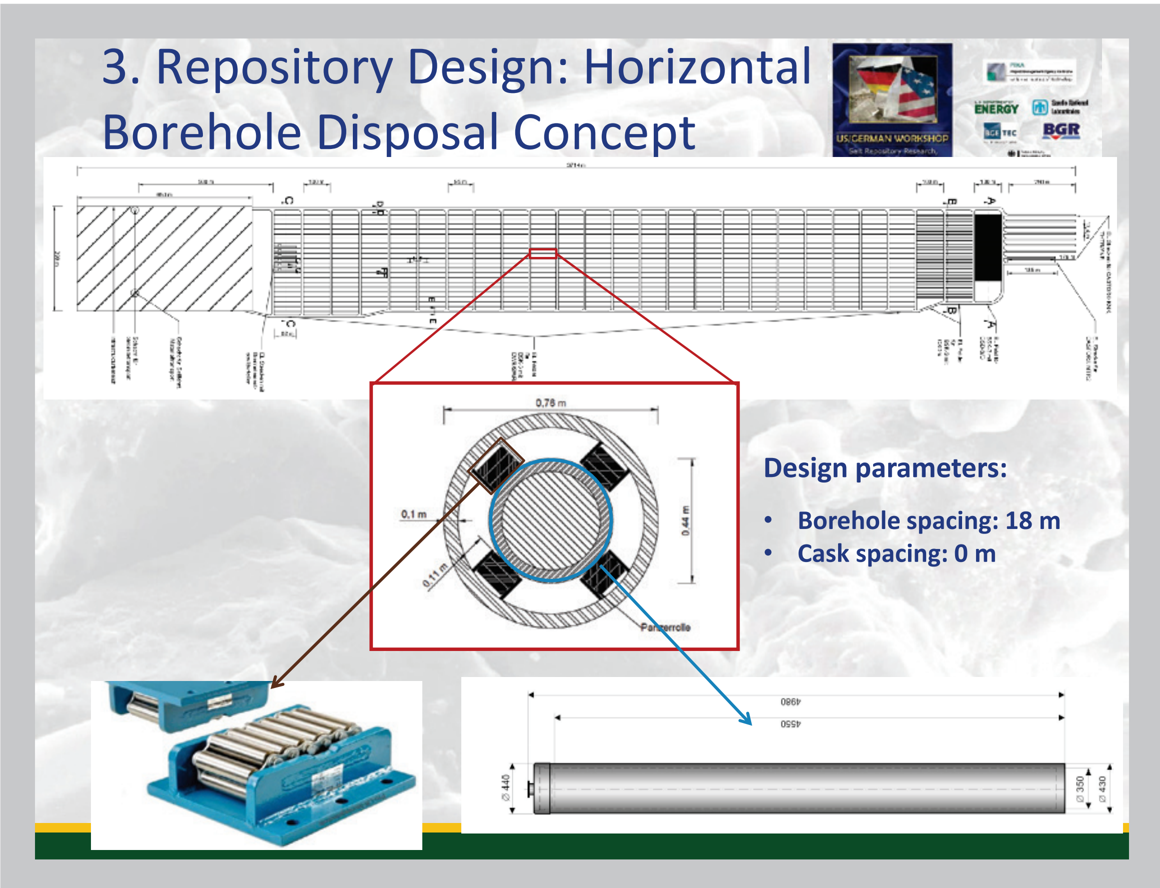
2. Thermal design in Salt Pillow



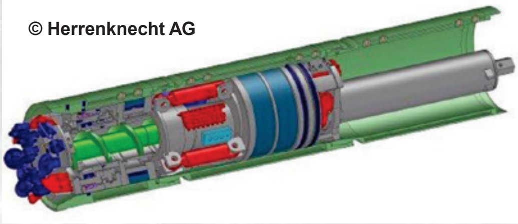


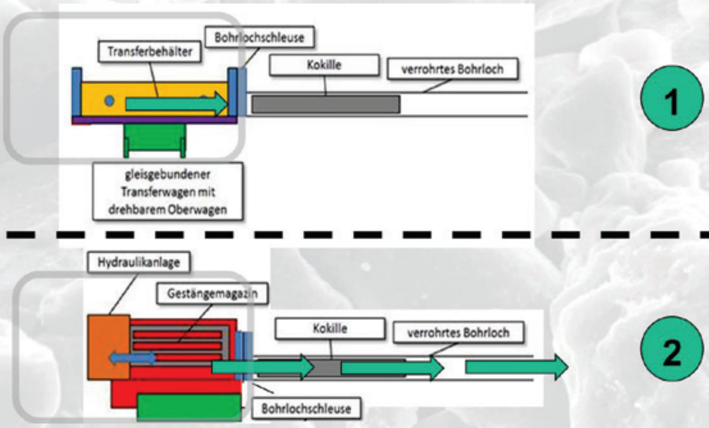



2. Thermal design
in flat-bedded salt formation
Location of the Repository
in the Geology
-700 m NN
Repository mine layout
Design Area
Drift Disposal Concept
Temperature [°C]
Time [a]
Design Point
Drift Spacing: 36m
Drift Spacing: 37m
Drift Spacing: 38m
Drift Spacing: 39m
Drift Spacing: 40m
Horizontal borehole disposal concept
Design Point
Borehole Spacing: 10 m
Borehole Spacing: 15 m
Borehole Spacing: 18 m
Borehole Spacing: 20 m
Borehole Spacing: 25 m
Borehole Spacing: 30 m
ENERGY
BGR
US/GERMAN WORKSHOP


3. Repository Design: Horizontal
Borehole Disposal Concept
0,78 m
0,1 m
0,44 m
0,11 m
Panzerrolle
Design parameters:
• Borehole spacing: 18 m
• Cask spacing: 0 m
4980
4550
Ø 440
Ø 350
Ø 430
ENERGY
BGR
US/GERMAN WORKSHOP

4. Emplacement Technology: Horizontal Borehole Concept





Summary

- 2 generic geological models for flat-bedded and salt pillow formation have been developed
- Design and Planning of 4 different disposal concepts in bedded salt formations have been realized
- A new idea for an emplacement technology for the horizontal borehole disposal concept has been developed
- The KOSINA project have shown the feasibility of HLW-repository in bedded salt formations


Wilhelm Bollingerfehr[1] (Coordinator), Niklas Bertrams[1], Dieter Buhmann[2], Ralf Eickemeier[3], Sandra Fahland[3], Wolfgang Filbert[1], Jörg Hammer[3], Jonathan Kindlein[2], Markus Knauth[4], Tatjana Kühnlenz[3], Wenting Liu[3], Wolfgang Minkley[4], Jörg Mönig[2], Till Popp[4], Sabine Prignitz[1], Klaus Reinhold[3], Eric Simo[1], Eike Völkner[3], Jens Wolf[2]
[1] BGE TECHNOLOGY GmBH, Peine, [2] GRS mBH, Braunschweig, [3] BGR, Hannover, [4] IfG GmBH, Leipzig
Thank you for your attention!
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages
BETREUT VOM
PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie

M. Knauth

KOSINA Project Results: Safety Concept / Safety Assessment and Geomechanical Integrity Analyses of Generic Repositories in Bedded Salt Formation

US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation

Markus Knauth
IfG Leipzig GmbH

Hanover, Germany
September 10-11, 2018

Outline

1. **Safety and Demonstration Concept**

2. **The derived numerical modeling tasks for the safety analysis within the KOSINA project:**

   - *analyses of the integrity of the geological barriers*

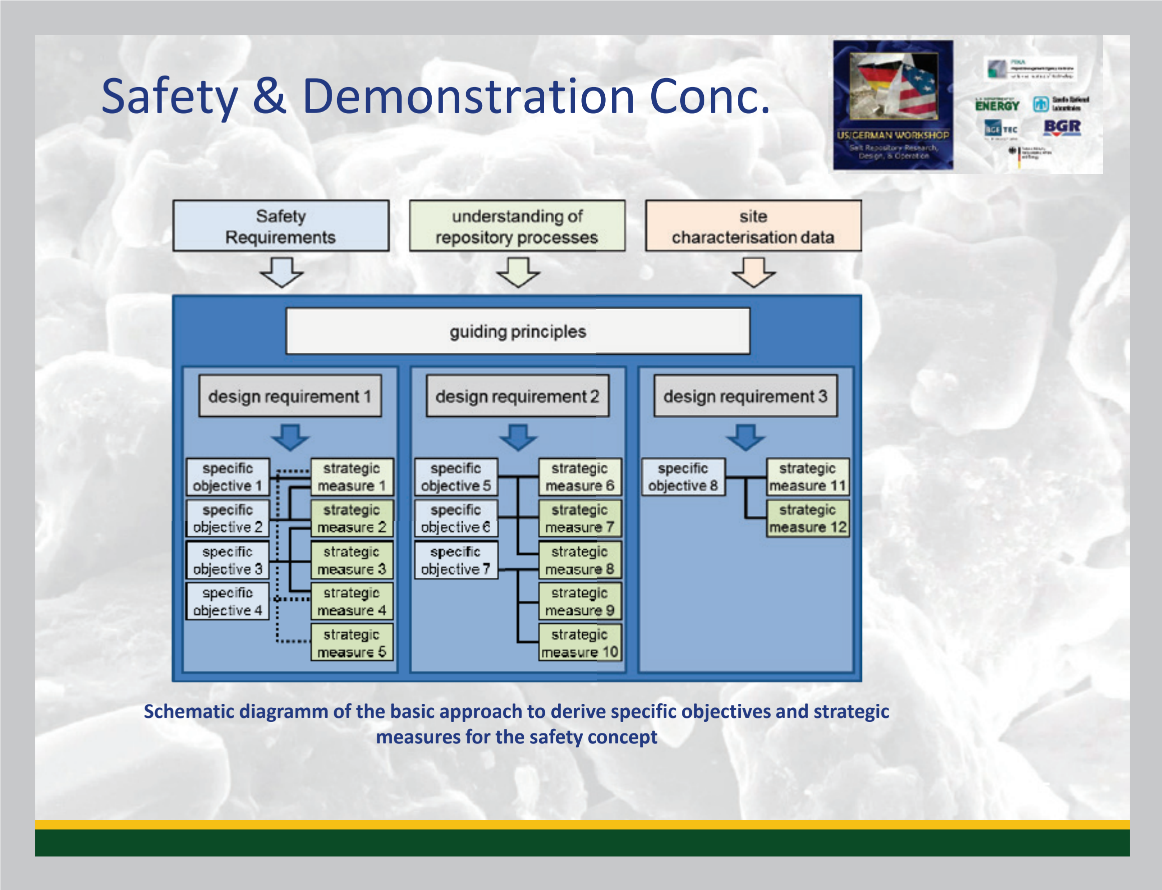
   - *analyses of radiological consequences*

Outline

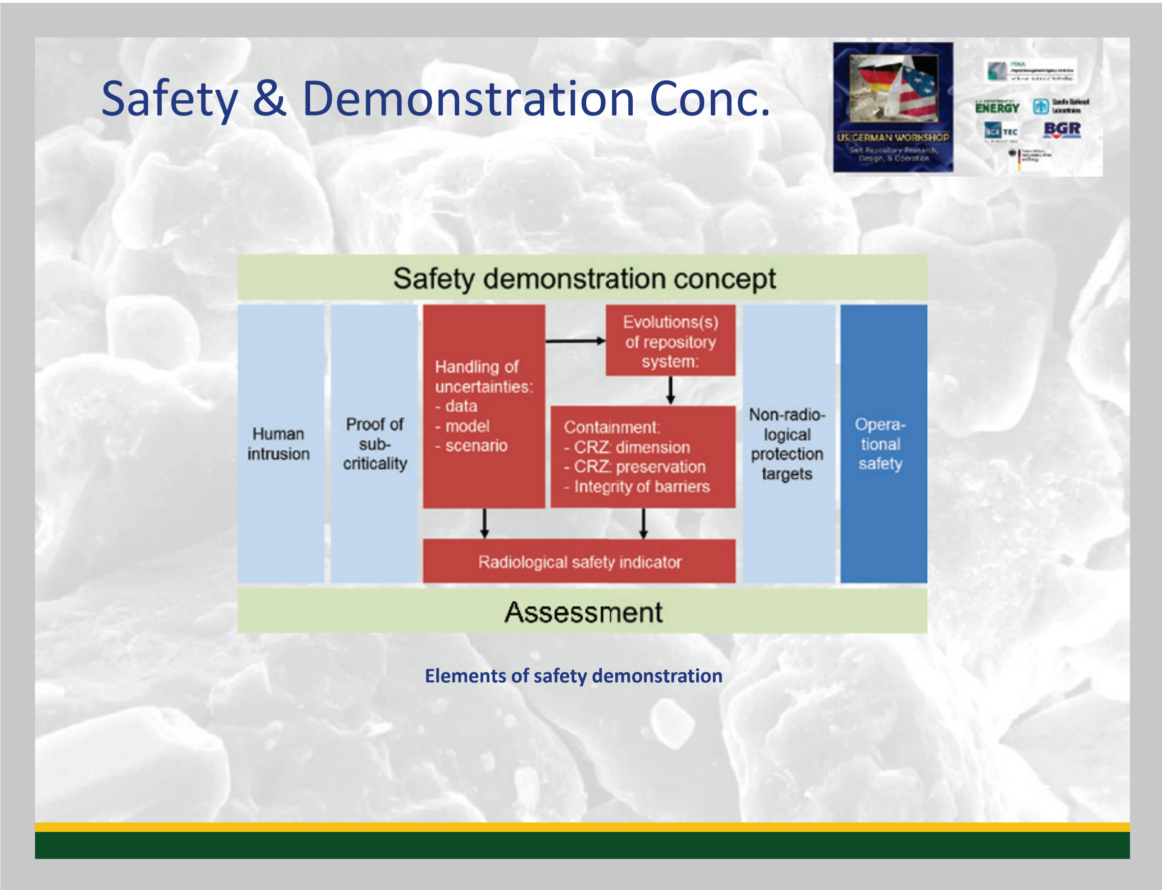
Safety & Demonstration Concept

Safety & Demonstration Conc.

- A **safety concept describes** in a verbal, argument-based way **how the natural conditions, processes and technical measures contribute to** accomplishing and maintaining the required level of **long-term safety**.
- its **fundamental principle = concentration and containment** of radioactive and other contaminants in the waste in the containment-providing rock zone (CRZ),
- guiding principles, design objectives and strategic measures are derived
- A **safety demonstration concept describes the means**, such as analyses and arguments, which are **used to demonstrate safety of a repository system** on the basis of the safety concept
- **decisive elements**:
  - the demonstration of integrity of the geological barrier
  - the demonstration of integrity of the geotechnical barriers
  - the scenario analysis
  - the evaluation of the identified scenarios
  - complemented by concepts on how to consider criticality, non-radiological protection targets and operational safety.



Schematic diagramm of the basic approach to derive specific objectives and strategic measures for the safety concept



Elements of safety demonstration

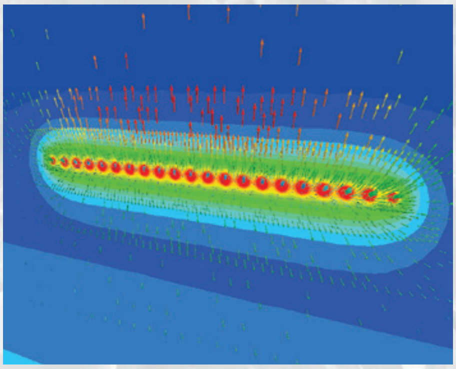
Barrier integrity

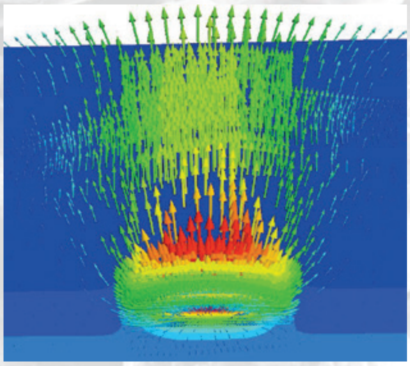
Integrity of geological barriers

Barrier integrity

- **Disposal of heat-generating radioactive waste leads to a thermal expansion in and around the repository**

→ ***Question***: Is barrier integrity preserved in spite of the hereby induced geomechanical stress and strains?





Barrier integrity

- Numerical models by BGR and IfG using different constitutive laws, model dimensions and modeling approaches

BGR

- Large far-field models
- Fully 3D
- Smeared (averaged) heat sources
- Continuum mechanics
- TM-coupling

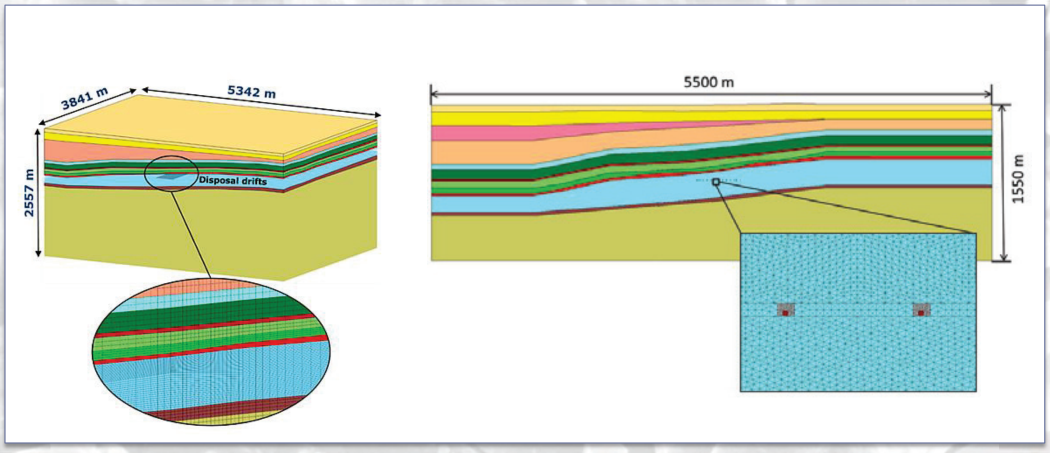
IfG

- 2D- & /3D-slice models
- Explicit modeling of emplacement drifts, waste canisters etc.
- Discontinuum mechanics
- THM-coupling

→ Mutual checking and comparison of the different methods

Barrier integrity

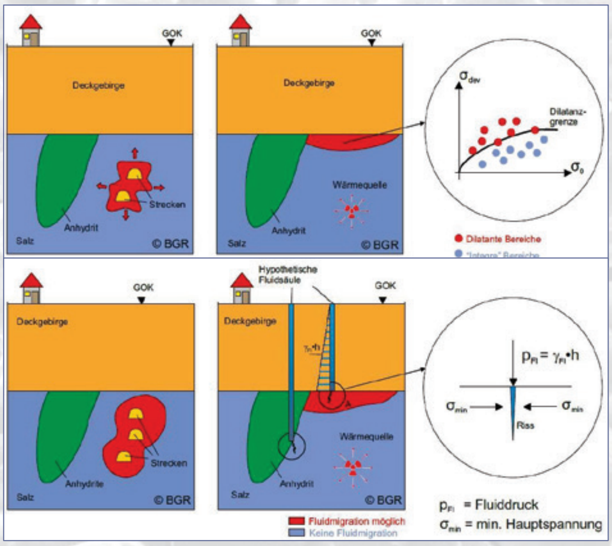
Numerical models, example of drift disposal of Pollux® - casks in flat-bedded salt



3D-Model

2D-Model

Barrier integrity



Dilatancy Criterion

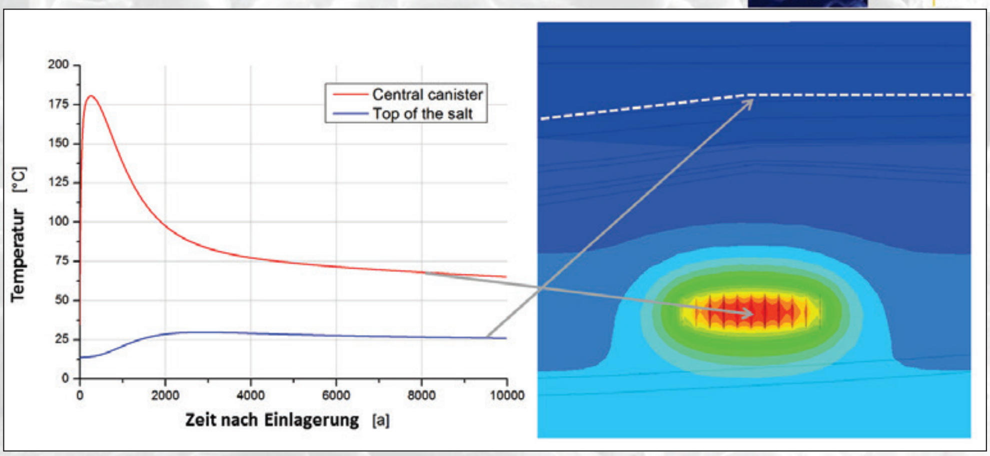
- Stresses max not exceed dilatancy boundary. If deviatoric stresses exceed this boundary, micro-fracturing occurs which leads to a progressing damaging of the rock salt, thereby increasing permeability.

Fluid pressure criterion

- The hydrostatic pressure of a thoeretically acting fluid column up to the surface should not exceed the minumum principle (least compressive) stress.

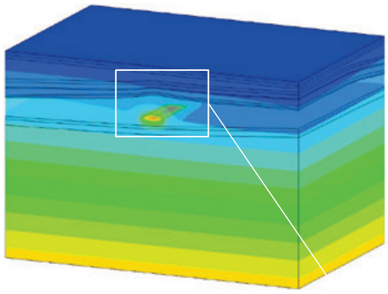
→ When one of those is violated, it has to be shown that no continuous violation from groundwater aquifer to emplacement horizon exists.

Barrier integrity



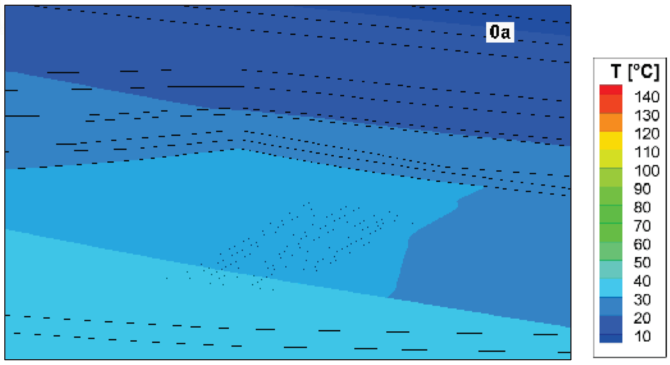
- **Rapid increase in temperature after emplacement**
- **Max. temperature close to design temperature (200 ° C)**
- **Lower max. temperature in models with smeared heat sources**

Barrier integrity

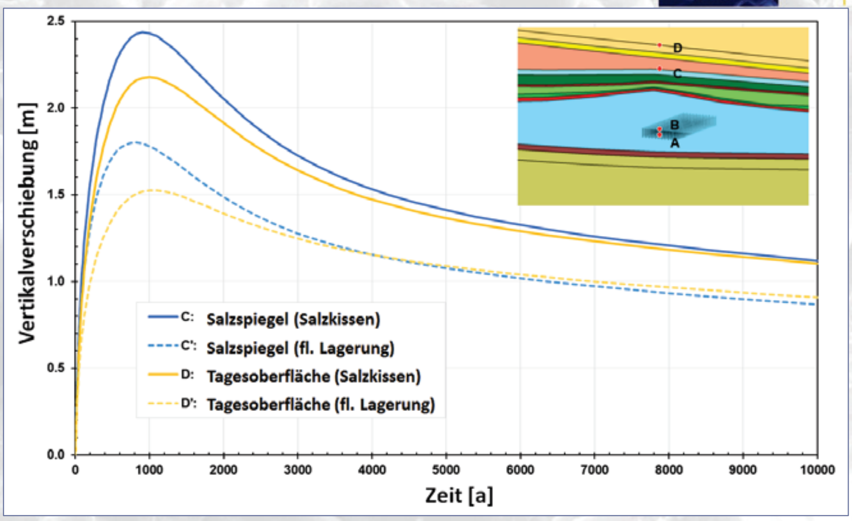


Temperature development in the example „direct disposal of transport casks in salt pillow“

100 years after emplacement



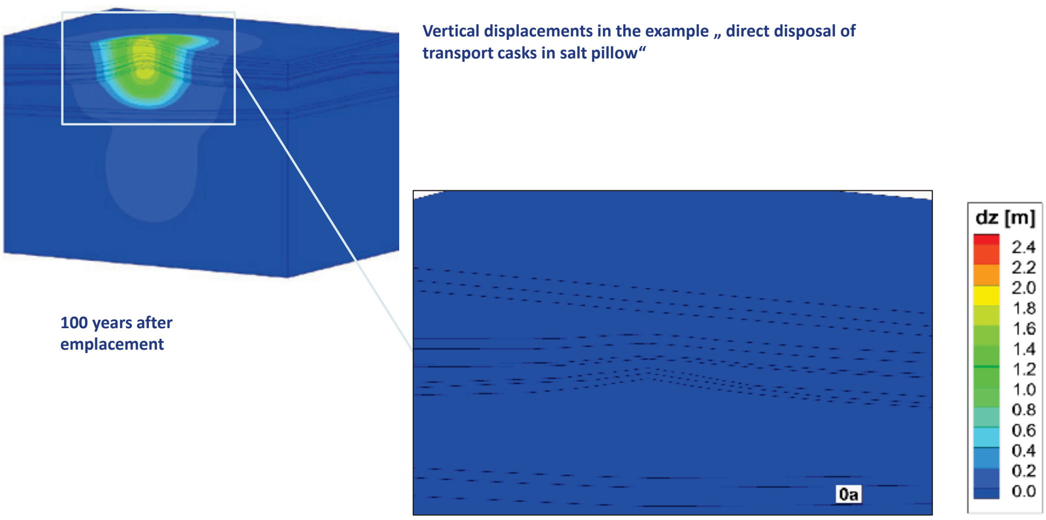
Barrier integrity



- Uplift above repository, max. between 1,5-2,5 m (depends on geologic structure and repository design variant)
- Max. after about 800 – 1000 years after emplacement

Barrier integrity

Vertical displacements in the example „ direct disposal of transport casks in salt pillow“

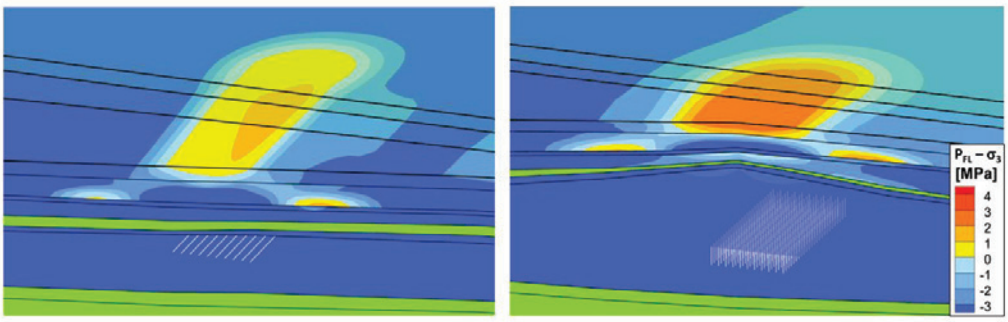


100 years after emplacement

Displacement magnified x100

Barrier integrity

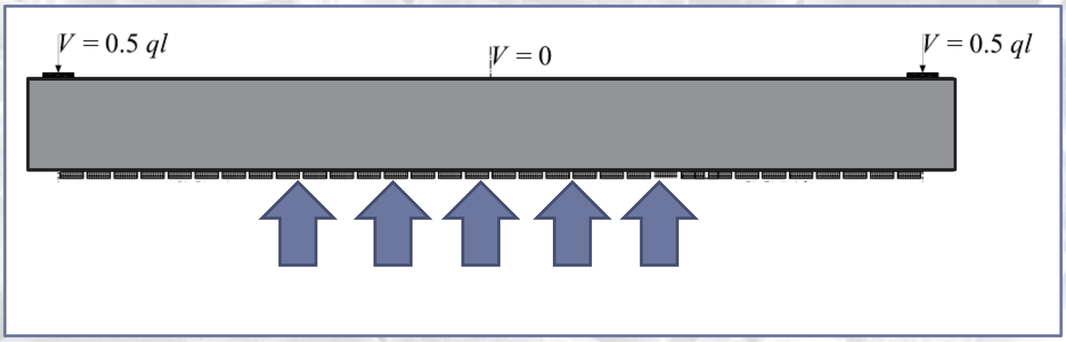
Fluid pressure criterion (approx. 50 years after emplacement) for drift emplacement in flat-bedded salt (left) and vertical borehole disposal in the salt pillow (right).



- Violation of the fluid pressure criterion at the top of the salt
- Only temporary violation, penetration depth max. 60 m
- > 300 m undisturbed barrier at any given time during the simulation

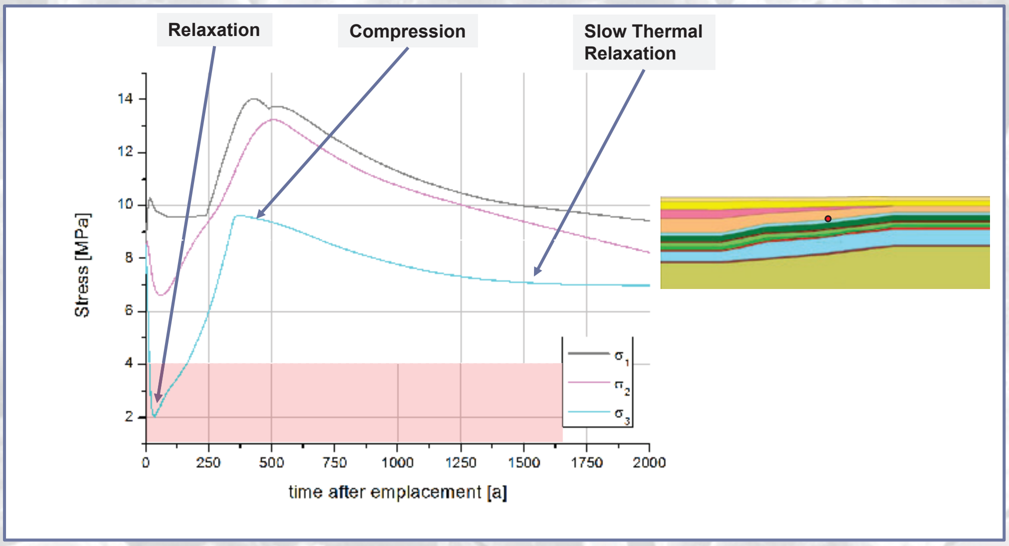
→ Integrity of barrier is preserved

Barrier integrity



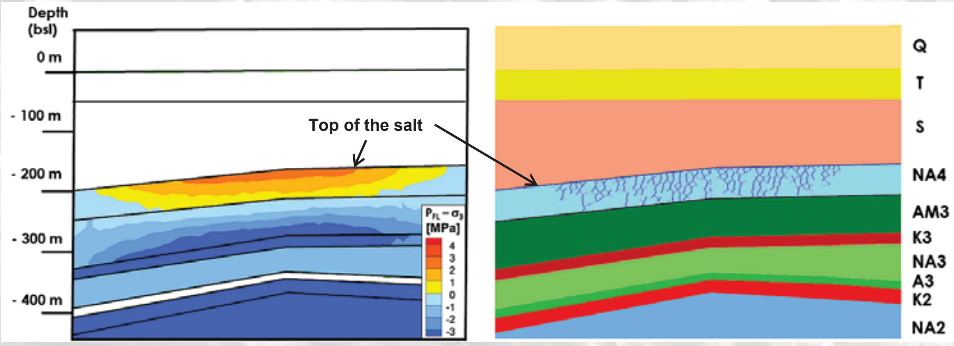
Bending beam analogy

Barrier integrity



Development of principle stress at top of the salt (drift emplacement in flat-bedded salt)

Barrier integrity



- Coupled discontinuum-mechanical simulation confirms the violation area of the fluid pressure criterion
- Predominantly the reduction of horizontal stresses leads to vertically aligned fluid percolation into the top of the salt
- Also in these simulation always > 300 m undisturbed barrier remaining

Radiological Consequences

Analysis of Radiological Consequences

Radiological Consequences

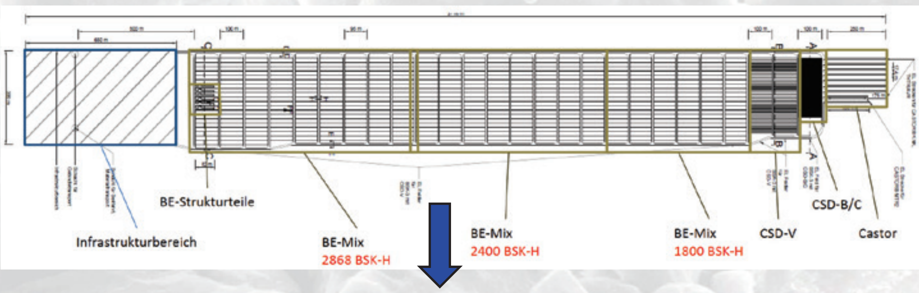
- Numerical analysis of the long-term behavior of the repository in terms of potential radionuclide release (performed by GRS Braunschweig)

→ Propagation calculation of radionuclides in the fluid phase

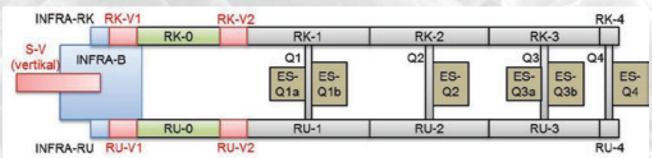
Radiological Consequences

- Modeling „horizontal borehole disposal“

Grouping of areas based on the repository layout:



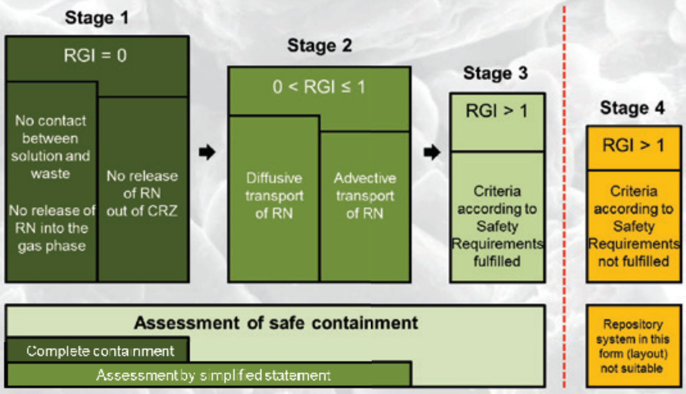
Derivation of a LOPOS segmented-structure model



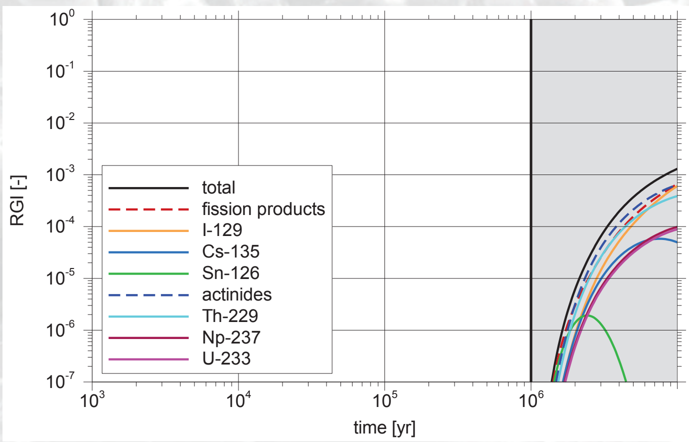
Radiological Consequences

- Evalution of consequences using the indicator RGI (radiol. Gerinfügigkeits-index)
- Yearly stream of radionuclides distributed on the yearly water consumption W [m³/a] of a collective of 10 adults

→ Negligible release at an RGI ≤ 1



Radiological Consequences



Radiological consequences (RGI) for base case scenario of drift disposal concept

Summary

- Performed num. Simulations on barrier integrity
  - 2 disposal concepts in 2 generic geological models (each)
  - Different model dimensions, constitutive models and modeling methods (BGR +IfG)
  - Good agreement in results
- Uplift-induced temporary violation of the fluid pressure criterion in a limited area at the top of the salt
- Penetration depth and duration of violation depends on disposal concept and geological model
- Barrier integrity preserved in all cases, always at least 300 m of undisturbed rock salt
- Analysis of radiological consequences shows no exceedance of RGI (by far) within the demonstration period (and longer)

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Thank you for your attention!

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D. Ware, D. Weaver, B. Dozier, S. Otto, J. Rutqvist, Y. Wu

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US DOE Office of Nuclear Energy (DOE-NE) Borehole Heater Tests at WIPP on Coupled Processes

Kris Kuhlman, Melissa Mills, Courtney Herrick, Ed Matteo, Martin Nemer
Sandia National Laboratories

Phil Stauffer, Hakim Boukhalfa, Doug Ware, Doug Weaver, Brian Dozier, Shawn Otto
Los Alamos National Laboratory

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WIPP Coupled Processes Test

- **Goals of Bedded Salt Field Test**
  - Brine availability, transport, and chemistry in bedded salt formation
  - Changes in permeability, porosity, and borehole closure during test
  - Compare similar heated/unheated tests
  - Collect data to validate numerical/constitutive models
- **Modular Design**
  - Waste Isolation Pilot Plant (WIPP) providing test access/infrastructure
  - Central test borehole
    - *(~12.7-cm [5"] diameter, 6 m long, 2 m test interval)*
  - Satellite observation boreholes
    - *(multiple locations and various diameter)*
  - Packer or plug isolation of boreholes from drift air
  - Two parallel tests: heated (120 C) and unheated (~30 C) conditions

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Test Motivation

- **Generic Investigation of Processes in Bedded Salt**
  - Validation data for numerical models
  - Generic investigation of bedded salt formation
- **Bedded vs. Domal Salt**
  - Bedded salt is layered and includes clay, polyhalite, or anhydrite layers
  - Bedded salt has higher brine content than domal salt
  - Previous German heater tests in domal salt
- **Previous Heater Tests in Bedded Salt**
  - Large-diameter vertical boreholes
  - Crossed significant (i.e., mapped) clay layers
  - Test response was dominated by non-salt layers
  - Previous Results more difficult to transfer generically
- **Planned Horizontal Test Orientation**
  - Avoids mapped clay, polyhalite, or anhydrite layers
  - Test interval beyond room disturbed rock zone (DRZ)
  - Interval completed in single geologic unit (MU-0 at WIPP)

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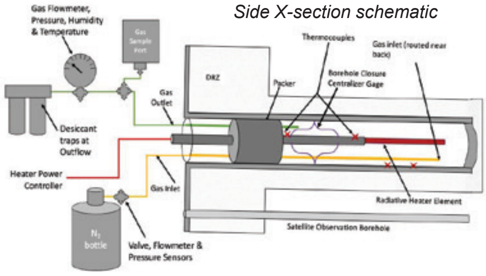
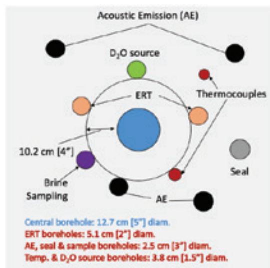
Test Design

- **Two Test Arrangements (heated + unheated)**
- **Packer-Isolated Interval in Main Borehole**
  - Single inflatable packer
  - Infrared radiative heater* (~400 W)
  - Vapor extraction with dry N_2
  - Gas/vapor sampling
  - Thermocouples
  - Gas permeability tests behind packer
  - Borehole closure
- **Satellite Observation Boreholes**
  - 2 Electrical resistivity tomography boreholes*
  - 4 Acoustic emission monitoring boreholes*
  - 2 Temperature observation boreholes
  - 1 Liquid brine sampling borehole
  - 1 Deuterated water tracer spike
  - 1 Cement-plug/borehole interaction test

** Heated test only*

Side X-section schematic





Drift view of borehole locations

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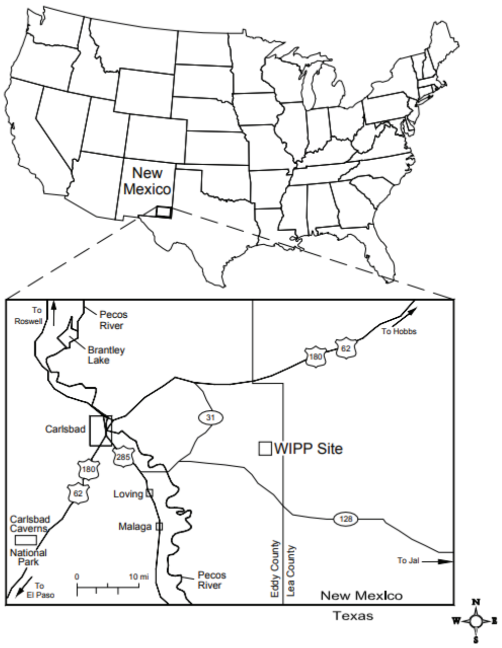
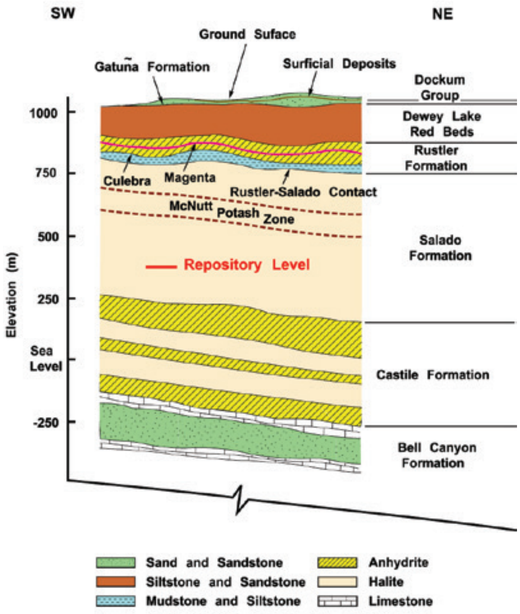
WIPP Context





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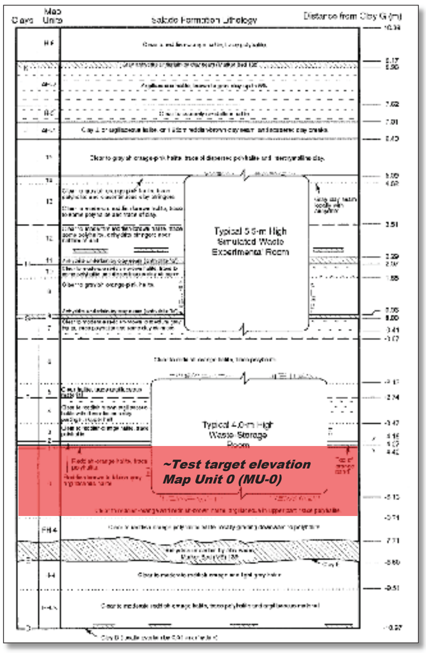
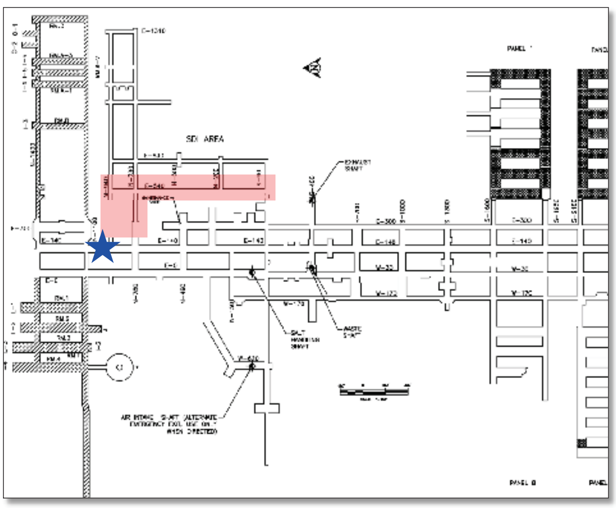
WIPP Bedded Salt Test Location



- **New Boreholes to be Drilled Late 2018**
  - Boreholes located in SDI area (red)
  - Current test location at blue star



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Heated Borehole Expectations

- **Three Sources of Water in Salt**
  - Intergranular brine
    - *Moves due to liquid pressure, thermal expansion & vapor transport*
  - Intragranular brine (fluid inclusions)
    - *Moves due to thermal gradients (becomes intergranular brine)*
  - Hydrous minerals
    - *Dehydration temperatures for each hydrous mineral (steam transport)*
- **Heated Borehole Wall ~120 C**
  - Borehole closure due to salt thermal expansion + accelerated creep
  - Increased brine flow due to thermal expansion of brine
  - Permeability of salt will decrease during heating
  - Acoustic emissions due to cracking from heating and creep
- **Monitoring will continue after shutdown of heater**
  - Permeability will increase significantly at cool down (brine pulse)
  - Acoustic emission burst during cooldown
  - Some borehole closure will be reversed (while some lost to creep)

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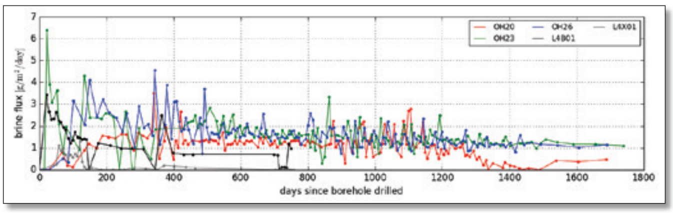
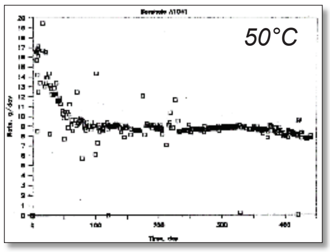
Brine Inflow Expectations

- **Brine Inflow**
  - Highest flowrate initially
  - Exponential decay of rate with time
- **More Brine Inflow at Higher T**
  - Vapor from dehydration of clay & gypsum
  - Brine from fluid inclusions
- **1997 Unheated Brine Inflow Study**
  - INTRAVAL Study (Beauheim et al. 1997)

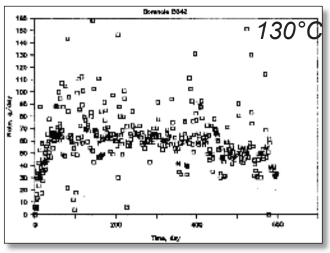
Kuhlman et al. (2017)



Unheated borehole brine inflow at WIPP in MU-0 (did not cross mapped clay layer)



Vertical WIPP boreholes



Vertical boreholes intersected clay layers (Rooms A & B) Nowak & McTigue (1987)

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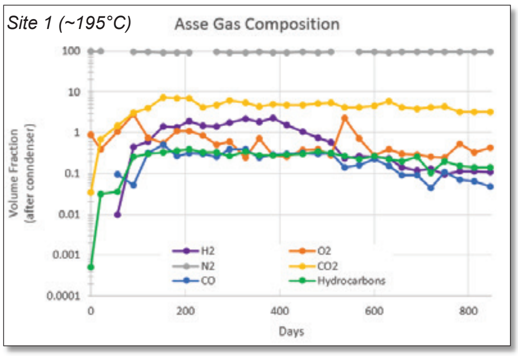
Gas Composition Expectations

- **Gases From:**
  - Possible volatiles in salt (e.g., hydrocarbons at Asse)
  - Dissolved gas in brine (~15 MPa pore pressure in far field)
  - Components in seals and packers?
- **Water Vapor from Brine**
  - Natural H_2O
  - D_2O tracer breakthrough
    - Transport time through salt
    - Fractionation in borehole
    - Tried at Avery Island (Krause, 1983)
- **Acid gas from Salt & Brine**
  - Decomposition of hydrous Mg salts
  - Equilibration of $P_{HCl(g)}$ into condensed steam



Data from *Coyle et al. (1987) BMI/ONWI-624*

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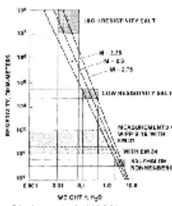
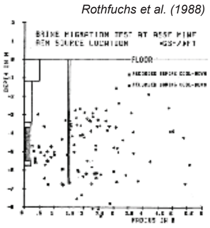
ERT/AE Expectations

- **Electrical Resistivity Tomography (ERT)**
  - ERT electrodes cemented into 2 boreholes
- **Salt Apparent Resistivity**
  - Function of porosity and brine saturation
- **Conduct 3D ERT Surveys Through Time**
  - Estimate evolution of porosity/saturation
  - ERT conducted in heated test only
- **Acoustic Emissions (AE)**
  - AE monitored during heat up & cooldown
  - Locate AE sources near heated borehole
  - AE correlated with permeability increases
  - AE system installed in heated test only
- **Ultrasonic Wave Travel-time Data**
  - May estimate extent/evolution of DRZ

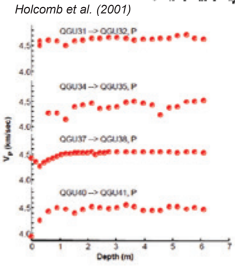


Skokan et al. (1989)

Rothfuchs et al. (1988)



Holcomb et al. (2001)



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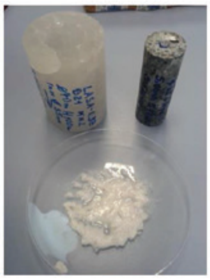
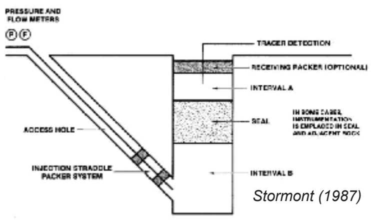
Cementitious Seals Expectation

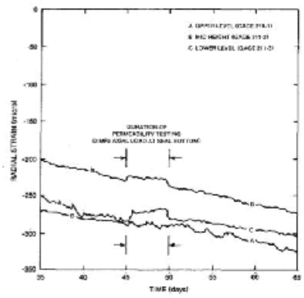
- **Emplace Pre-fabricated Cement Plug**
  - Snug fit into satellite borehole
  - Gas line embedded in plug
  - Monitor seal evolution as borehole closes
- **Upscale GRS Lab Seals Tests (DOPAS)**
- **Compliment Field Scale Sealing Tests**
  - ERAM Test Seal - salt concrete
  - Asse tests - Sorel cement and salt concrete
  - WIPP Field Seals Tests
- **Post-test Overcore for Salt/Cement Interface**



Czaikowski & Wieczorek (2016)



Stormont (1987)



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Probable Test Data for Comparison

- **Central Borehole**
  - Water production and temp/power time series
  - Borehole permeability measurements before/during/after test
  - Borehole diameter time series
- **Acoustic Emissions (AE) Timeseries**
  - Location and timing of AE during heating/cooling
- **4D Electrical Resistivity Tomography**
  - 3D evolution of porosity/saturation during heating/cooling
- **Brine and Gas Composition**
  - Brine and gas composition samples collected before/during/after
  - Water isotope (i.e., D_2O) samples to delineate tracer breakthrough
- **Comparison of Parallel Heated and Unheated Tests**
  - Effects of heat on borehole closure, borehole permeability, brine production, brine composition & gas composition

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Proposed Project Timeline

- **Construction/Testing**
  - New boreholes to be cored late 2018, instrumentation installed ASAP
  - Heated test conducted for ~9 months
  - Unheated test conducted ~12 months
  - Likely follow-on test (similar setup) at different power/temp.
- ***2019:* Initial Test Execution**
- ***2020:* Distribute Initial Test Data**
- ***2021:* Simulate Single Processes (+ Thermal)**
  - Brine production, D_2O transport
  - Thermal-Hydrologic (TH), Thermal-Mechanical (TM), Thermal-Chemical (TC)
  - Follow-on test data available
- ***2022:* More Coupled Processes**
  - Salt permeability/porosity as a function of damage (THMC)
- ***2023:* Include ERT/AE/Brine Composition Data**

- **Possibly Interested Parties**
  - US, Germany, UK, Spain, Netherlands, Poland

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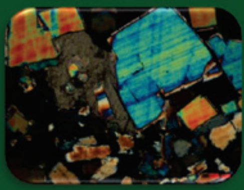

Supplemental Discussion – Comparison of Bedded vs. Domal Salt

9th US/German Workshop on Salt Repository Research, Design, and Operation

- Steven R. Sobolik, Sandia National Laboratories, Albuquerque, New Mexico, USA

- Hannover, Germany
- September 10-11, 2018

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Introduction

- US-German Workshops have focused effort on developing thorough understanding of salt repository design, analysis, operation, and long-term prediction.
- Necessary component of these efforts is predictive modeling of the mechanical behavior of the repository during the operational period and long-term.
  - Validation (Benchmark comparison of WIPP Rooms B & D)
  - Salt mechanical models & properties such as creep, strength, and dilatancy envelopes are based on laboratory tests
- Inevitably discrepancies exist between model results and observed behavior.

Characteristics of Repository Modeling

- Prediction of future repository behavior for operational concerns and long-term performance
- License application – demonstrate repository behavior compliance to specific set of regulatory standards
- Prediction of room closure rates for disposal, worker safety, and seal performance
- Capability to predict salt response to short-term stress changes (other than post-mining transient creep) not currently required

Cavern Modeling

Requirements have evolved over time

- Models originally required to provide prediction of surface subsidence, rate of cavern closure for capacity planning; used single creep model, set of properties based on limited lab tests
- Early predictions were for long-term (20-50 years) future behavior; models eventually required validation with past behavior
- As storage sites age, new issues include highly variable cavern closure rates, cavern integrity, well casing integrity, accessibility to oil due to cavern geometry features (sagging roofs, salt fall damage to hanging strings)
- These issues require **confident** analysis of transient creep response of salt to short-term, large pressure changes

Progression of Complexity of Salt Cavern Geomechanical Models

Earliest Models	Progression of Model Complexity	Reason for Model Advancement
Primary Purpose: Long-term projection of surface subsidence, cavern volume closure	Primary Purpose: Analysis of individual cavern behavior, use as diagnostic tool, aid for developing strategies for well & cavern integrity management and remediation	As the sites age after 35+ years of use, creep-induced and other problems occur, requiring modeling tools with better resolution, validation, and problem-solving utility
Simplified dome geometries (30-degree wedge to simulate 19-cavern field; half-dome with symmetry axis)	Full dome included in model; initially as extruded "cylinder" of footprint, now as genuine rendering of shape based on seismic data	Need to know geomechanical behavior of specific caverns based on geometry, location, proximity to side of dome (post-Bayou Corne)
Caverns shaped as simple cylinders or frustums	Caverns shapes based on axisymmetric (and now, true) renderings of sonar-measured geometries	Need to know GM behavior resulting from cavern geometry – effect on dilatant/tensile stresses, casing integrity
Power law creep model (single steady-state mechanism)	M-D creep model (Multiple steady-state creep mechanisms with transient; Munson, 1998)	Need to evaluate cavern response to transient large ΔP events such as workovers

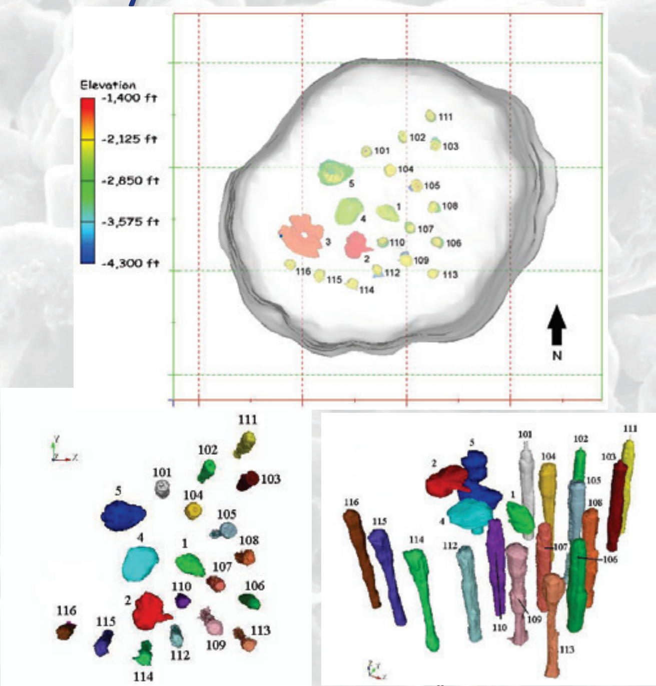
Progression of Complexity of Salt Cavern Geomechanical Models

Earliest Models	Progression of Complexity	Reason for Advancement
Single set of salt creep properties based on lab tests of up to 6 samples (Munson, 1998)	Cavern-specific creep properties (K_0 transient multiplier, A_2 steady-state coeff.) calibrated to try to match measured cavern volume closures	Volume closure rates for caverns of similar geometry, depth vary across a site: West Hackberry by factor of 3, Bryan Mound by factor of 10
Model predictions compared to historical cavern volume closure, surface subsidence, one single A_2 multiplier for entire site (power law creep)	Same data used for model calibration, with partial success; for West Hackberry, K_0 from Munson multiplied by 18.2, A_2 by 0.89-3.2	Better match of individual cavern closure performance hopefully leads to more confident predictions of future cavern behavior
Prescribed constant wellhead pressure with workovers at 5-year intervals	Historical wellhead pressures through current times, then future prescribed pressures	More accurate past history; sympathetic pressure behavior of caverns adjacent to those under workover
Simplified renderings of salt dome, caprock, surrounding rock as single-unit, homogeneous (no faults or shear zones), perfectly bonded	Inclusion of regions with significantly different creep properties; inclusion of low E/low strength interface zones between salt & caprock, salt and surrounding rock	Site-specific observations: casing damage at salt-caprock interface at Big Hill; interface zone, inward-slope at salt dome wall for Bayou Choctaw; different salt zones at Bryan Mound

Two SPR model examples

- Bryan Mound – highly variable salt dome
  - Highly heterogeneous salt
  - Bizarre cavern shapes, caused by anhydrite/clay seams and impurities, faults, and shear zones
  - Gas intrusion from outside the formation into several caverns
  - Caprock steam-mined for sulfur in 1920s
  - Abandoned large-diameter cavern in middle of site, ongoing concern for potential cavern collapse
- West Hackberry – well-constrained salt dome (not included in these slides)
  - Homogeneous salt
  - Axisymmetric caverns
  - No obvious fault or shear zone features
  - Competent caprock

Bryan Mound SPR Site



Bryan Mound site includes:

- ~226 MMB of oil storage.
- 4 unusually-shaped storage caverns (#1, 2, 4, 5) built in 1940s-1950s.
- 16 cylindrical-shaped storage caverns (#101-116) built in early 1980s.
- Approximately 230 m sandstone overburden, 85 m anhydrite/ carbonate caprock over salt dome.
- **Highly heterogeneous salt** with anhydrite/clay seams, faults, shear zones
- Caprock mined for sulfur in 1920s – large vugs, thermal signature remain

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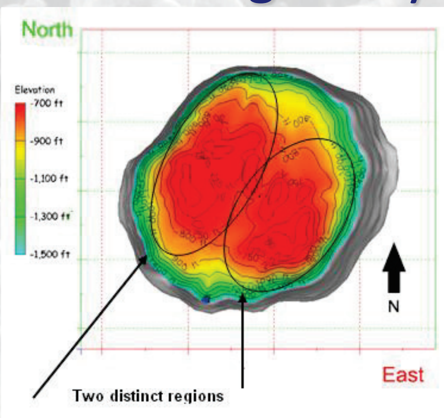
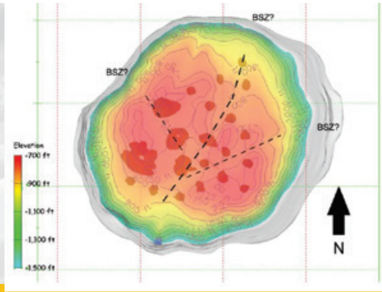
Heterogeneity of Salt





- Salt dome is bisected by several boundary shear zones consisting of faults, salt spines, anhydrite/clay seams, and other anomalies (from seismic, sonar, borehole data).
- Due to these features, the salt creep rates are highly heterogeneous across the site.

Cavern	Closure, BBL/yr	Cavern	Closure, BBL/yr
BM101	5,365	BM109	8,543
BM102	4,944	BM110	3,150
BM103	11,680	BM111	7,813
BM104	2,948	BM112	6,858
BM105	3,683	BM113	10,223
BM106	10,460	BM114	21,304
BM107	4,061	BM115	21,034
BM108	2,702	BM116	6,135

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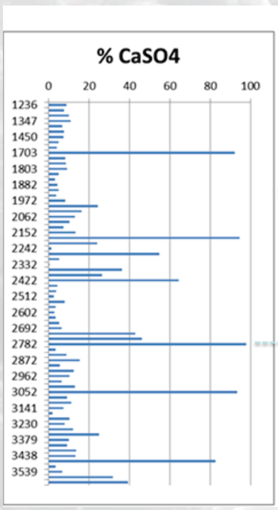
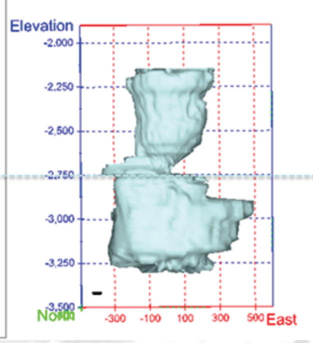
Bryan Mound Cavern 5

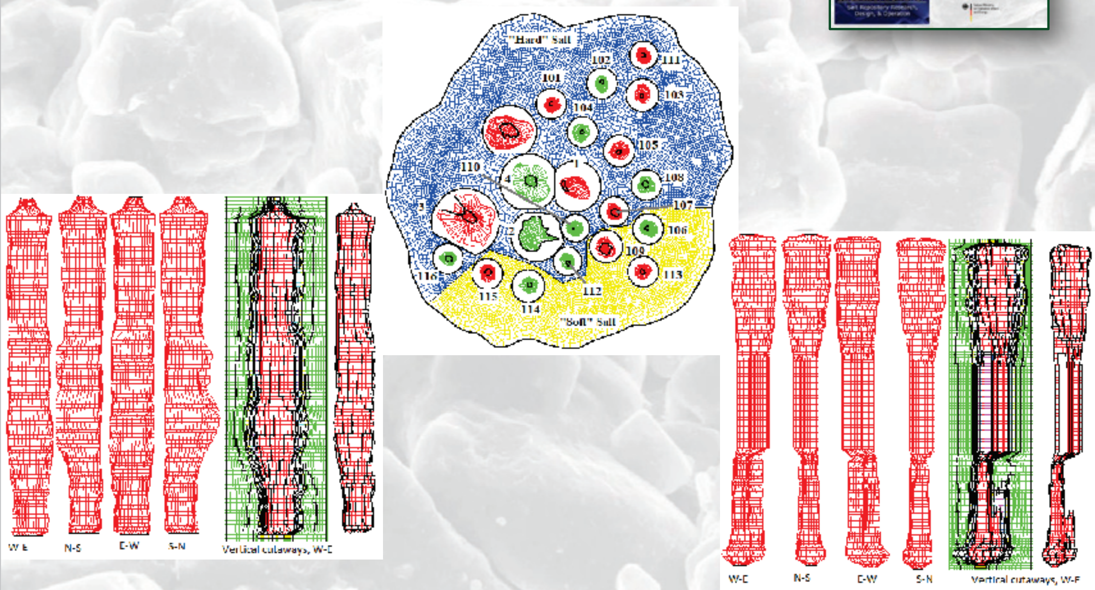
- 36 MMB volume (largest SPR cavern)
- Accessibility to oil in lower lobe
- Salt falls from neck region damaging string
- Emulsion issues when water is pumped in for oil removal
- Gas intrusion issues (anhydrite providing possible flow path)
- Casing failures due to large roof diameter
- Effect on stability of nearby caverns
- Difficulty in modeling creep due to heterogeneous impurity content



Example: Anhydrite % from well BM5 core samples taken in 1957

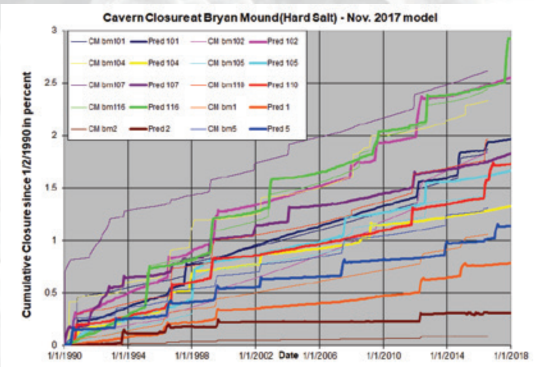


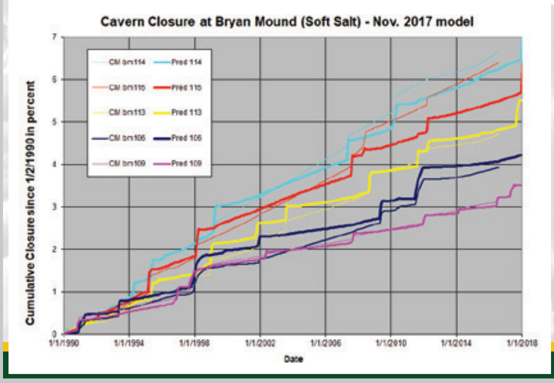
Full Dome Model for Bryan Mound



- All caverns meshes mapped to sonar-based geometries (BM-103, 105 shown)
- 5 leach layers ("onion skins") included for nearly all BM caverns

Bryan Mound – Cavern Closure





Salt of Cavern	A_2 multiplier	K_0 multiplier
Hard salt	2.3	1.0
Soft salt	24.0	1.0
BM-1	6.0	1.0
BM-2	19.08	1.0
BM-3	19.08	1.0
BM-4	31.0	1.0
BM-5	1.94	1.0
BM-101	1.89	0.1
BM-102	5.0	0.1
BM-103	50.0	0.5
BM-104	1.46	2.0
BM-105	1.85	1.0
BM-106	25.	1.0
BM-107	1.5	1.0
BM-108	0.14	1.5
BM-109	7.0	1.0
BM-110	1.5	1.0
BM-111	20.0	0.16
BM-112	1.5	1.5
BM-113	40.0	1.0
BM-114	200.0	1.0
BM-115	200.0	1.0
BM-116	4.36	1.0

- **2018 predictions using cavern-specific creep properties**
- **Cavern closures range from 0.1% to 1.0% over 20 years**
- **Improved (somewhat) correlation ; however, overpredict surface subsidence by factor of 1.5-2**

Summary

- Geomechanical modeling is not exact, often not close.
- Pre-repository prediction of behavior will ultimately not match measured behavior due to the application of homogeneous properties to a heterogeneous domain.
- Requirements of a site model will change/evolve during the lifetime of the site (pre-construction, early operations, later operations), and models will need to evolve accordingly.
- Laboratory tests will present a limited picture of the properties of salt in a repository domain.
- Knowledge of the nonconformities of a bedded or domal salt (faults, interfaces, clay or anhydrite seams, etc.) will introduce issues that may need to be addressed in upgraded mechanical models.

T. Popp

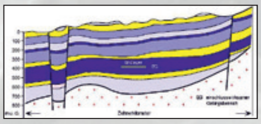
9th US/German Workshop on Salt Repository Research, Design, and Operation

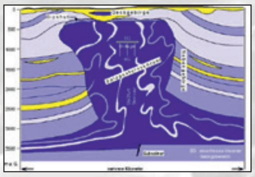
Hannover, Germany
September 10th and 11th, 2018

Break out session

Bedded salt vs. domal salt

T. Popp with contributions from F. Hansen, S. Fahland and others



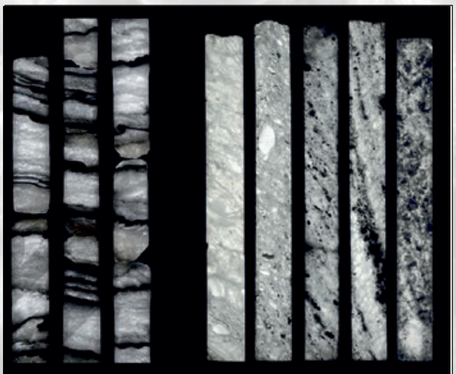


- **Role of textural and structural differences**
- **Relevancy for**
  - Mining safety – room stability
  - Mechanical / hydraulical anisotropy
  - Fluid flow
- **Bedded salt**

  A natural multi-barrier system …
- **Discussion ….**

Bedded salt vs. domal salt

The scope – role of texture and structure



Staßfurt-Hauptsalz, Teutschenthal Mine	Staßfurt-Hauptsalz, Gorleben Salt dome

Polished Core Slices (1m length – transmission light)

Bedded salt vs. domal salt

Textural characteristics

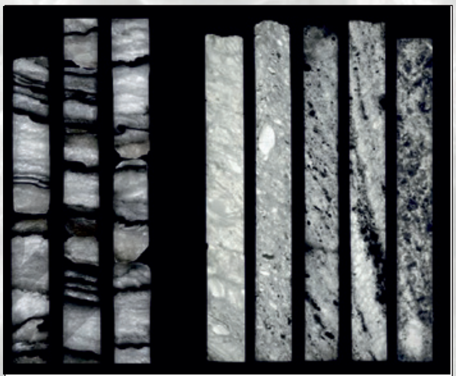
Source: BGR

Property	Bedded Salt		Domal salt / salt diapir
Subtype	Flat bedded salt	Pillows	
Lateral extent	Large	Sufficient	Sufficient
Thickness	Limited	Significant	large
Geology / uniformity	Simple	Lateral inhomogeneous	Complex
	• Anhydrite/clay layers • Salt clay inter-beddings		• Homogenized salt portions
Cap rocks	• Intact cap rock with overlaying clay rocks • In the lower part dry		• Disturbed • Often water bearing
Petro-physical properties	Anisotropy ➢ *Mechanical /hydraulical weakness planes* ➢ *Scarce data sets*		Isotropy ➢ *Low permeability* ➢ *Comprehensive rock-mech. data*
Fluid path way scenarios	• Flat bedded foliation: ➢ *lateral fluid flow due to sulfate/clay layers*		• Steep inclined foliation: ➢ *Fractured „Main Anhydrite"* ➢ *Dissolution of the potash seam*

9th US/German Workshop on Salt Repository Research, Design, and Operation | Institut für Gebirgsmechanik GmbH Leipzig | Break-Out-Session: Bedded vs. domal salt | 2 / 12

Bedded salt vs. domal salt

The scope – role of texture and structure



Staßfurt-Hauptsalz, Teutschenthal Mine | **Staßfurt-Hauptsalz, Gorleben Salt dome**

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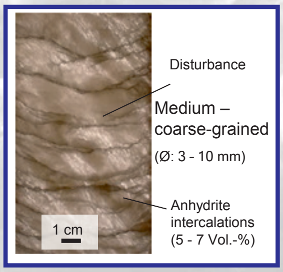
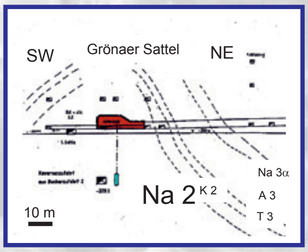
Bedded salt vs. domal salt

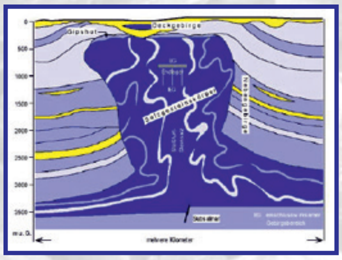
Texture and structure - the scale of investigation



Lab investigations - Single specimens (10 - 25 cm)



In-situ-Investigations – Field scales (10 - 25 m)

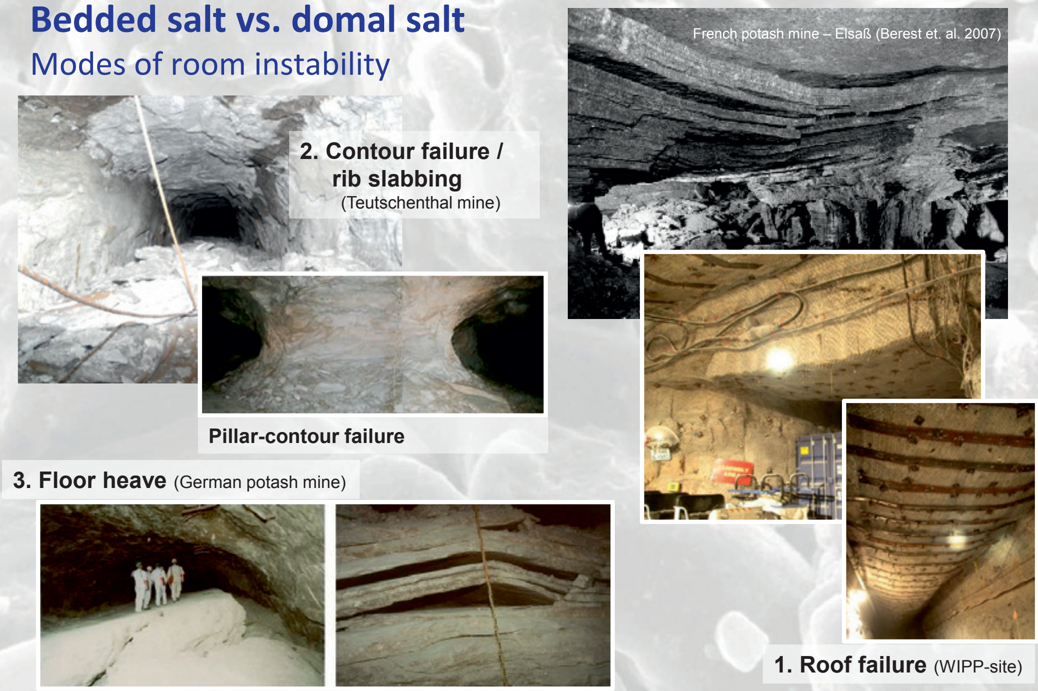


Modelling – Forecast (10 cm - 10 m - 100 m)

➢ Assessment of textural and structural phenomena is always related to the observation scale and the site

Bedded salt vs. domal salt

Modes of room instability



Bedded salt vs. domal salt

Room stability in operating nuclear waste repository in salt

Mode of Instability	Type of Salt Deposit	Significance	Corrective Action
Roof Fractures	Bedded	Roof separates along clay partings and may lead to roof falls creating a safety hazard.	Roof bolting and reducing the length of roof spans can be used. At least one meter of salt should be left in roof to avoid slabbing.
	Domal	Roof slabs and/or separates and may lead to roof falls creating a safety hazard.	Bolting may help control slabs that have already formed. Small falls can be prevented by screening. Roof bolts are more properly placed immediately after creating the opening and before the sagging of the roof.
Rib Slabbing	Bedded and Domal	Not significant structurally unless progressive. Could create safety hazard.	Pillar cable wrapping helps but does not stop pillar slabbing. Cables break and the total slab mass comes down all at the same time rather than in pieces.
Floor Heave	Bedded	Disruptive, requiring maintenance. Could create problems with buried waste canisters.	Can be eliminated by cutting slots in the floor with an undercutter.

Arlo F. Fossum (1983): Outcome of the Working Group - ”Room Stability in Salt Repositories”

Relevancy:

➔ Near field performance of the repository

- Optimized repository design
- Reduction of uncertainties in the operational period

Influence factors:

- Geological site conditions
- Design of underground openings
- **Time** and interaction with the emplacement technique and waste, e.g. stress distribution, heat release

Investigation approach:

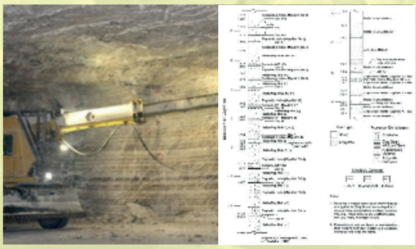
➔ interacting methods of

- Field analysis
- Laboratory testing
- Numerical modelling

Bedded salt vs. domal salt

Approaches of site related lab investigations

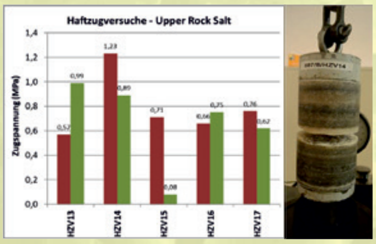
(1) Site analysis (mapping) / sampling



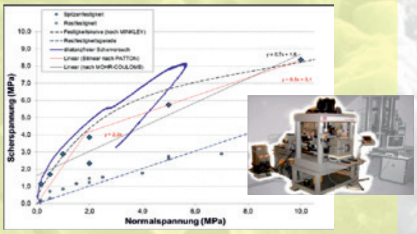
Tensile failure without external force, block was supported by wood wedges

Sample preparation for the direct shear test, already collapsed into two parts **before** the shear test

(2) Lab testing



Direct tensional tests on bedded salt



Shear strength of lithological interfaces

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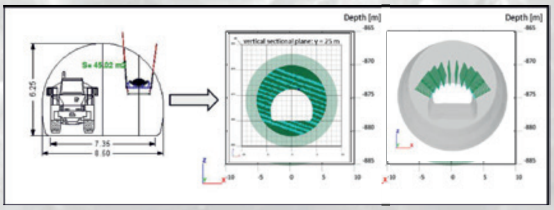
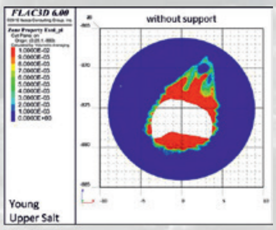
Bedded salt vs. domal salt

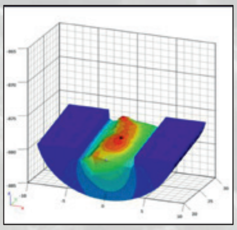
Actual state of understanding of instabilities / prediction



Rock mechanical for evaluation of the stability of the main drift (ramp) for a potash mine in a bedded salt formation



Plastic volumetric deformations <1 % on after 8 years of mining



Floor heave along the ramp at the time of 10 years

- Differences between bedded/domal salt are obvious
- The understanding, especially of roof failure mechanisms, has been largely improved in the last decades
- Geomechanical modelling is on a high level, e.g. discontinous approaches are available
- The data base of host rock properties (e.g. tensional strength, shear strength) or bolts is scarce

➢ Construction of a repository in bedded and domal salt requires in all cases site-specific information and modelling

- Optimized room design
- Appropriate rock support / bolting-scheme
- Monitoring program of roof stability
- Suggestions for maintenance

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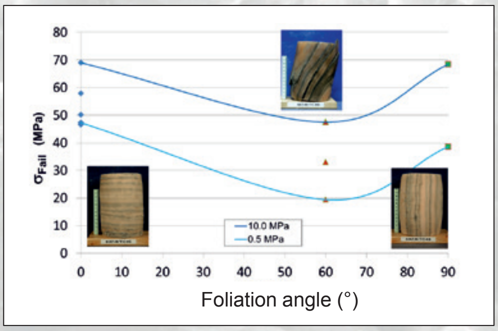
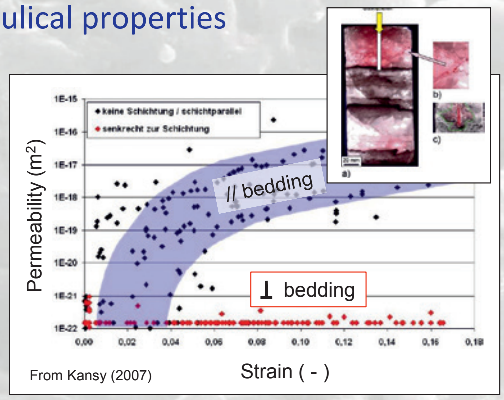
Bedded salt

Anisotropy of mechanical and hydraulical properties



Triaxial strength testing of bedded salt with different loading directions



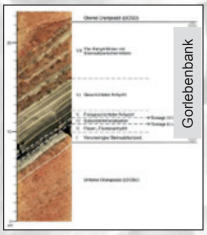
Permeability testing of bedded salt during deformation (loaded // or perpendicular to the foliation

- Bedded salt is mechanical /hydraulical anisotropic due to weakness planes
- Intact sulfate / clay intercalations are canalizing fluid flow - **impervious layers**
- Scarce data sets (lab- and field testing)

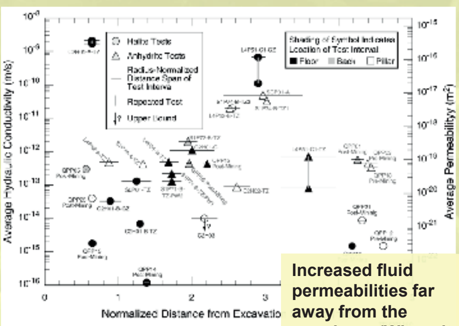
Bedded salt vs. domal salt

Fluid flow scenarios – anhydrite / clay beddings

- **Can radionuclides (in brine or gas) be transported away from the repository through the host rock?**
- **Inflow of water into the repository?**



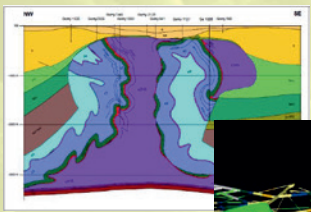
Bedded salt – Relevancy of sulfate-clay intercalations?



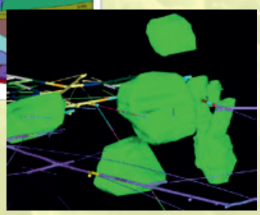
From Beauheim & Roberts (2002)

Increased fluid permeabilities far away from the openings (Wipp-site)

Domal salt – Relevancy of the Main Anhydrite: fractured/healed ?



Source: BGR



Separated anhydrite-blocks at the Gorleben site = no pathways

Selection of the best repository site?

Properties of potentially suitable host rocks

Property	Rock salt	Clay/ claystone
heat conductivity	high	low
permeability	practically impermeable	very low to low
strength	medium	low to medium
deformation behaviour	visco-plastic (creep)	plastic to brittle
stability of cavities	self-supporting	artificial reinforcement required
in situ stresses	lithostatically isotropic	anisotropic
dissolution behaviour	high	very low
sorption behaviour	very low	very high
heat resistance	high	low

Source: BGR

Rock salt

" ... , rock salt is practically impermeable to gases and liquids, has very high heat conductivity, and has visco-plastic properties which cause underground cavities to seal up. …"

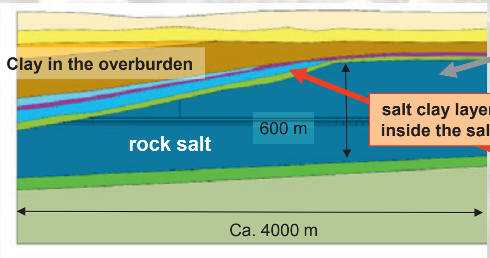
Argillaceous rocks

" ... The known properties of argillaceous rocks which are favourable for hosting repositories are in particular the very low permeability and high sorption capacity. Argillaceous rock formations have proven their long-term effectiveness as geological barriers where they form tight seals, e.g. above hydrocarbon reservoirs.. …"

➢ **Combination of the advantages of both host rocks**

Natural geological multi-barrier system

Bedded salt in Germany

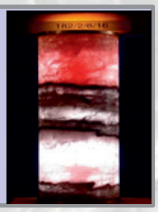


- Intact cap rocks in the overburden consisting of clay formations
- Bedded intra-saliferous salt clays as additional clay-barriers
- Rock salt with bedding planes / discontinuities (no vertical flow)

➢ **Unique advantage, but where to find …..**

Limitation of vertical flow

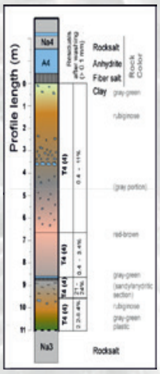
Bedded rock salt with anhydrite intercalations



Salt clay Intercalated in the saliferous formation (up to 12 m thick)

Composition:

54 % Clay minerals
22 % Quartz
15 % Anhydrite
Accessory (gypsum; halite, Hematite)



Source: Minkley et al. (2010)


Discussion!
9th US/German Workshop on Salt Repository Research, Design, and Operation
IfG
Institut für Gebirgsmechanik GmbH Leipzig
Break-Out-Session: Bedded vs. domal salt
13 / 12

E. Simo


Joint Project Proposal:
Design and Performance Guideline of
Geotechnical barrier systems in Salt formations
Eric Simo
BGE TECHNOLOGY GmbH
Ed Matteo, Teklu Hagdu
SANDIA
Hanover, Germany
September 10-11, 2018
US/GERMAN WORKSHOP
Salt Repository Research,
Design, & Operation
PTKA
ENERGY
Sandia National Laboratories
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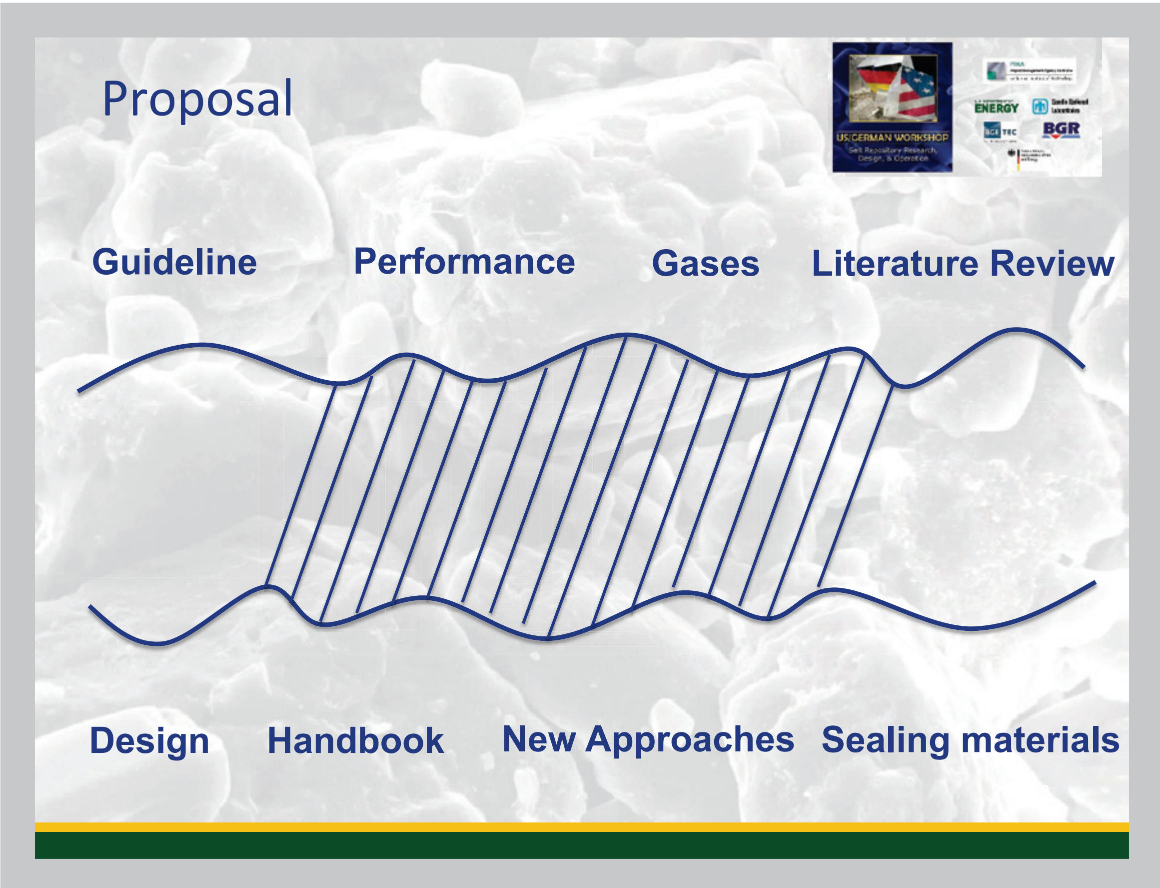
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