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PROCEEDINGS

11th US/German Workshop on Salt Repository Research, Design, and Operation 2021

BGE TEC 2021-19

Tagungsband

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Executive Summary

The US/German Workshop on Salt Repository Research, Design, and Operation looks back on many years of successful collaboration between researchers and practitioners in Germany and the USA. The initial focus on radioactive waste management has been supplemented by several other fields such as evaporite mineral mining, hydrocarbon storage, and long-term nuclear waste isolation, and has created a basis for a fruitful collaboration. For the organizational team and regular participants, the 10th anniversary in 2019 was an important milestone for this successful work. Over time, the bilateral collaboration has grown and intensified. Further nations enrich the agendas and profiles of the workshops. Today, experts from the UK, the Netherlands, and Poland are regular guests as well as contributors.

The proceedings in hand summarize a multifaceted workshop. The four different topics of the individual sessions are filled out with diverse contributions. All contributions illustrate the continuing progress and the developments in the field of radioactive waste disposal in a salt repository. On four session dates, different topics were set into focus. The first session focused on the status of national programs and was the start of the workshop. Session 2 focused on the compaction of crushed salt. The third and fourth sessions handled Engineered Barrier Systems (EBS), materials and backfilling as well as modelling aspects. All sessions provided an excellent opportunity for exchange and discussion. For the first time, the workshop was held in virtual mode, which allowed a continuation of the scientific and technical exchange under the difficult pandemic situation. Another positive aspect was that due to the virtual format, it was also possible to include more participants, especially young members from different organizations and universities. In this regard, the workshop also marks a transition between generations and an excellent opportunity to share the knowledge of several decades of work. On the flip side, however, face-to-face exchange between participants was not possible and discussions were rather limited, which also restricted the possibility to gather inspiration for further tasks and more detailed work. To compensate for this, the organizational team plans to have a physical meeting for the 12th US/German Workshop on Salt Repository Research, Design, and Operation in 2022, although the pandemic situation still makes plans uncertain. If a personal meeting is again not possible, a virtual event will be a good alternative.

Acknowledgements

The 11th US/German Workshop on Salt Repository Research, Design, and Operation was hosted virtually in four sessions distributed over the year 2021. Sandia National Laboratory provided an excellent technical basis for the online video conferences. Special thanks to Kristopher Kuhlman for initiating the online meeting room. The organization and participation of a conference is always a time-consuming task. Thanks also to all members of the organizational team – Kristopher Kuhlman (Sandia National Laboratories), Michael Bühler (Project Management Agency Karlsruhe), Wilhelm Bollingerfehr and Philipp Herold (both BGE TECHNOLOGY GmbH) – for the preparation of the agenda as well as the moderation of the sessions. Special thanks go to Wilhelm Bollingerfehr for his constant and tireless willingness to organize the workshop and to pass on his enthusiasm to a new generation. A scientific and technical workshop of course lives from the contributors and participants. The authors within the four sessions were the following:

Session 1 – National Program:	Astrid Göbel, Timothy Gunter, Jeroen Bartol, Simon Norris
Session 2 - Crushed Salt:	Nina Müller-Hoeppe, Kristoph Svenson, Dirk Naumann, Melissa Mills, Svetlana Lerche, Larissa Friedenberg, Stefan Pötzsch
Session 3 - EBS, Materials and Backfill:	Rahil Gholami, Florian Rempel, Maren Heidmann-Ruhz, Jan Aurich, Thorsten Meyer, Steve Sobolik, Julius Bauermeister
Session 4 – Modelling Challenges:	Nina Müller-Hoeppe, Edward Matteo, Eric Simo, Michael Rutenberg, Melissa Mills, Eric Guiltinan, Richard Jayne

These Proceedings comprise the main chapters National programs (summarized by Wilhelm Bollingerfehr), Compaction of crushed Salt (summarized by Larissa Friedenberg and Oliver Czaikowski), Engineered barrier systems (summarized by Nina Müller-Hoeppe) and current modelling challenges (summarized by Kristopher Kuhlman). The technical and editorial reviews of this document were provided by the staff of BGE TEC, thanks to them as well. The proceedings are published electronically and will be posted on the websites of the hosting organizations Sandia National Laboratories, Project Management Agency Karlsruhe (hereinafter referred to as PTKA), and BGE TECHNOLOGY GmbH (hereinafter referred to as BGE TEC).

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1 Introduction

Researchers and practitioners in Germany and the USA have shared their expertise in salt science and technology for many years. This includes evaporite mineral mining, hydrocarbon storage, and long-term nuclear waste isolation. These relationships rejuvenated in 2010, when Germany emerged from a 10-year moratorium of the exploration of the Gorleben site. Researchers restarted salt repository workshops and adopted a more formal approach. In 2011, a Memorandum of Understanding (MoU) between the US Department of Energy (US DOE) offices of Environmental Management and Nuclear Energy and the German Ministry of Economics and Technology officially sanctified the workshop relationship and broadly described its aspirations. Rapidly, a fruitful collaboration established. For the organizational team and the other participants, the 10th anniversary in 2019 was an important milestone for this successful collaboration. Over time, the bilateral collaboration has intensified. Further nations enrich the agendas and profiles of the workshops. Today, experts from the UK, the Netherlands, and Poland are regular guests as well as contributors.

However, the pandemic situation all over the world did not leave the US/German workshop unscathed. Due to the respective national situations and travel restrictions, the series of workshops had to be put on hold in 2020. Out of an ongoing uncertain situation but a very strong interest in a scientific and technical exchange, it was decided to adapt the workshop mode. As many other events, the US/German workshop, too, changed to a virtual event, and the 11th US/German Workshop on Salt Repository Research, Design, and Operation was held online in 2021. Four sessions, 3 hours each, were planned for the early afternoon (Central Europe Time – CET), which was in the morning for the US colleagues (Mountain Daylight Time – MDT). The new virtual workshop mode allowed spreading the different sessions over the year. On four dates, different topics were set into focus. In February 2021, the workshop was kicked off with the first session, which focused on the status of national programs. Within a poll between all participants the topic for the following session in June was selected. The majority of participants decided to focus on crushed salt and the latest activities related to testing and modelling. So in June 2021, session 2 focused on this topic. In early September, the third and fourth sessions dealt with Engineered Barrier Systems (EBS), materials and backfilling as well as modelling aspects. All sessions provided an excellent opportunity for knowledge exchange and discussions. Compared with former workshops held in person, the list of topics and sessions was reduced because of the limited timeframe per session. At the same time, the use of virtual meeting tools allowed a larger number of participants to join the workshop and take part in the discussions. From this perspective, the 11th US/German Workshop was a success and ties in with its predecessors.

The report in hand summarizes the 11th US/German workshop by presenting key aspects of all sessions and includes the slides of all presentations in the appendices.

2 National Programs and Site Selection Processes

In previous workshops, the starting points of national repository programs were explained (usually a law or policy that describes the processes and goals to be used in geological waste disposal). Organizational structures and implementation plans were presented as well. It was made obvious that in order to achieve the safety goals, basic components are common to all programs: a safety and safety demonstration concept; properties of waste inventory, waste form, selected host environment, facility operations, and engineered barriers. Together, these components of the disposal system provide the required safety functions that ensure containment and isolation of the radioactive waste.

This year, the workshop focused on the progresses in SNF/HLW repository programs (in particular on the progress in site selection) of the US, Germany, the Netherlands, and UK.

2.1 Status of the United States Spent Fuel and High-Level Radioactive Waste Management Program

During the workshop, Timothy Gunter gave an overview of the status of the United States Spent Fuel and High-Level Radioactive Waste Management Program. The related presentation is included in the Appendices.

2.1.1 SNF/HLW Inventory

In the United States of America, the main sources of nuclear waste are the operation of commercial NPPS, the national defense activities, and the science and technology research activities. The estimated total inventory of SNF and waste from reprocessing within the relevant 39 States amounts to:

- 84,400 MTHM commercial SNF,
- 2,300 MTHM non-commercial SNF, and
- 10,500 MTHM Reprocessing waste (vitrified, tank and calcine).

While in the past, most of the SNF was stored in pools, nowadays dry storage application increases and will be the ultimate and only technical solution in the 2050s.

2.1.2 Fuel Cycle Research and Development (R&D)

The research and development activities focus on Spent Fuel Disposition R&D and an Integrated Waste Management System (IWMS).

- Spent Nuclear Fuel Storage and Transportation

The most important activities are the investigations and experiments concerning extended storage of SNF and retrievability and transportation after extended storage. The R&D work includes aspects of high-burnup spent nuclear fuel as well as security assessments as well.

- Generic Disposal

Research in the field of generic disposal focuses on the development of the direct disposal of Dual Purpose Canisters (DPC) and safety assessment modelling applying high performance computing for repository systems. In addition, international collaboration and enhanced research activities are planned to support disposal concepts in multiple geologic media.

- Integrated Waste Management System (IWMS)

The development and implementation of an IWMS incudes design and planning activities for site preparation at stranded sites, transportation coordination efforts, and evaluation of options for rail cars.

2.1.3 Interim Storage/Nuclear Waste Fund Oversight

In parallel to the R&D activities, another research focus is the development of interim storage capabilities, which was authorized by Congress in the FY2021 appropriation (December 2020). The development of an efficient nuclear waste fund oversight was launched as well.

2.1.4 Summary

The SNF/HLE repository program of the United States focuses on near-term progress and sustainable solutions. On the one hand, R&D activities will be continued in areas of SNF/HLW storage and transportation, generic geologic disposal, and direct disposal of dual-purpose canisters. On the other hand, development of transportation capabilities (railcar and programmatic elements) will be investigated as well as possible interim storage solutions.

2.2 Status of Site Selection Procedure in Germany

During the workshop, Astrid Göbel gave an overview of the status of the site selection procedure in Germany. The related presentation is included in the Appendix.

2.2.1 Introduction

In 2017, BGE, the German implementer of a HLW repository, launched the site selection procedure with the goal to identify the site that best meets the stipulated safety requirements for disposing of SNF/HLW in Germany over a period of 1 million years. The responsibilities for the selection procedure for a site in the three host rock types (rock salt, claystone, and crystalline rock) and the types and amounts of waste to be disposed of had been shown at the 10th US-German-Workshop last year. During this year’s workshop, first interim results could be presented.

2.2.2 Interim Results of the Site Selection Procedure

As explained earlier, the site selection procedure in Germany consists of three phases and several steps, which will gradually reduce the number of potential sites (see Figure 1). Results of Step 1 of Phase 1: Sub-areas were identified and the results compiled in a sub-area interim report, which was published in September 2020.

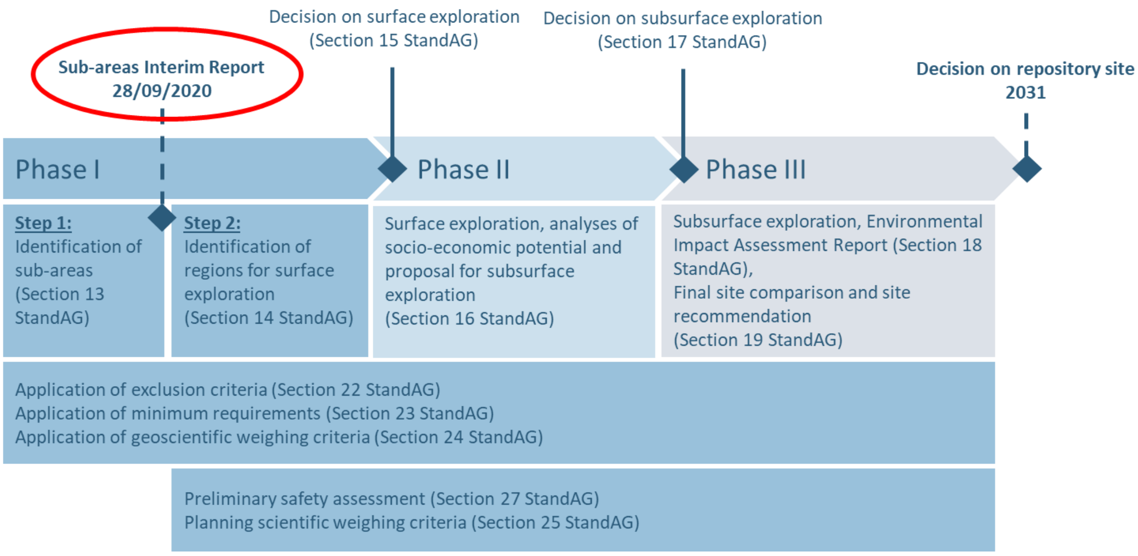

Figure 1: **Stepwise Implementation of the Site Selection Procedure in Germany, based on BGE (2020)**

Based on the geoscientific data collected from the federal and regional authorities and application of the exclusion criteria, regions that meet the minimum requirements were identified. For these regions, the geoscientific weighing criteria were applied. Afterwards, the remaining regions were identified with respect to their overall geologic suitability. There were no areas that could not be classified due to insufficient geological data. A total of 90 sub-areas with an area of approx. 240 874 km², which are expected to have favorable geologic conditions for the final disposal of high-level radioactive waste (~54% of Germany), were identified. Figure 2 shows a map of Germany with the identified sub-areas.

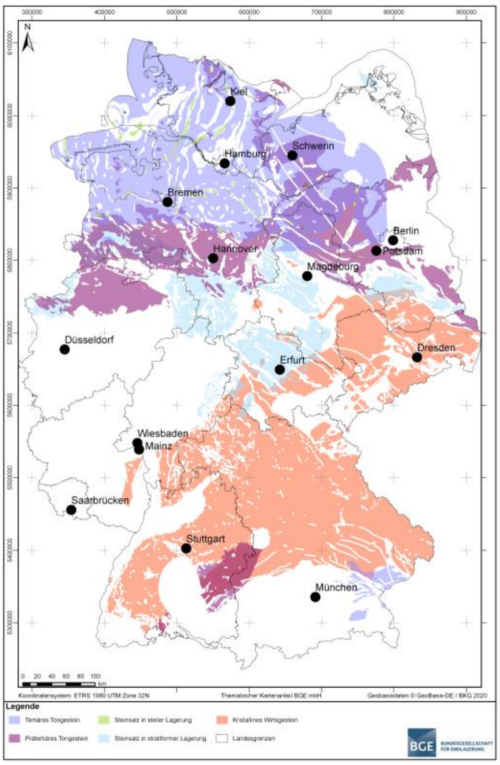

Figure 2: **General map of Germany with the identified sub-areas (all host rocks), based on BGE (2020)**

Depending on the type of host rock, the total of 90 sub-areas can be divided into three groups:

- 9 sub-areas in claystone host rock: surface of approx. 129 639 km²
- 7 sub-areas in crystalline host rock: surface of approx. 80 786 km²
- 74 sub-areas in salt host rock (60 steep salt rock structures + 14 stratiform salt formations): surface of approx. 30 450 km²

The sub-area interim report showed a surprising result regarding the suitability of the Gorleben salt dome. The Gorleben-Rambow salt dome meets all minimum requirements but BGE concluded that, based on the application of the geoscientific weighing criteria according to Section 24 StandAG, the summarized assessment of the identified Gorleben-Rambow area shows that the site is "not favorable“. The Gorleben-Rambow salt dome will thus not be considered in BGE’s further work on the proposals concerning the siting regions.

2.2.3 Outlook

Throughout the next months, sub-area conferences will take place to display the results and the method applied to the interested audience in a transparent and participatory manner. However, BGE has already launched Step 2 of Phase I, with the aim to identify regions for surface exploration, see section 14 of StandAG (2017).

In parallel to the site selection procedure, BGE has developed a comprehensive RD&D agenda that is crucial for implementing the German Site Selection Procedure in order to close gaps and to gain knowledge. This includes participation in appropriate national and international RD&D programs.

2.3 R&D program and Disposal Concept in the Netherlands

During the workshop, Jeroen Bartol gave an overview of the status of the R&D program and Disposal Concept in the Netherlands. The related presentation is included in the Appendices.

2.3.1 Introduction

In the Netherlands, COVRA is responsible for the collection, treatment, and storage of radioactive waste. It was decided to first store the waste in an interim storage facility above ground for at least 100 years and to eventually dispose the waste in a single deep GDF in 2130.

2.3.2 Long-term research program

Based on the assessments of the initial safety case (summary of the achievements of the OPERA project), the topics and priorities for future research were derived. For a GDF in rock salt or clay, the host rock has been given the highest priority, followed by the engineered barrier system (e.g. disposal waste package). Figure 3 shows the timeline of the Dutch R&D program.

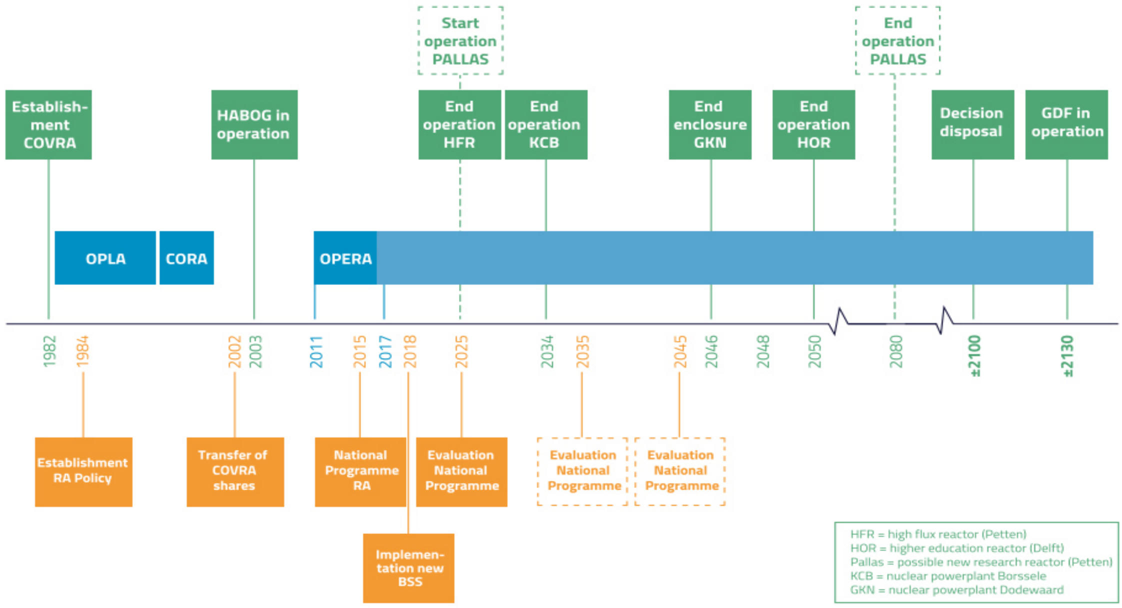

Figure 3: **Timeline of the Dutch Research Program for radioactive waste disposal, based on COVRA (2021)**

The research focus – in particular for the near future – has been placed on the following aspects:

- **host rock salt**: geotechnical properties, evolution of permeability-porosity, interaction gas-rock, brine availability, subrosion processes, bedded salt, diapirism rates, etc.
- **waste package**: advantages/disadvantages of self-shielded super container

2.3.3 Disposal concept

COVRA's disposal concept consists of disposing of all categories of radioactive waste (SNF, HLW as well as LLW) in a single, deep GDF in the Netherlands. The idea is to build a repository in Zechstein domal rock salt. For the repository, two levels will be excavated in the salt dome: one upper level (750 m below see-level) for LILW-TENORM and a lower level for HLW (800 below see-level).

Disposal in galleries is the preferred option because this technology may facilitate the emplacement and retrievability, which is a requirement in the Netherlands. However, a series of RD&D activities will be launched in order to develop a suitable repository concept. This includes aspects like:

- Design of the repository mine (separate sections for LLW and HLW)
- Ventilation and safety measures
- Decision process for waste package selection
- Transport and emplacement technology
- Engineered barriers (backfill, seals etc.)
- Logistic aspects (e.g. simultaneous mining and emplacement activities)

COVRA is interested in international collaboration, e.g., to evaluate the Dutch RD&D program as well as to develop scientifically and technically profound and mature solutions.

2.4 Status of Site Selection in UK

During the workshop, Simon Norris gave an overview on the status of the site selection process in the UK. The related presentation is included in the Appendices.

2.4.1 Introduction

In the UK, RWM is responsible for the siting, design, operation, and safe closure of a GDF for all kinds of radioactive waste, which stem from a range of activities including nuclear power generation, medicine, research, and defense-related nuclear programs. Most of this radioactive waste can be disposed of safely in facilities on the surface. However, a suitable DGF (Deep Geological Disposal Facility) is still needed for the high-level waste. In this year's workshop, an update was given on the process to identify a suitable site and a willing community to host a GDF in the UK.

2.4.2 Siting Process

RWM has developed and published a plan how to proceed in interacting with communities to develop a siting process for a GDF (see Figure 4). For this purpose, it was decided to evaluate potential areas and sites based on six siting factors:

- Safety and security – safety and security must be assured and endorsed.
- Community – social and economic opportunities, community wellbeing, and how a GDF can align with the potential host community's vision.
- Environment – independent regulatory requirements have to be met when constructing a GDF.
- Engineering feasibility – the ability to construct and operate a GDF in a given location will need to be ensured.
- Transport – the safe and secure transport of waste, people, and other materials.
- Value for money – it is a duty to ensure that value for money is delivered.

In this context, the range of community benefits has to be considered; e.g. jobs and skills, infrastructure investments as well as community support.

Figure 4: **Overview of RWM`s interaction with communities over time in the siting process, based on RWM (2020)**

The siting process starts with initial discussions with interested parties about the evaluation of safety and short and concise qualitative evaluations of the existing information. For this purpose, RWM has summarized information about the geology across the country in the National Geological Screening (NGS) reports. In a second phase, working groups will be installed, which will deal with the identification of search areas and data gaps and additional information. In a third and comprehensive step, community partnership will be strived for. Here, all aspects of repository siting, construction, operation, and closure will be discussed.

2.4.3 Concept of a Geological Disposal Facility

In order to facilitate the understanding of what a GDF may look like, basic information and data were compiled by RWM. Three rock types, commonly found all over the UK, can be considered for a GDF: Higher strength rock, Lower strength sedimentary rock, and Evaporite. The surface facilities may require 1 km², while the underground part of a GDF may cover an area of up to 20 km². The access to the underground can be realized by shafts or ramps. The surface facilities must not necessarily be located directly above the underground area, but can be 10-15 km away. The waste volume to be considered amounts to a total of approx. 750,000 cubic meters of packaged waste. A GDF will operate for more than 100 years to receive all of the legacy waste and the waste arising from new nuclear stations. The costs for a GDF is projected to several billion £.

With regard to a GDF in rock salt, RWM has published the report “UK Halite Deposits - Structure, Stratigraphy, Properties and Post-closure Performance”. In addition, RWM is eager to benefit from international precedents, e.g. WIPP (USA) and Gorleben, Morsleben, and ASSE (all Germany) as well as from international collaboration e.g. this US-German Workshop on Salt Repository Research, Design and Operation.

3 Compaction of Crushed Salt

3.1 The KOMPASS Project

The KOMPASS project was initiated by a consortium of German partners that consist of BGE TECHNOLOGY GmbH, BGR, GRS gGmbH (coordinator), IfG, and TUC together with international associative partners from Sandia and Utrecht University and COVRA with the aim to develop methods and strategies for the reduction of deficits in the prediction of crushed salt compaction in order to improve the prognosis quality. To fulfil the objective a combination of experimental investigations, microstructural examinations, and numerical strategies was conducted as presented in the sections below. Efforts to improve the prediction of crushed salt compaction began during the first phase of the KOMPASS project (Czaikowski et al., 2020). The second project phase (Friedenberg et al., 2022) started in July 2021 and includes:

- Advancement of different techniques for producing pre-compacted samples for further investigations;
- Systematic investigations of permeability to demonstrate hydraulic tightness in the long-term;
- Advancement of the tools for microstructure investigation methods to characterize pre-compacted samples, assess long-term compacted samples, and investigate moisture impact on deformation behavior;
- Execution of long-term compaction experiments following the complex experimental investigation strategy developed in KOMPASS I to derive necessary model parameters taking into account individual functional dependencies;
- Benchmarking of the long-term compaction tests with various existing numerical models for model development and optimization;
- Application of a numerical demonstrator to illustrate the relevance and progress achieved in the project;
- Evaluation of numerical models with respect to the requirements for a long-term safety analysis.

Special thanks go to Melissa Mills (Sandia), Svetlana Lerche (TUC), Kristoff Svensson (BGR), Till Popp (IfG), Dirk Naumann (IfG) and Larissa Friedenberg (GRS) for their contributions to the US/German Workshop from 06/2021 and this related session 3 report.

3.2 Microstructural Investigations Presentation

To date, the individual contributions of microstructural deformation mechanisms to the overall compaction of loose crushed salt into a cohesive, load-bearing and low-permeable material remain speculative. Yet, such a differentiation would strongly improve our process-based understanding of salt compaction, which, in turn, is essential to correctly modelling the compaction's long-term rheological behavior.

In general, three main types of deformation mechanisms were identified in rock salt (e.g. Jackson & Hudec, 2017): (1) cataclasis, (2) dislocation creep, and (3) solution-precipitation creep (Table 1). To some degree, the abundance of each indicator type provides the corresponding mechanism's contribution to the overall compaction.

Table 1: Deformation mechanisms and respective indicators

Deformation mechanism	Indicators	Quantification
Cataclasis	Microfractures	Statistical
Dislocation creep	Bended grains	Subjective
Dislocation creep	Subgrain size and subgrain orientation	Statistical
Solution-precipitation creep	Recrystallization and over-grows	Subjective
Solution-precipitation creep	Fluid inclusions	Statistical

In theory, indicators for cataclasis would show an increased abundance at the beginning of compaction, where the punctiform grain-grain contacts fail due to the increasing compaction stress. With ongoing compaction, the grain contact areas become larger and grain breakage will be overruled by solution-precipitation. This mechanism, however, is known to be very sensitive to the saturation state and may be less prominent in dry salt. Intracrystalline plasticity, in turn, is thought to be controlled mostly by time and temperature, both factors influencing the mobility of dislocations. Hence, intracrystalline deformation indicators should be more present in a dry, hot and long-lasting compaction.

However, our microstructural investigations of a-priori compacted samples showed no such detailed differentiation. This holds also true for severely compacted crushed salt (< 6 % porosity). Note that we subjectively counted the indicators' abundancies in samples from past multiphase (strain-rate changing) triaxial and oedometric tests. Figure 5 shows exemplary micrographs of observed indicators. Figure 5a shows a microfracture, which is an indicator for cataclasis. Figure 5b shows subgrains, which are indicators for dislocation creep. Figure 5c and Figure 5d show indicators for solution-precipitation creep – fluid inclusions (5c) and flush grain boundaries as well as a bulged grain edge (5d). Their stress path evolution yielded an almost homogeneous abundance of all possible indicators, and a retroactive differentiation of the indicators to certain compaction states seems impossible.

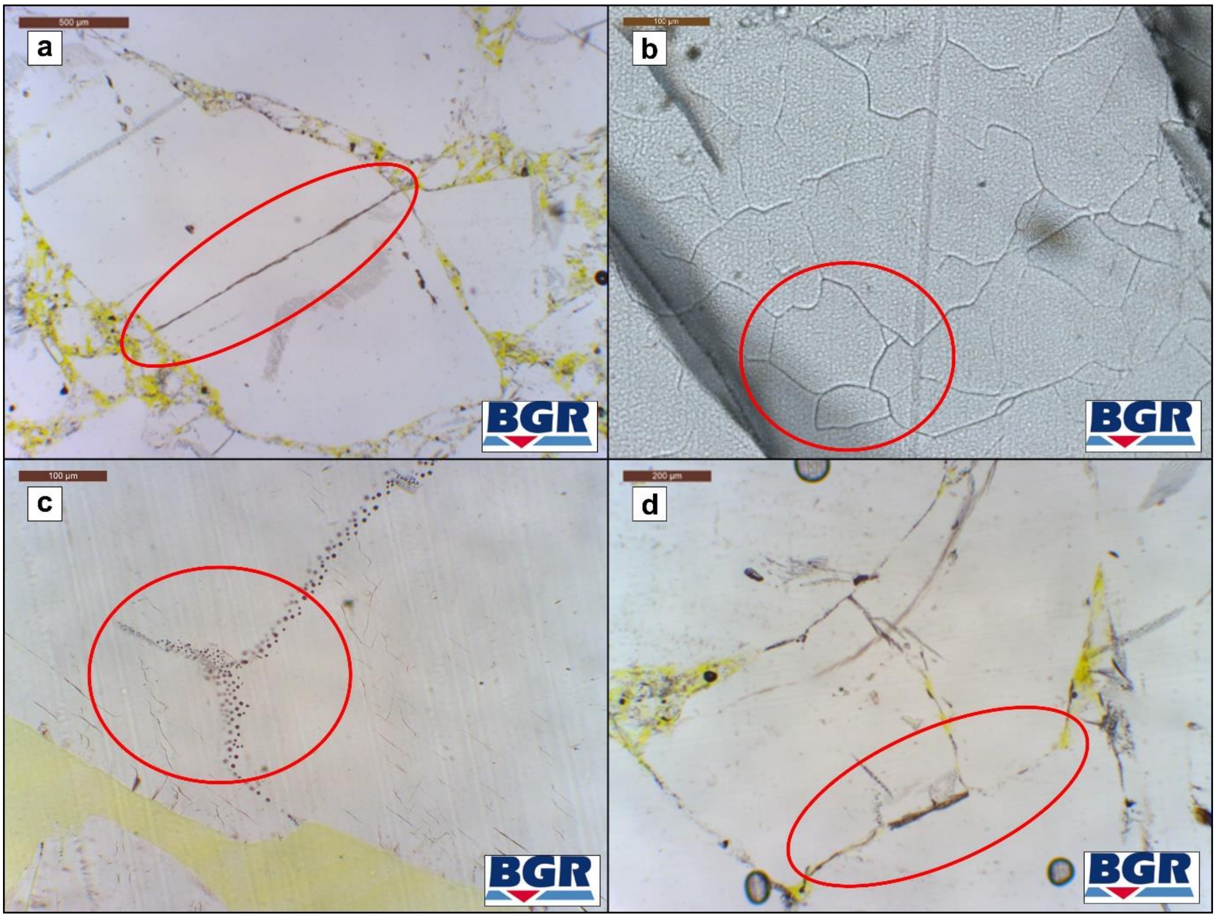

Figure 5: **Exemplary microstructure indicators. a: microfracture (image width ~5 mm); b: subgrains (image width ~1 mm); c: fluid inclusions (image width ~1 mm); d: flush grain boundaries (image width ~2 mm), based on Czaikowski et al. (2020)**

Yet, we still see the potential in identifying the indicators' abundancies and strive for better analysis in our upcoming work (KOMPASS-II). For this improvement, we plan to investigate samples from compaction tests with more stable environmental controls. This way, we may be able to successfully assign deformation indicators to certain environmental and material intrinsic controls. Therein, we also compare a 40-year-old, real-used backfill material to the rather quickly compacted laboratory samples

3.3 Natural and Technical Analogues

A key uncertainty for granular salt consolidation is the timespan necessary for reaching a state of residual porosity, which ensures its function as technical and, fortunately, salt-specific long-term barrier for sealing necessary entrances (drifts or shafts) to the repository. Due to the limited duration of laboratory tests, a time gap exists for demonstrating that disaggregated salt readily consolidates into an impermeable solid under a wide range of modest stress and temperature conditions.

However, natural geologic deposits themselves provide evidence that high porosity evaporite crystals solidify readily into rock salt with negligible porosity, as demonstrated by petrography studies of modern saline pan halite and Quaternary shallow-buried (0 m – 200 m) halite sediments, as published e.g., by Casas & Lowenstein (1989) and Warren (2006). As exemplarily shown for Dead Sea sediments in Figure 6, the diagenetic modification of halite begins contemporaneously with deposition, is most intense within the upper few meters of deposition, and is essentially complete within the first 45 m of deposition or, at least, within 100 m. At the same time, the pore space cementation reduces the porosity of halite crusts from more than 50 % near the surface to less than 10 %.

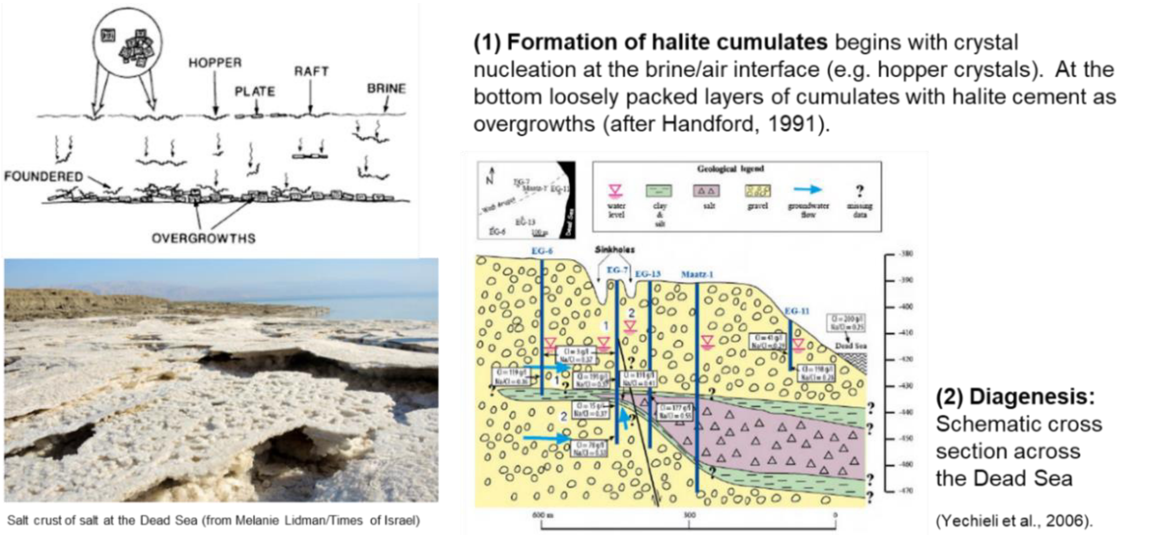

Figure 6: **Synoptic view of formation of halite beds (example: Dead Sea) , based on Czaikowski et al. (2020)**

Thus, it is important to note that undeformed halites from the Permian Salado and Rustler Formations of New Mexico are interpreted to have undergone a depositional and early diagenetic history similar to the modern and Quaternary analogues.

The diagenetically induced loss of porosity result mainly from chemical changes such as changes of the mineralogical/ (cementation). Textural effects (mechanical induced compaction), in the pore space of deposited salt aggregates is also documented as origin of loss of porosity. From all the effects changes of petrophysical properties are expected, e.g. compression wave velocities (Vp), shear waves (Vs), and electrical resistivity (ρx) in laboratory and field conditions, and their relationship, in addition, to porosity / permeability interrelations (e.g., see Figure 7).

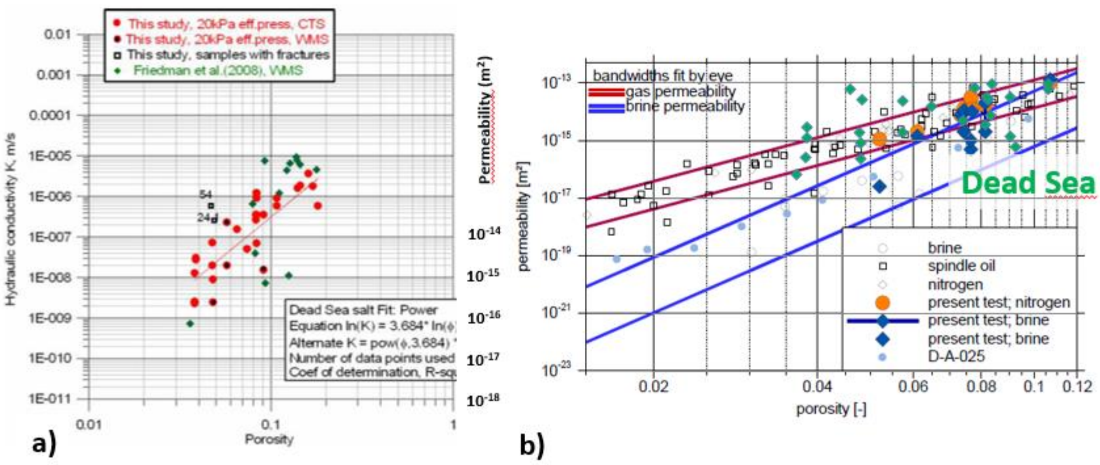

Figure 7: **Permeability / porosity relationships. a) core measurements from Quaternary halite beds of Dead Sea sediments (after Ezersky & Goretsky, 2014); b) lab measurements on crushed salt with single data and bandwidths, in addition, with the results from a) (modified after REPOPERM-data sets from Kröhn et al., 2009)**

Also, technical analogues, as observed in salt mines during closure of underground rooms, demonstrate that convergence of underground openings leads to complete re-compaction of crushed salt that was created during “self-backfill” processes, as shown (Figure 8).

Understanding of the underlying micro-structural processes during crushed-salt consolidation is essential for subsequent development of physics-based models, as argued by Hansen et al. (2014). At given stress conditions, brine content seems to be the key factor, which varies with respect to formation and impurity quantities.

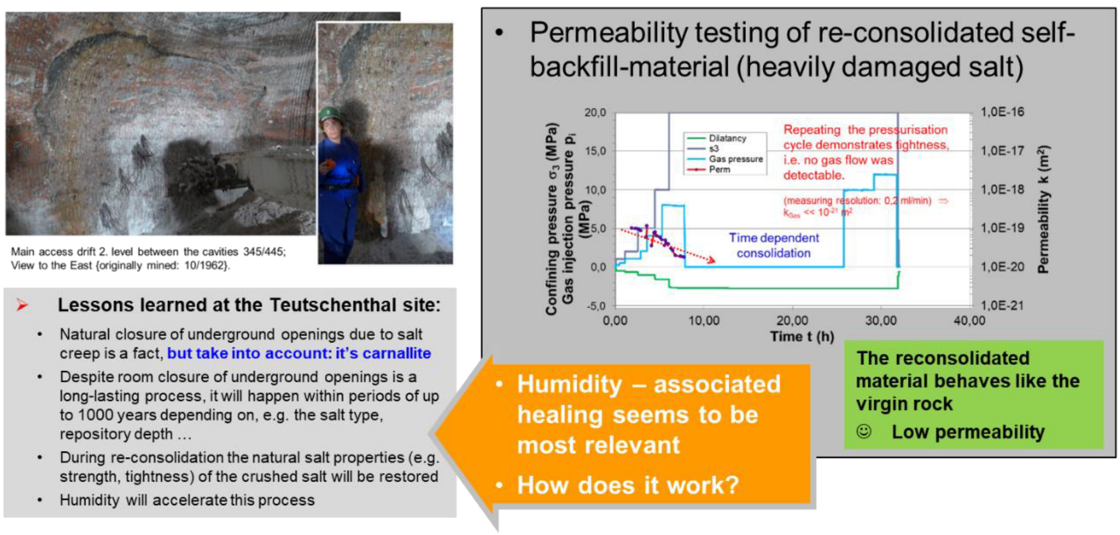

Figure 8: **Synthesis of observations from drift closure in the Teutschenthal mine, where permeability measurements on compacted material demonstrated that the original tightness of the disturbed salt is restored (modified, after Popp et al., 2018)**

Occurrence of fluids in the virgin salt and, in addition, comparable deformation structures were identified by BGR and SANDIA in the Sondershausen material (see above):

- Diffusive mass transfer by solution
  - Fluid inclusions, as observed along planes or lines and connected fluid inclusions
  - Grains with rounded edges and even, flush grain-to-grain contacts (indicator for pressure solution

The presence of brine strongly affects microstructural evolution and the mechanical and transport properties of the material (e.g., Schenk & Urai, 2004), although the structure of the halite grain boundaries, which contain water, is still a matter of debate. One model proposes that a thin fluid film transmits the contact stress, thus diffusion transports dissolved material. On the other hand, the thin film fluids may be squeezed out resulting in islands of solid-solid contact, through which the contact stresses are transmitted. Water-filled channels surround islands of solid-solid contact and are conduits through which material diffuses.

A simplified summary, suggested by Christopher Spiers (personal communication with Till Popp), indicates that microscopic findings provide a consistent picture of fluid distribution and mobility inside granular aggregates, as schematically shown in Figure 9.

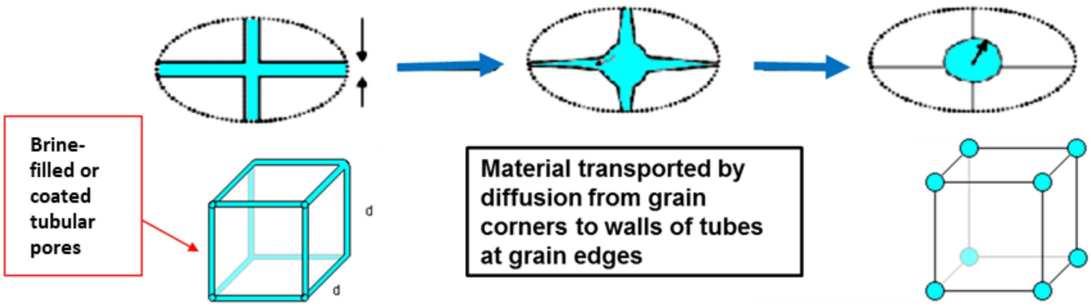

Figure 9: **Schematic of fluid redistribution in granular aggregates during compaction. (left) initial situation with cubic grains and pore fluid channels along cube edges; (right) isolated spheres at cube corners (modified, after Popp & Naumann (2021))**

During isostatic compaction salt is transported by fluid-assisted diffusion processes, specifically dissolution and precipitation, due to differences in chemical potential between points in the solid at grain boundaries under high stress and those under lower stress (Figure 10). As mentioned before, additional driving force (chemical potential drop) both along and across grain boundaries can be provided by internal plastic deformation of the grains, giving rise to combined grain boundary migration and solution-precipitation creep.

However, there is experimental evidence from analogue investigations on crystalline materials that the fluid topology in a low porosity mono-phase polycrystalline aggregate (as it is the case for crushed salt) is controlled by the balance between solid-solid and solid-fluid interfacial energies, and hence the dihedral angle θ. In the case of θ > 60°, the fluids will be present inside isolated inclusions, whereas for θ < 60°, the fluid forms an interconnected network of grain boundary triple junctions.

Referring to crushed salt conditions there is no doubt that if the fluids existing in the primary pore space (mostly air and water vapor) are compressed, they may be partially squeezed out during the transition to a low-pore-space regime. However, migration out of the consolidating material continues as long as a connected porosity and adequate permeability exists. All observations confirm effective reconsolidation until only a few % porosity remains. At that point, the relative saturation within the intergranular pore space increases.

As the granular salt continues to consolidate, the brine or air effective permeability are even lower than the intrinsic permeability, and the mobility of fluids in highly compressed salt is very low. Of course, this range of conditions is very challenging to cover experimentally and remains an area of active research.

3.4 Modelling-related Experimental Aspects

The compaction behavior of crushed salt is rather complex and involves several coupled thermo-hydro-mechanical processes. It is influenced by internal properties, like mineralogy, grain size distribution, porosity (or current compaction state), and humidity as well as boundary conditions such as temperature, deformation rate, or stress state (stress level and geometry). In the current state, the database and process understanding of the crushed salt compaction behavior have still some important gaps in knowledge regarding the material behavior. Existing laboratory data has been derived mostly in oedometer tests with loss of knowledge about the three-dimensional mechanical behavior and with overlapping of several processes and influencing factors, i.e. an isolated analysis is not possible. Consequently, existing numerical models still need to be verified and validated, especially in the range of low porosities.

In the framework of the KOMPASS I project, a proposal for an extended laboratory program for the systematic determination of the THM-coupled long-term behavior of crushed salt was developed (Figure 6). The focus was on gaining a systematically structured database by an isolated consideration of individual processes and influencing factors to allow a clear-cut analysis and determination of functional relations regarding each influencing factor and so to avoid the necessity of assumptions and curve fittings. In addition, a test TUC-V2 (phase I with duration of 150d) was performed from the designed laboratory database and made available within the framework of KOMPASS I for benchmark analysis and constitutive model development and validation. The special innovative feature of this test was the isolated observation of the influence of the deviatoric stress on the compaction behavior of crushed salt, but also the isolated observation of the influence of porosity on the creep behavior of crushed salt. The continuation of the investigations related to the proposed laboratory program is planned within the framework of the ongoing project KOMPASS II.

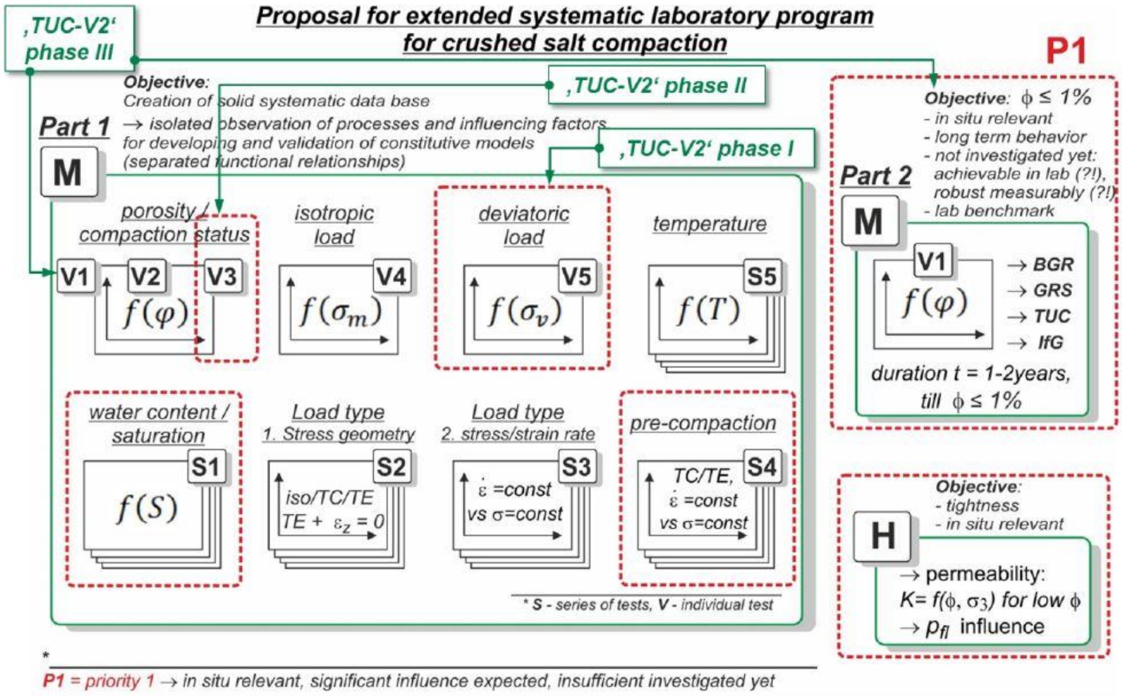

Figure 10: **Proposal for an extended laboratory program for the systematic determination of the THM-coupled long-term behavior of crushed salt with prioritization (red) and allocation of the TUC-V2 test phases I, II and III (green), absed on Friedenberg et al. (2021)**

3.5 Future Work of Relevance for Long-term safety (LTS)

As crushed salt is a possible backfill material for a repository of heat-generating radioactive waste in rock salt, the evolution of its compaction process is of importance for long-term safety. Requirements for the long-term safety analysis comprise flow processes, radionuclide mobilization and transport, drift convergence due to salt creep and the subsequent backfill consolidation, heat flow processes and the influence of temperature on drift convergence, as well as model uncertainties in backfill consolidation models. Especially the radionuclide mobilization and its transport are influenced by the hydraulic properties of the backfill material, which subsequently are influenced by its compaction state. The KOMPASS project strives for the investigation of the porosity-permeability relationship building the experimental basis for the permeability derivative with time as input for long-term safety modelling

4 Engineered Barrier Systems – Towards Robustness and Reliability

4.1 Overview

Backfilling and sealing of salt repositories has been a topic 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 heat transfer properties, its capability to stabilize mine openings, and its great potential to re-establish the natural rock salt barrier by reconsolidation in the long term. Until the crushed salt is reconsolidated enough to assume the barrier function, additional plugging and sealing measures – e.g. shaft and drift seals – are necessary to prevent brine intrusion from the overburden into the salt repository.

According to salt mining experience, suitable sealing materials, e.g. clay/bentonite, various types of concrete – salt concrete and Sorel concrete – and asphalt/bitumen are available. Practical construction experience was gained from several in-situ projects, see 7th US-German workshop 2016 for an overview. Meanwhile, further results have been evaluated, and new pilot tests – many of them ion 1:1 scale have been started – considering outstanding functional components of sealing systems. Up to now the feasibility and functionality of the components of several sealing system designs have been demonstrated and thus the conclusion that safe containment of radioactive waste in rock salt is a realistic option has been backed up. As an additional result of the in-situ tests, it became evident which steps within the construction process are difficult to realize and thus could cause weak spots or which design elements of an individual seal cause uncertainties themselves. For the Morsleben repository, which is under licensing for closure, these potential weak spots and uncertainties are currently being evaluated, taking into account site-specific conditions and their potential future evolutions in order to assess their influence on the drift seals' functionalities in the long term. Consequently, work as well as R&D projects focus on identifying the seals' weaknesses in order to eliminate or reduce them and to improve seals' robustness and reliability.

Regarding long-term robustness and reliability, two presentations were provided by technical staff of BGE and GRS. SNL contributed investigations on bedding planes, which constitute natural zones of weakness. A technical procedure to assess mechanical properties of clay seams in salt was presented. TUC considered the contact zones of drift seals as unavoidable zones of weakness, introducing a technical measure to identify the hydraulic properties of the contact zones combined with options to improve these properties and to eventually rate the level of improvement. TUBAF presented a new technical approach to construct bitumen/gravel columns, which improves robustness and reduces uncertainties.

4.2 Optimization of Drift Seals with Respect to Long-term Functionality

Within the closure concept of the Morsleben repository, drift seals were planned in the past that were mainly made of salt concrete M2. Meanwhile, experience has been gained on MgO-based construction materials, and different emplacement technologies are available. In order to increase robustness and reliability of the drift seals´ functionalities by reducing uncertainties, site-specific conditions and their future evolutions were evaluated again in order to identify FEP that may cause uncertainties with respect to the seals´ functionalities. The corrosion process turned out to be one of the most relevant processes affecting functionality in the long term. Two types of corrosion must be distinguished – homogenous and localized corrosion (Figure 11). As homogenous corrosion is a slow process, the localized corrosion is decisive due to its rapidity. Although small volumes of a corroding liquid may pass e.g. the contact zone at the very beginning (Figure 11), this process may increase exponentially. Experimental set-ups to investigate corrosion processes of very tight materials are complex and a time-consuming process.

In order to investigate corrosion of a typical drift seal configuration on a laboratory scale, an experimental setup was developed. In a pre-damaged hollow salt cylinder, a core of sealing material is embedded, thus creating a laboratory scale drift seal configuration (Figure 12). Four different mixtures of sealing material were investigated this way – salt concrete M2, M4, Type Asse, and the Sorel concrete A1. Two types of salt solutions were used: NaCl-saturated solution and IP21 solution, which were selected for reference solutions in experimental tests. As expected, salt concrete remains stable in the case of NaCl-solution, and Sorel concrete remains stable in the case of IP21 solution at a temperature of 25 °C. They both corroded when the salt solutions were interchanged. The test result of the laboratory A1-seal is shown in Figure 11. In the case of IP21 solution, the permeability tends to 10^{-18} m² in the long-term.

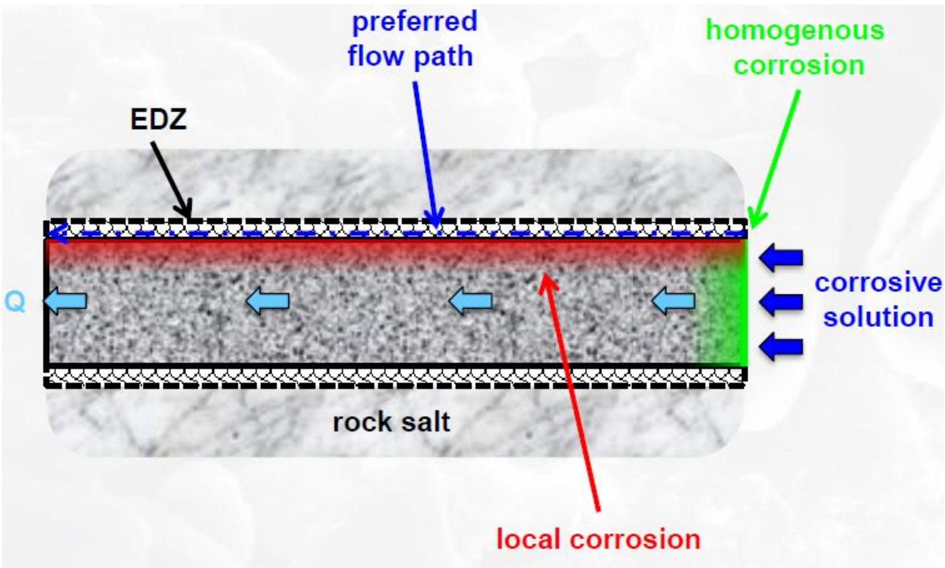

Figure 11: **The hydraulic resistance of drift seals is determined by three elements that act in parallel - the seal´s body made of magnesia-based concrete, the excavation damaged zone (EDZ) close to the drift contour, and the contact zone between the seal's body and the drift contour, based on Gholami et al. (2021)**

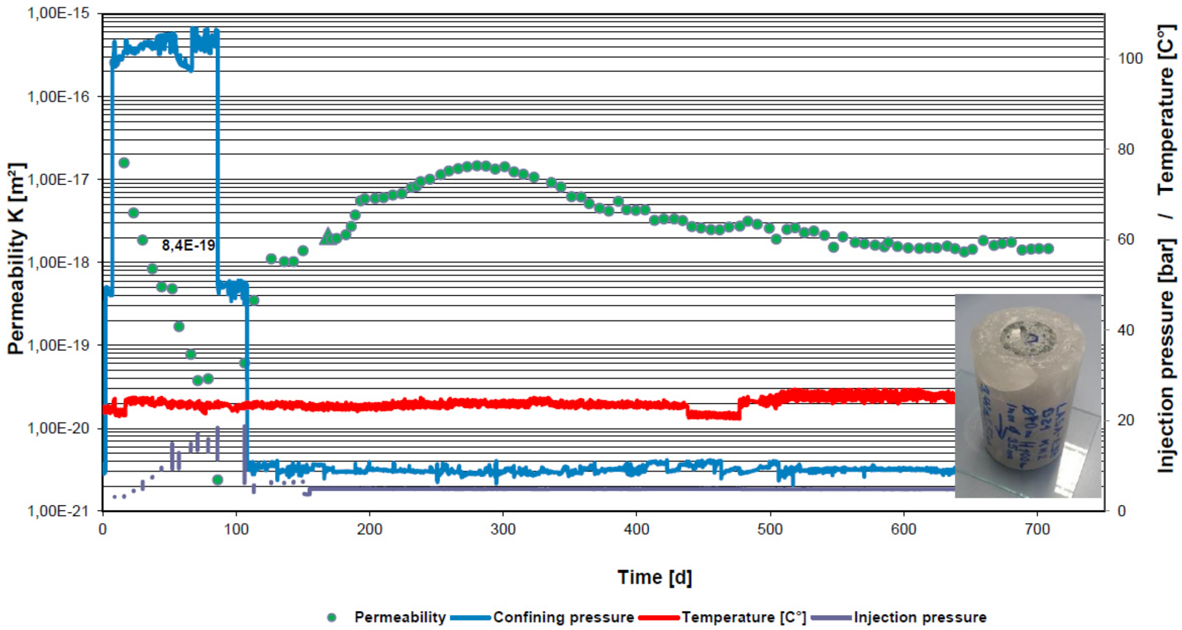

Figure 12: **Sorel concrete A1 laboratory scale seal exposed to IP21 solution – permeability evolution, based on Meyer (2021)**

As one result of the scenario analysis, it turned out that at the drift seals´ locations in the ERAM, $MgCl_2$-rich brine is expected whose $MgCl_2$ concentration guarantees stability of MgO-phases. Consequently, the drift seal material selection was revised, and MgO material will be applied for all drift seals. This optimization eliminates the uncertainty induced by corrosion processes in the long term and improves the drift seals´ robustness and reliability.

In the case of elevated temperature, however, permeability of the Sorel concrete A1 seems to increase slowly. Thus, further investigations are needed to determine the temperature-related stability of Sorel concrete in order to derive a temperature limit at the drift seals´ locations. It is necessary to design a sealing system of long term functionality, if heat-generating radioactive waste is disposed of in salt.

4.3 Mechanical and Hydraulic Zones of Weakness – Determination of Properties

A further important aspect is the influence of natural and unavoidable technical inhomogeneities as layer boundaries and interfaces whose properties may constitute zones of weakness and cause uncertainties even in the operational or early post-closure phase of a radioactive waste repository. As inhomogeneities and interfaces have become significant recently, research activities presently focus on experimental setups to determine their properties and on the reproducibility of experimental results, the latter being a challenge in the case of interfaces.

Practical experience from WIPP shows that deformations and consequently simulated rates of room closure highly depend on the behavior of plane interfaces, especially clay seams. Furthermore, roof falls frequently detach on clay seams, thus affecting operational safety. Therefore, the mechanical behavior of bedding planes was part of the joint R&D project WEIMOS. Within this project, shear-test series using test specimens with different types of interfaces were carried out. Due to the practical relevance of the salt clay interface, the research activities focused on it. The first test series on test specimen gained from NM core samples showed much higher shear strength and stiffness than anticipated, which is due to interstitial salt crystals grown through contacts. As there was a consistent behavior, the resulting strength and stiffness behavior are assumed to be an upper boundary. In a second test series, artificial clay seams were used to establish a plausible lower boundary for strength and stiffness.

The artificial clay seam test specimens were manufactured as follows:

- salt cores were cut in two pieces,
- at the side where the clay becomes applied 1.3 mm deep asperities were created spaced 6 mm apart (Figure 13)
- the other side remained plane
- the seam side was filled with a clay mixture of bentonite and nearly saturated brine and was supported by a PVC tube in order to create a definite seam thickness.
- next, the artificial clay seam was consolidated and the excess of pore fluid was vented.

The result was that approximately 1/3 of pre-consolidation thickness was achieved, and the clay hardened showing a fresh water moisture content of 13 - 17%. Important was that no asperity to asperity contact evolved (Figure 13). Eight samples of salt with artificial clay seams of two different thicknesses were subjected to displacement-controlled direct shear tests at three different normal loads. The maximum and final shear strength were determined for each test. Although none of the tests achieved a true residual stress plateau, the final shear stresses reasonably conformed with Mohr-Coulomb behavior. The Mohr-Coulomb parameters were similar to those of a highly consolidated, saturated clay. The comparison of both test series is shown in Figure 14. As in-situ WIPP clay seams vary significantly in visual and tactile character, the relation to artificial seam tests will be unknown until tests on in-situ samples can be performed.

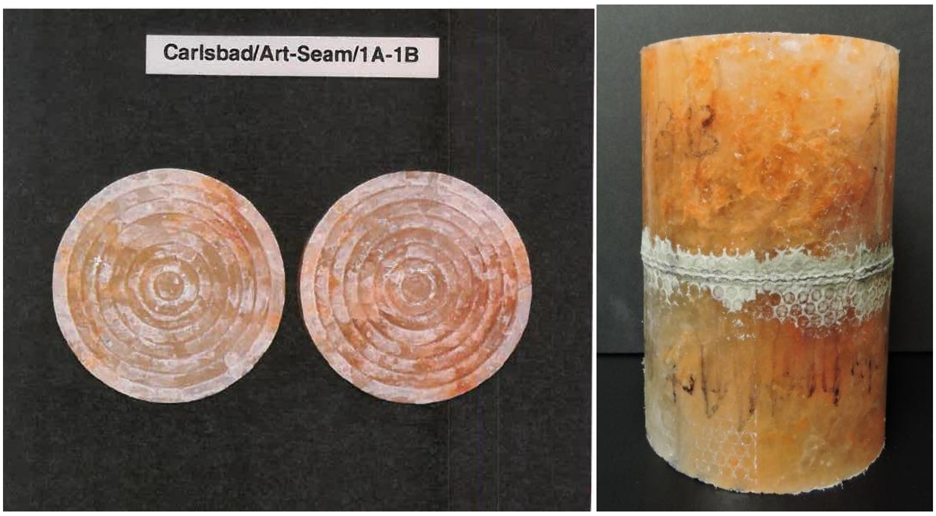

Figure 13: Decisive details of artificial clay seam, based on Sobolik et al. (2021)

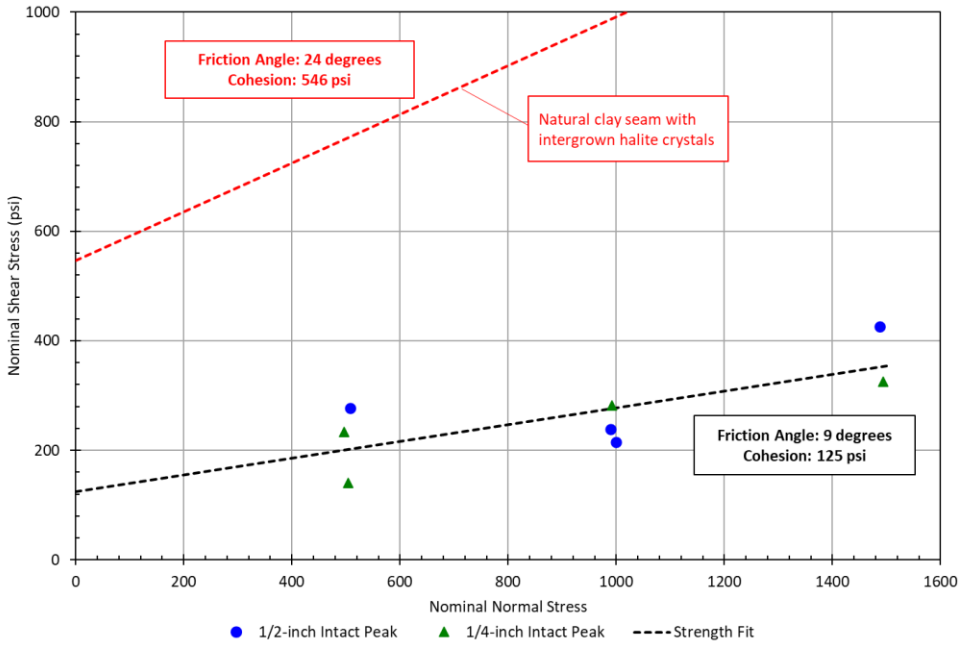

Figure 14: **Shear test results of natural clay seams and artificial clay seams, based on Sobolik et al. (2021)**

The contact zone between a sealing body and the former drift contour constitutes a further zone of weakness (Figure 11). In addition to being a zone that triggers localized corrosion. it may be a significant element when regarding hydraulic resistance of the seal, especially in the early post closure phase of a radioactive waste repository. Thus, the hydraulic parameters of the contact zone are decisive. Up to now, the hydraulic parameters of the contact zone have been determined in a pointwise manner using permeability measurements in boreholes or using small test specimens of core samples from the contact zone. In the joint R&D project STROEFUN, a method to test the permeability of the contact zone along the entire contour of a seal's cross-section has been developed. Furthermore, it is possible to improve the contact zone by injection measures and to perform the permeability test again in order to evaluate the improvement. To test this method, an in-situ test is carried out in the Teutschenthal salt mine.

In August 2021, several layers of site-mixed MgO-concrete were emplaced to form the lower part of a sealing body – a half dam. Before the start of concreting, wireless measuring and monitoring devices were installed in the drift (Figure 15) in order to monitor the setting process by measuring temperature and pressure evolution. Some measuring results achieved up to now are shown in Figure 15. The R&D project is ongoing.

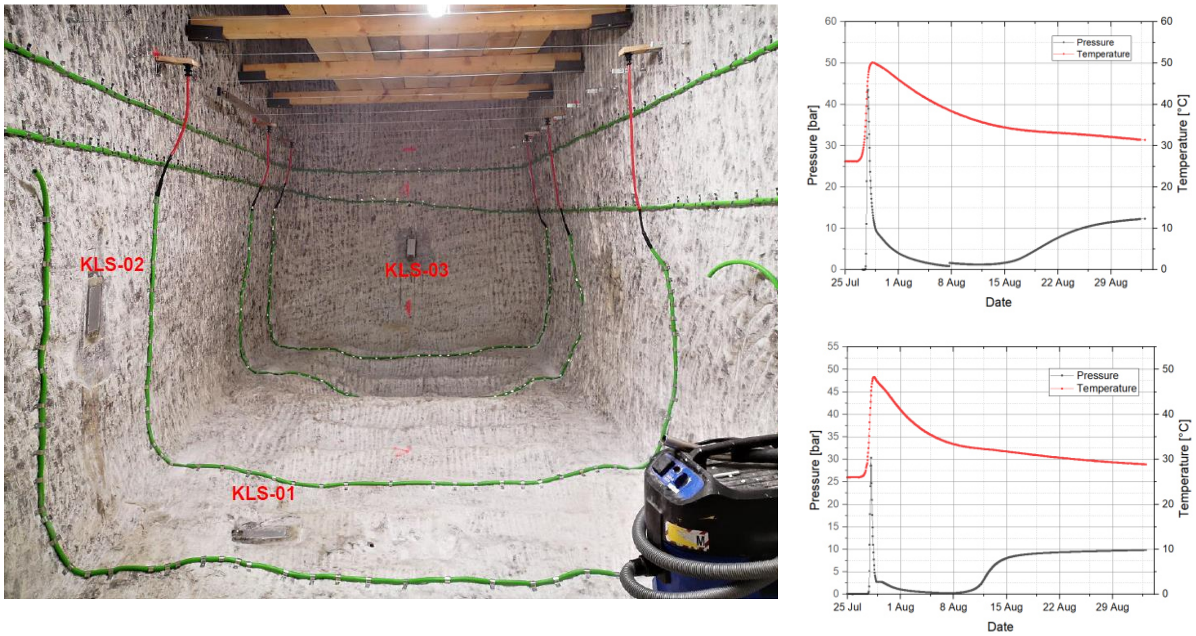

Figure 15: **Test location and position of temperature/pressure measuring devices at the drift contour, and measuring results of KLS-02 (above) and KLS-03 (below), based on Bauermeister (2021)**

4.4 Successful Improvement of a Technical Component

Many components of shaft sealing systems were investigated in the past. Bitumen is a very proven sealing material in underground mining and landfill construction. In future HLW/SF-repositories a diversified and redundant sealing system can benefit from materials based on bitumen. However, with elements made of pure bitumen a risk of uprising gas voids is given.
The functional element of a bitumen-filled gravel column can be realized. Bitumen filled gravel columns have both a static function (abutment) and a sealing function. The penetration of hot bitumen into existing pathways in the surrounding contact zone of the rock is advantageous due to the rheologic properties of the bitumen. Furthermore, observations were made that bitumen/gravel columns obstruct mobile voids.

An alternative to the bitumen-filled gravel column would be the dense stone asphalt newly developed within the joint R&D project ELSA II (Figure 16). The sealing capability of the stone asphalt was tested at a medium scale by means of borehole tests (Figure 17). For stone asphalt, the gravel aggregate (=rounded crushed stone) is pre-dried as with conventional asphalt, and the aggregate and bitumen are heated in a mixing plant (or in a laboratory mixer). The newly developed stone asphalt has essential advantages over the bitumen-filled gravel column. The stone asphalt acts as a seal and as an abutment as well but it adheres much better to the borehole contour than the bitumen in the bitumen-filled gravel column, thus increasing the robustness of the sealing functionality. In addition, dust inclusions as with the bitumen-filled gravel column are eliminated due to premixing.

In principle, there is no limit to the height at which stone asphalt can be placed in a shaft. With the bitumen-filled gravel column, the layer height is limited to the height up to which the bitumen can penetrate the gravel. Stone asphalt would have to be transported in heatable containers to the shaft and in the shaft. However, such containers still have to be developed. A 1:1 scale test is still pending.

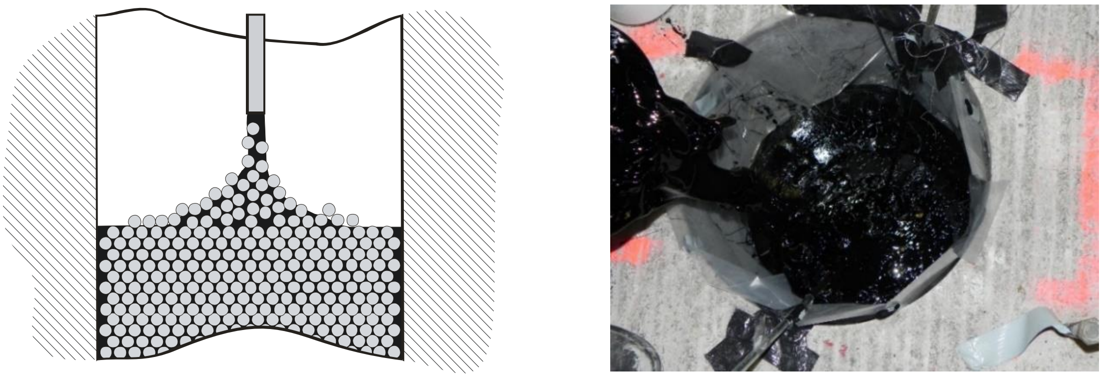

Figure 16: **Dense stone asphalt. Sketch of emplacement process and practical realization in a medium scale (borehole) pilot test, based on Aurich (2021)**

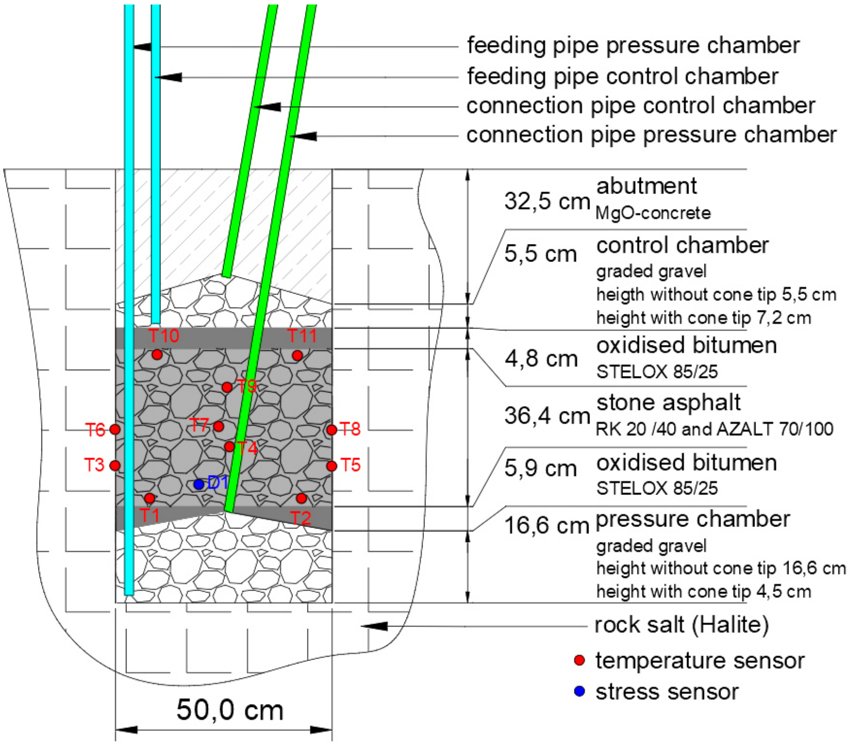

Figure 17: **Functionality of dense stone asphalt - experimental setup of borehole tests, based on Aurich (2021)**

4.5 Summary

Salt repository performance requires effective closure and sealing measures in order to conserve the natural dry environment of a salt repository and to avoid radionuclide release. To cover the period until the salt barrier is re-established, seals are required. The technical feasibility of several sealing components has already been demonstrated in the past. Consequently, present research activities focus on improving their robustness and reliability.

Corrosion was identified to be a source of uncertainty in the long term. Reduction or elimination of corrosion processes by design modification was illustrated using the drift seals designed to seal the Morsleben repository for example. Inhomogeneities and interfaces as zones of weakness may affect repository safety already in the operational or early post closure phase. As a first step, efforts to determine the properties of interfaces precisely have been made. A successful modification of the construction process of bitumen/gravel columns increases robustness and reliability of this sealing component.

5 Modeling Challenges

The last technical session of the eleventh US/German Workshop included different aspects of modeling related to salt repositories. The modeling session spanned the development of conceptual and mathematical models for creep in Sorel concrete, to numerical modeling of various processes in salt repositories. The numerical modeling included (i) two-phase hydrological-mechanical and thermal-hydrological-mechanical benchmarking, (ii) repository modeling to better understand the role of engineered barriers, and (iii) multiple aspects of modeling the Brine Availability Test in Salt (BATS) experiment ongoing at WIPP.

Dr. Nina Müller-Hoeppe from BGE TEC presented an analysis of the laboratory testing and modeling campaign as part of the UVERSTOFF project, which investigates the viscous behavior of Sorel (i.e., MgO) concrete. As it will take years before granular salt reconsolidates to have the same permeability as virgin salt, the drift seals are important to guarantee early containment. The study is motivated by the need to understand and predict the viscoelastic mechanical behavior of Sorel concrete (i.e., MgO binder and crushed salt aggregate) drift seals in a repository, which may be exposed to increased temperature. Aged Sorel concrete has potentially complex behavior, somewhere between granular salt and conventional concrete. Different rheological conceptual models have been used to explain laboratory experiments conducted at GRS, estimating the model parameters from data.

Eric Simo, also from BGE TEC, next introduced the RANGERS project, a three-year-project that investigates the role of engineered barriers in a salt repository. The project includes summaries of the state of the art and of numerical models of whole-repository performance for a hypothetical two-phase repository in a salt pillow from the KOSINA project. The major EBS-centric scenario to be considered includes the hypothetical complete loss of shaft seals and drift seals. BGE TEC and Sandia are modeling different components of the integrity and performance assessment systems, with the goal to bring together the results by the end of the project. BGE TEC showed preliminary FLAC3D thermal-mechanical results for a HLW repository, and Sandia showed preliminary PFLOTRAN thermal-hydrological results on the same numerical model mesh. This collaborative effort between BGE TEC and Sandia is both advancing the state of the art and developing the capabilities of all team members.

Michael Rutenberg from TU Clausthal presented results from the benchmarking exercise called BenVaSim (Benchmarking for Verification and Validation of TH2M Simulators with special regard to fluid dynamic processes in repository systems). The results are not specific to salt repositories, but are highly relevant, as illustrated by the large overlap between the 13 participants (6 organizations) with the attendees of the US/German workshop. The results presented included a 1D two-phase HM model with three cases (basic scenario, mobile phases, and constant gas source). In general, the comparison between the different models was good, but as more complexity was added, there were more deviations between the models. Some preliminary results were presented for a 1D two-phase THM model that included gas and heat source terms, as well as drift, drift seal, and host rock. The spread of predictions between the different models for this second test case was much larger. Even though the test cases looked simplistic, matching numerical models to one another has proven not to be straightforward. The models had many differences governing equations or their implementation, which makes it hard to get similar predictions. Despite the issues, the comparison was successful and was seen as generally beneficial to the numerical modeling community.

The last three presenters covered different aspects of the Brine Availability Test in Salt (BATS), a heater test ongoing underground at the Waste Isolation Pilot Plant (WIPP) near Carlsbad NM. Melissa Mills from Sandia National Laboratories first presented an overview of the field test, which is a collaborative effort between Sandia, Los Alamos, and Lawrence Berkeley National Laboratories, with the WIPP Test Coordination Office. The summary presented samples of the multiple types of data collected during heating, cooling, and tracer testing since the project started in January 2020 (e.g., temperatures, acoustic emissions, electrical resistivity tomography, gas composition, water isotopes, and borehole closure). A look ahead to the next phases of BATS was also presented, set to begin in early 2022. Richard Jayne from Sandia National Laboratories next presented ongoing numerical modeling efforts related to TH modeling of the 2020 BATS heater test. Due to the large number (14) of nearly horizontal boreholes in a relatively small area, meshing the domain requires leveraging advanced tools, including VoroCrust and LaGrit, before simulations can be made with PFLTORAN. Eric Guiltinan, from Los Alamos National Laboratory, finally presented numerical modeling results related to the in-drift water isotope data collected and the gas tracer tests (Kr & SF6) conducted between boreholes in the salt. The water isotopes were shown to fractionate in the borehole, and the FEHM models were able to generally reproduce this behavior. Gas transport through partially brine-filled fractures is a complex two-phase thermal-hydrological flow problem, which was also simulated with FEHM. Generally, the BATS test provides unique data for benchmarking models and building our understanding of the coupled THMC processes going on in the excavation damaged zone during heating. BATS also provides a platform for building field testing and numerical modeling capabilities relevant to heat-generating waste disposal.

This final session of the US/German Workshop illustrated the diverse range of ongoing modeling and experimental programs and highlighted the collaborative nature of much of this work. The experimental and numerical modeling cycles are often iterative, with modelers helping to design better experiments, and experimentalists producing ever more complex data that require new conceptual and numerical models. Also, coupled THM process models and experiments often reveal complexities or deficiencies in models that are less obvious when only considering individual processes at a time.

6 Concluding remarks and outlook

The proceedings in hand summarize a multifaceted workshop. The four different topics of the individual sessions are filled by diverse contributions. All contributions illustrate the continuing progress and further developments in the field of disposal of radioactive waste in salt repositories as the keynotes of the four topics point out. This basis has been established over many years, also through successful international cooperation. In addition to the individual research and development projects themselves, joint workshops, such as the US/German Workshop on Salt Repository Research, Design, and Operation, are an important event for such a cooperation. This is also demonstrated by the diverse contributions from joint projects e.g. such as the KOMPASS project.

The new virtual mode allowed a continuation of the workshop under the difficult pandemic situation. As a result, the scientific and technical exchange in the field of salt repository research, design, and operation between the United States of America and Germany continued. The virtual mode also allowed including more participants and especially young members from different organizations and universities. In this regard, the workshop also marks a transition between the generations and an excellent opportunity to share the knowledge of several decades of work on Salt Repository Research, Design, and Operation. On the flip side, however, discussions were restricted and the direct exchange between colleagues including the inspiration for further tasks and potential collaboration was missing. The organization team intend to have a physical meeting for the 12th US German Workshop on Salt Repository Research, Design, and Operation in 2022. The pandemic situation still holds many uncertainties. If a physical meeting is again not possible, the virtual realization of the workshop offers a good alternative, as demonstrated.

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StandAG (2017) Standortauswahlgesetz vom 5. Mai 2017 (BGBl. I S. 1074), das zuletzt durch Artikel 1 des Gesetzes vom 7. Dezember 2020 (BGBl. I S. 2760) geändert worden ist

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Appendix A – Program and Presentations of Part 1 (February 2021)

Berlin time		2nd February 2021	
16:00	16:15	Welcome by the organizers	K. Kuhlman/SNL P. Herold/BGE TEC
16:15	16:20	Welcome	T. Lautsch/BGE
16:20	16:25	Welcome	H.-C. Pape/BMWi
16:25	16:30	Welcome	T. Gunter/DOE
NATIONAL PROGRAMS Chair: W. Bollingerfehr			
16:30	17:00	Status of US Program	T. Gunter/DOE
17:00	17:30	Status of German site selection	A. Göbel/BGE
17:30	18:00	Long term Dutch research program on rock-salt and updated disposal concept	J. Bartol/COVRA
18:00	18:30	Status of site selection UK	S. Norris/NDA
18:30	19:00	Discussion/Feedback Presentation of potential focus topics for Part 2 and survey by the auditory	K. Kuhlman/SNL P. Herold/BGE TEC

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Status of the United States Spent Nuclear Fuel and High-Level Radioactive Waste Management Program

Timothy C. Gunter
Federal Program Manager
Spent Fuel & Waste Science and Technology
Office of Nuclear Energy

11th U.S./German Workshop on Salt Repository Research, Design, and Operation
February 2, 2021

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

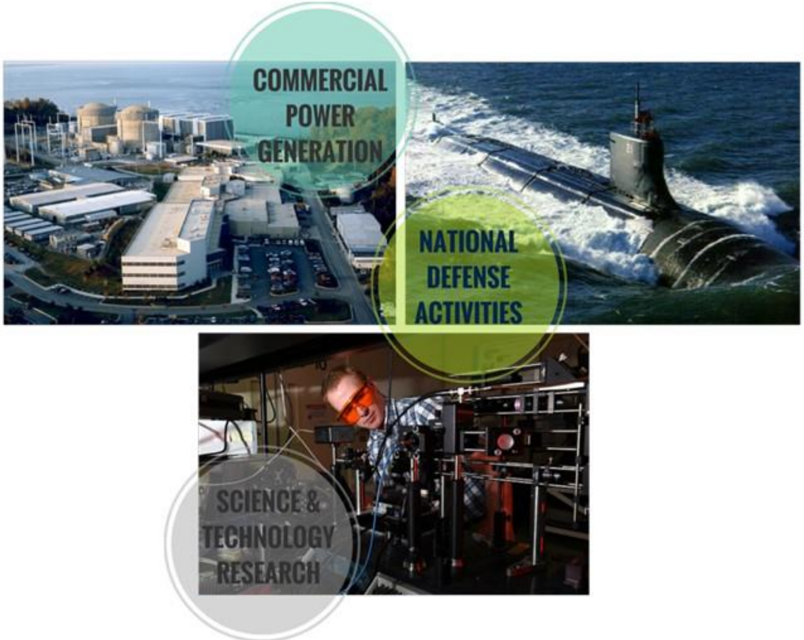
Overview

- **U.S. SNF/HLW Inventory**
- **Fuel Cycle Research and Development (R&D)**
  - Spent Fuel and Waste Disposition R&D
  - Integrated Waste Management System
- **Interim Storage/Nuclear Waste Fund Oversight**
- **Summary**

2

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Sources of Nuclear Waste



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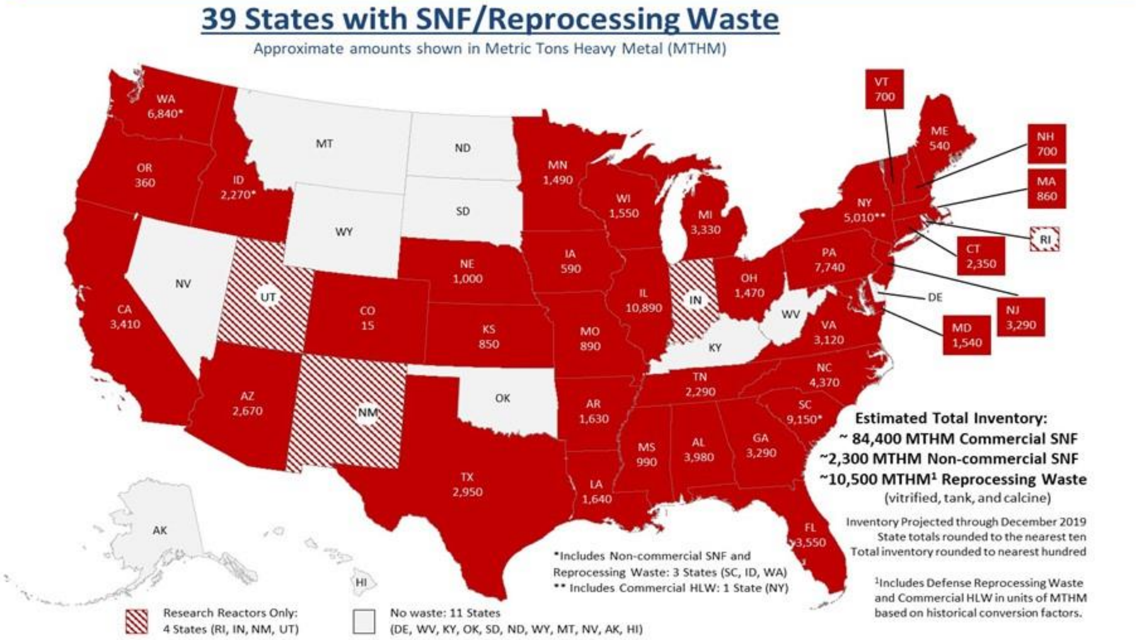
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

SNF/HLW Inventory



Source: SRNL 2020

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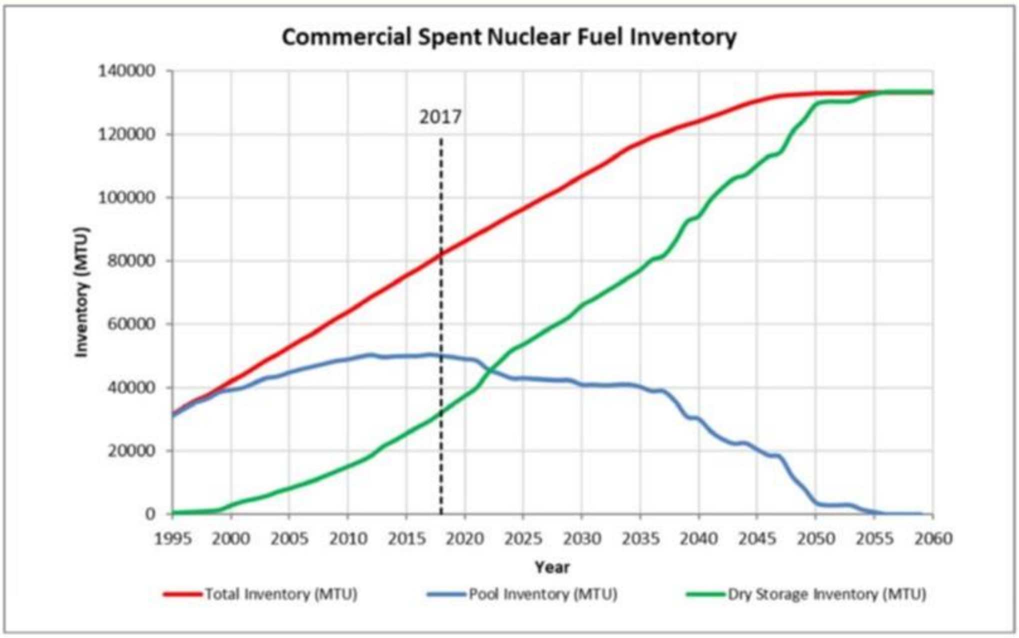
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Spent Fuel Inventory Projection



Source: Modified from Figure 1-5, SNL 2019

5

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Fuel Cycle Research & Development

Office of Spent Fuel and Waste Disposition (SFWD)

- **Spent Fuel Disposition R&D - Conduct generic research and development activities related to storage and transportation of spent nuclear fuel and geologic disposal.**
- **Integrated Waste Management System (IWMS) - develop and implement the design of an IWMS in support of the management and disposal of spent nuclear fuel and high-level radioactive waste.**

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Nuclear Energy

Storage and Transportation Research & Development

- **Extended storage of spent nuclear fuel**
  - Dry Canister Stress Corrosion Cracking R&D
  - Electric Power Research Institute (EPRI)/DOE High-Burnup Confirmatory Spent Fuel Data Project
- **Fuel retrievability and transportation after extended storage**
  - EPRI/DOE High-Burnup Confirmatory Spent Fuel Data Project
  - Thermal analysis of dry storage canisters
- **Transportation of high-burnup spent nuclear fuel**
- **Security assessments**

7

U.S. DEPARTMENT OF ENERGY
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Generic Disposal Research & Development

- **Direct Disposal of Dual Purpose Canisters (DPC)**
  - As-loaded criticality calculations
  - Recommendations for design enhancement options for existing and future DPCs
  - Potential canister filler materials (moderator exclusion)
- **Improved geologic disposal safety assessment modeling capabilities**
  - High performance computing for future repository system performance (PFLOTRAN)
- **International collaborations and enhanced R&D to support disposal concepts in multiple geologic media**
  - Experimental and modeling activities in salt, argillite, and crystalline rock, including collaboration with international communities

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Integrated Waste Management System

- **IWMS - Develop and implement the design of an integrated waste management system**
  - Site preparation activities at stranded sites
  - Transportation coordination efforts
  - Evaluation of options for rail cars

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U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Interim Storage and Nuclear Waste Fund Oversight

- **Interim Storage**
  - Development of interim storage capabilities authorized by Congress in the FY2021 appropriation (December 2020)
- **Nuclear Waste Fund Oversight**

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U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Summary

DOE's focus is on near-term progress and sustainable solutions:

- Continue R&D in areas of storage and transportation, generic geologic disposal, and direct disposal of dual-purpose canisters
- Continue development of transportation capabilities (railcar and programmatic elements)
- Planning for possible interim storage

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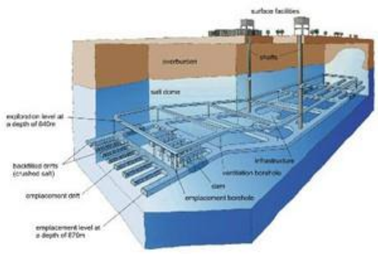
Questions

Questions/Comments?



Additional information at
www.energy.gov

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Nuclear Energy

References

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- SNL (Sandia National Laboratories) 2019. *Comparative Cost Analysis of Spent Nuclear Fuel Management Alternatives.* SAND2019-6999 Revision 1. June 2019. Albuquerque, New Mexico: Sandia National Laboratories.
- SRNL (Savannah River National Laboratory), 2020. *Spent Nuclear Fuel and Reprocessing Waste Inventory*. Shan Peters, Dennis Vinson, Joe T. Carter. September 2020. FCRD-NFST-2013-000263, Revision 7, Aiken, South Carolina: Savannah River National Laboratory

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11th US/German Workshop on Salt Repository Research, Design, and Operation

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

Sandia National Laboratories

PTKA Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

BGE TEC
BGE TECHNOLOGY GmbH

Astrid Göbel
Bundesgesellschaft für Endlagerung mbH

Part 1 of the online workshop
February 2, 2021

Brief retrospect

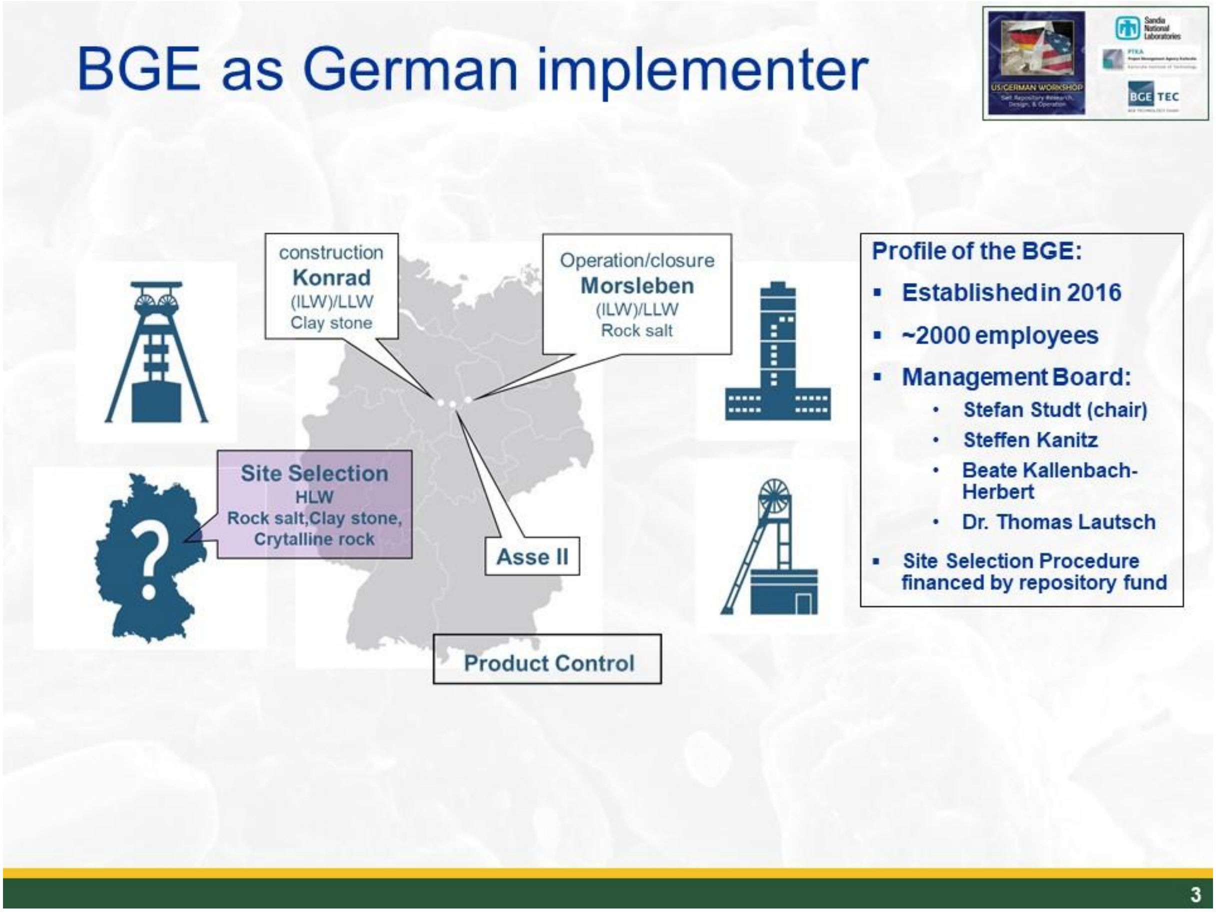
1977 Selection of the Gorleben site
1979 Start of investigation works at Gorleben site
2000 Moratorium to the Gorleben Site
1999 – 2002 AkEnd (issued its final report in 2002)

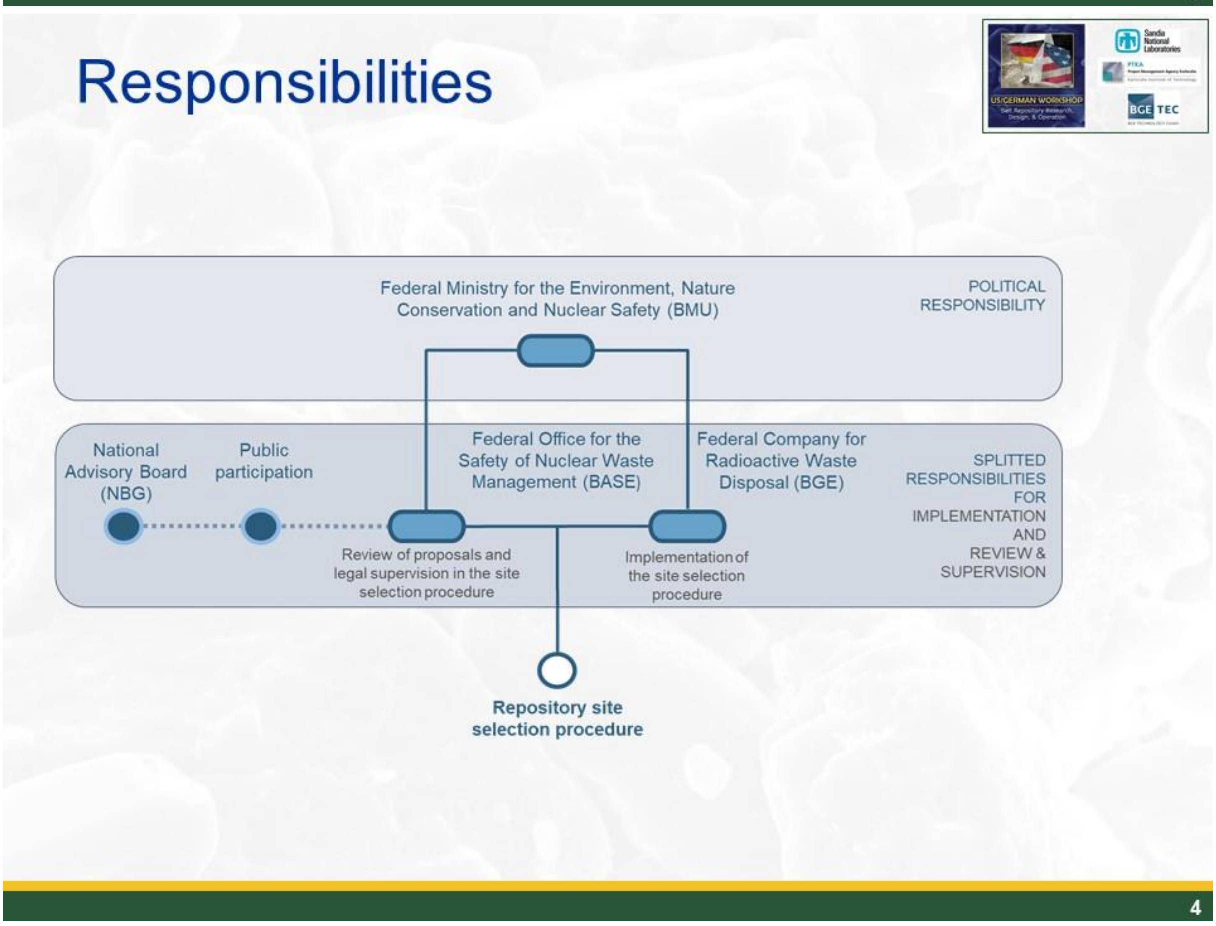
2013 restart The 'StandAG' (Repository Site Selection Act) comes into force. The aim of the site selection procedure is to find a site for a geological repository for mainly high-level radioactive waste (HLW) by means of a science-based and transparent procedure.

2016 restructuring The operational tasks of site selection, construction and the operation of the repositories and the Asse II and Gorleben mine sites are to be bundled in a state-owned company, the Bundesgesellschaft für Endlagerung mbH (BGE). The 'Commission for the Financing of the Nuclear Phase-Out', set up by the government, presents its recommendations: energy supply companies are to transfer around € 23.3 billion from the accrued provisions to a state fund.

2017 revision The revised StandAG (Repository Site Selection Act) comes into force.

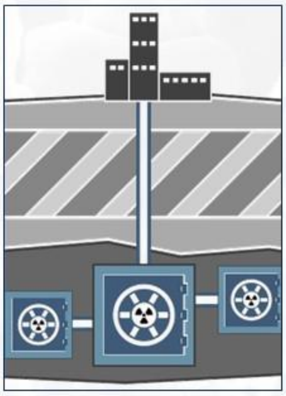
2


BGE as German implementer
construction
Konrad
(ILW)/LLW
Clay stone
Operation/closure
Morsleben
(ILW)/LLW
Rock salt
Site Selection
HLW
Rock salt,Clay stone,
Crytalline rock
Asse II
Product Control
Profile of the BGE:
Established in 2016
~2000 employees
Management Board:
Stefan Studt (chair)
Steffen Kanitz
Beate Kallenbach-Herbert
Dr. Thomas Lautsch
Site Selection Procedure financed by repository fund
3


Responsibilities
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
POLITICAL RESPONSIBILITY
National Advisory Board (NBG)
Public participation
Federal Office for the Safety of Nuclear Waste Management (BASE)
Federal Company for Radioactive Waste Disposal (BGE)
SPLITTED RESPONSIBILITIES FOR IMPLEMENTATION AND REVIEW & SUPERVISION
Review of proposals and legal supervision in the site selection procedure
Implementation of the site selection procedure
Repository site selection procedure
4

Regulatory framework

- Best possible safety conditions for the storage of HLW
- Repository location must be within the Federal Republic of Germany
- Deep geological disposal mine
- Best possible safety for a period of 1 million years
- Retrievability during operating phase
- Recoverability (Bergbarkeit) for 500 years after closure of the mine
- Science-based, transparent and participative selection procedure
- Self-questioning and learning process



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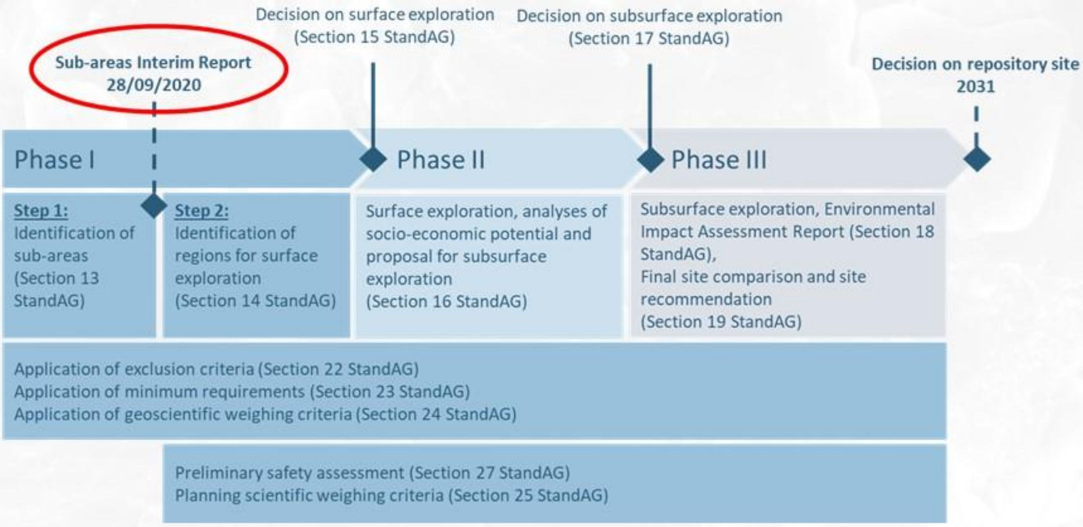
Phase wise implementation



6

Towards determination of sub-areas

where favourable geological conditions can be expected for the safe final disposal of high-level radioactive waste

From data delivery to the visualization of the data
- Review, homogenization, storing
- Around 280 data deliveries (>1 000 000 files, approx. 450 file types)
- Quantity and quality increase during the process
- Use of reference data sets, if needed

Application methodology
- Development
- Discussion
- Testing
- Consutations
- Adjustments

Application of exclusion criteria (Section 22 StandAG) to the whole of Germany – each of them as ko criterion

Application of minimum requirements (Section 23 StandAG) considering the host rocks rock salt, clay rock and crystalline rock

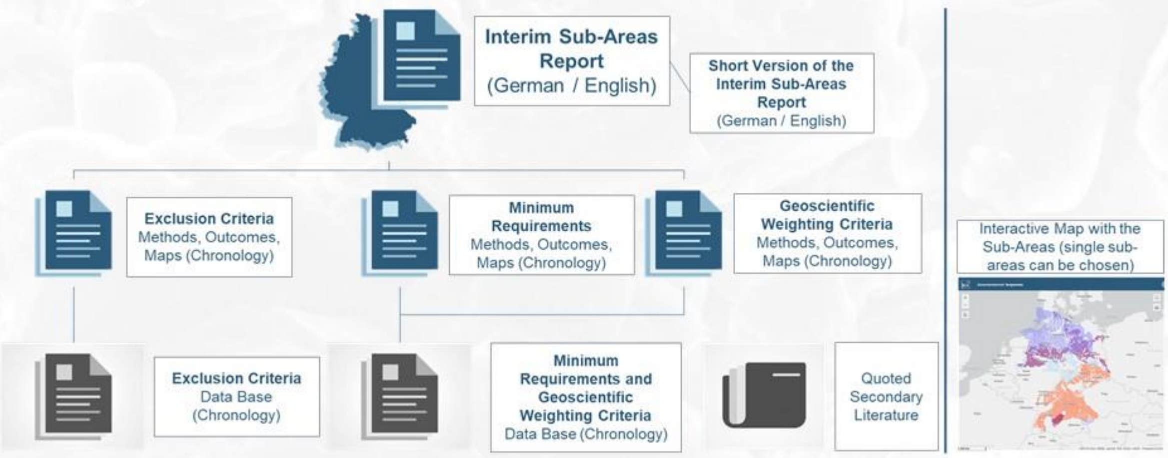
Identified areas

Application of geoscientific weighing criteria (Section 24 StandAG) pursuant to annexes 1-11, assessing the favourability of each identified area by
- Property of the criterion
- Indicator
- Value

Sub-areas

7

Milestone – sub-areas interim report



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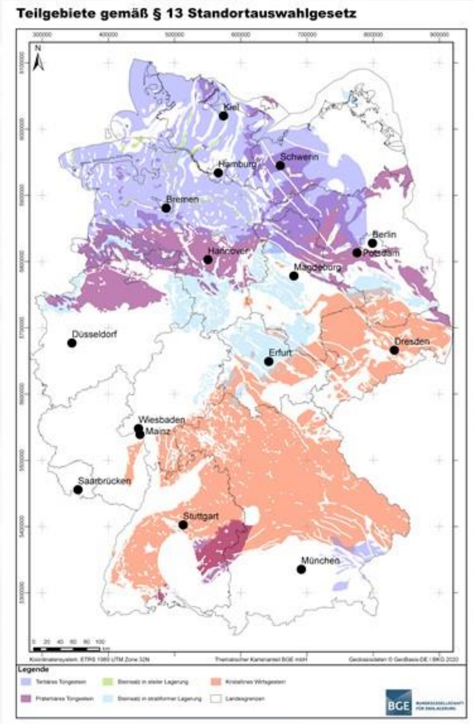
Sub-areas interim report

General map of the identified sub-areas **(all host rocks)**

- There were **no areas that could not be classified** due to insufficient geological data
- A total of **90 sub-areas with an area of approx. 240 874 km²** are identified which are expected to have favourable geological conditions for the final disposal of high-level radioactive waste (~54% of Germany)
- The sub-areas were identified according to stratigraphic units, therefore this map representation shows **a partial overlapping of several sub-areas**



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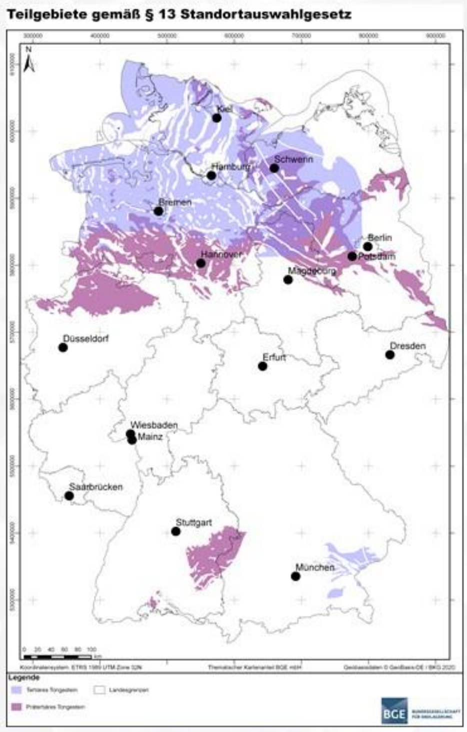
Identified sub-areas 1 - claystone

General map of the sub-areas in the host rock **claystone**

- **9 sub-areas** with a surface of approx. **129 639 km²** are identified in claystone host rock



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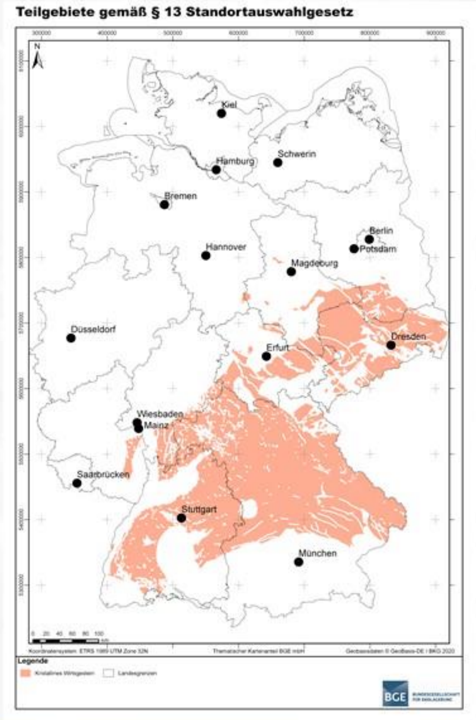
Identified sub-areas 2 - crystalline

General map of the sub-areas in the **crystalline** host rock

- **7 sub-areas** with a surface of approx. **80 786 km²** were determined in crystalline host rock

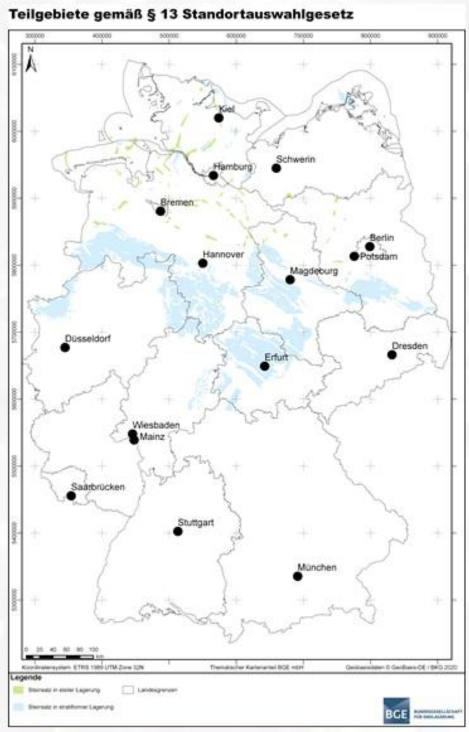


11

Identified sub-areas 3 – rock salt

General map of the sub-areas in the host rock **salt**

- **74 sub-areas** with a surface of approx. **30 450 km²** were identified in salt host rock
- 60 are located in steep rock salt structures
- 14 sub-areas are in stratiform salt formations



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Results – example Gorleben

Overall evaluation of Gorleben-Rambow salt dome:

- All exclusion criteria according to § 22 StandAG were applied to the Gorleben-Rambow salt dome. As a result, the drillings for oil/natural gas exploration with a radius of 25 m around the drilling track are excluded.
- In the current phase of the site selection procedure, the **Gorleben-Rambow salt dome meets all minimum requirements** according to § 23 StandAG. It has been designated as identified area no. 020_00IG_S_s_z.
- On the basis of the **application of the geoscientific weighing criteria** in accordance with Section 24 StandAG, the summarised assessment of the identified Gorleben-Rambow area was **"not favourable"** (Annex 11 (to Section 24 para. 5), the protection of the effective containment zone by the overburden)

This means that the provision of § 36 (1) sentence 5 no. 1 StandAG, according to which the Gorleben-Rambow salt dome is excluded from the procedure, applies. Therefore, the identified Gorleben-Rambow area was not identified as a sub-area.
The Gorleben-Rambow salt dome will therefore not be considered in the further work of the BGE on the proposals concerning the siting regions.

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Information & interactivity

BGE encourages participation

- Comprehensive information available on the dedicated information platform hosted by BASE
- Presentation of the sub-areas interim report (18-10 in Kassel and online, available on YouTube)
- Short explanation videos (available on YouTube and BGE homepage)
- Open access to technical meetings or dedicated sessions for discussion of technical aspects with CS
- Interactive map of Germany including links to further information about each sub-area, offering a search tool
- Online consultation sessions for each sub-area (available on YouTube)
- Online consultation of the methodology (BGE forum)

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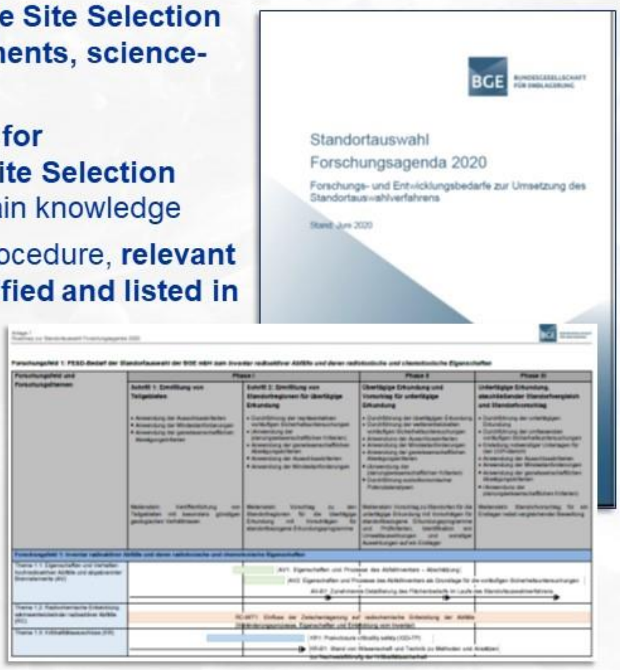
Research & development 1

According to § 1 of the StandAG, the Site Selection Procedure is, among other requirements, science-based

- The **inclusion of RD&D** is **crucial for implementation of the German Site Selection Procedure** to close gaps and to gain knowledge
- To implement the Site Selection Procedure, **relevant research needs have been identified and listed in a research agenda**
- **Current focus of RD&D** projects:
  - Disposal container
  - Uncertainty management
  - Limit temperatures
  - Characterisation of host rocks
  - THMC(B)-processes
  - Climate change



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Research & development 2

The Site Selection Department **participates in national and international RD&D cooperations** incl. URL activities

The **exchange with the BMWi on RD&D** has been reinforced with the overall objectives

- Joint efforts to foster the progress of the German disposal programme
- Optimisation of applicability through
  - Continiuous exchange on the BGE RD&D plan and the BMWi research funding programme
  - Continuous and up-to-date information about the site selection related plannings, schedules, needs and priorities
- Identification of themes and projects, suitable for cooperative coordination (e.g. co-funding)
- Fostering transfer of knowledge and state-of-the-art

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Outlook

- BGE has **launched Step 2 of Phase I** with the aim to identify regions for surface exploration (Section 14 StandAG)
- Execution of **representative preliminary safety assessments** (Section 27 StandAG, EndlSiUntV) to all determined sub-areas
- Based on the results, re-application of the **geoscientific weighing criteria** and, if necessary, consideration of **planning scientific weighing criteria** (Section 25 StandAG)
- Throughout the next months **sub-area conferences** will take place and will be supported
- **RD&D planning** will be refined

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Thank you for your attention

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

Sandia National Laboratories

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

BGE TEC
BGE TECHNOLOGY GmbH

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dialog@bge.de
www.bge.de

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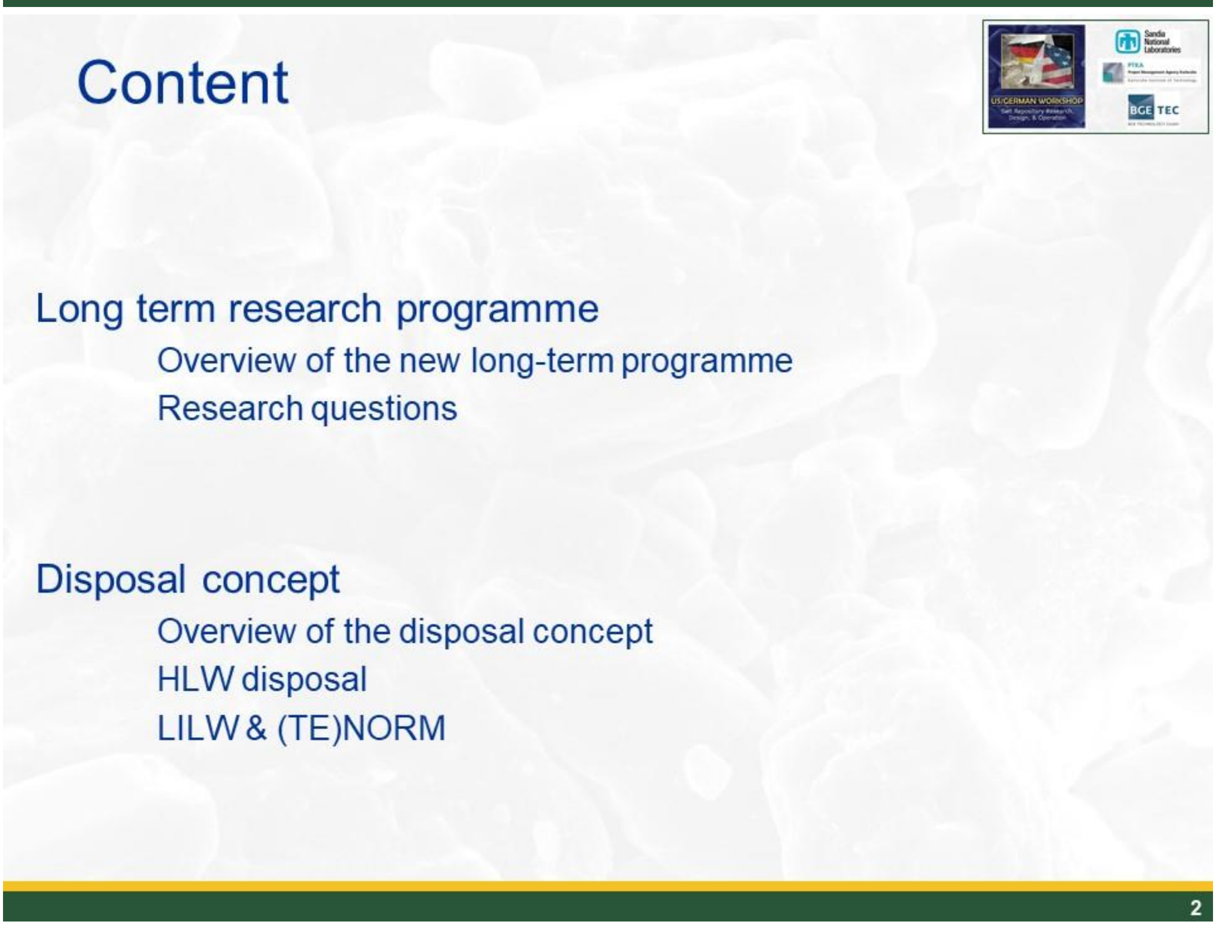
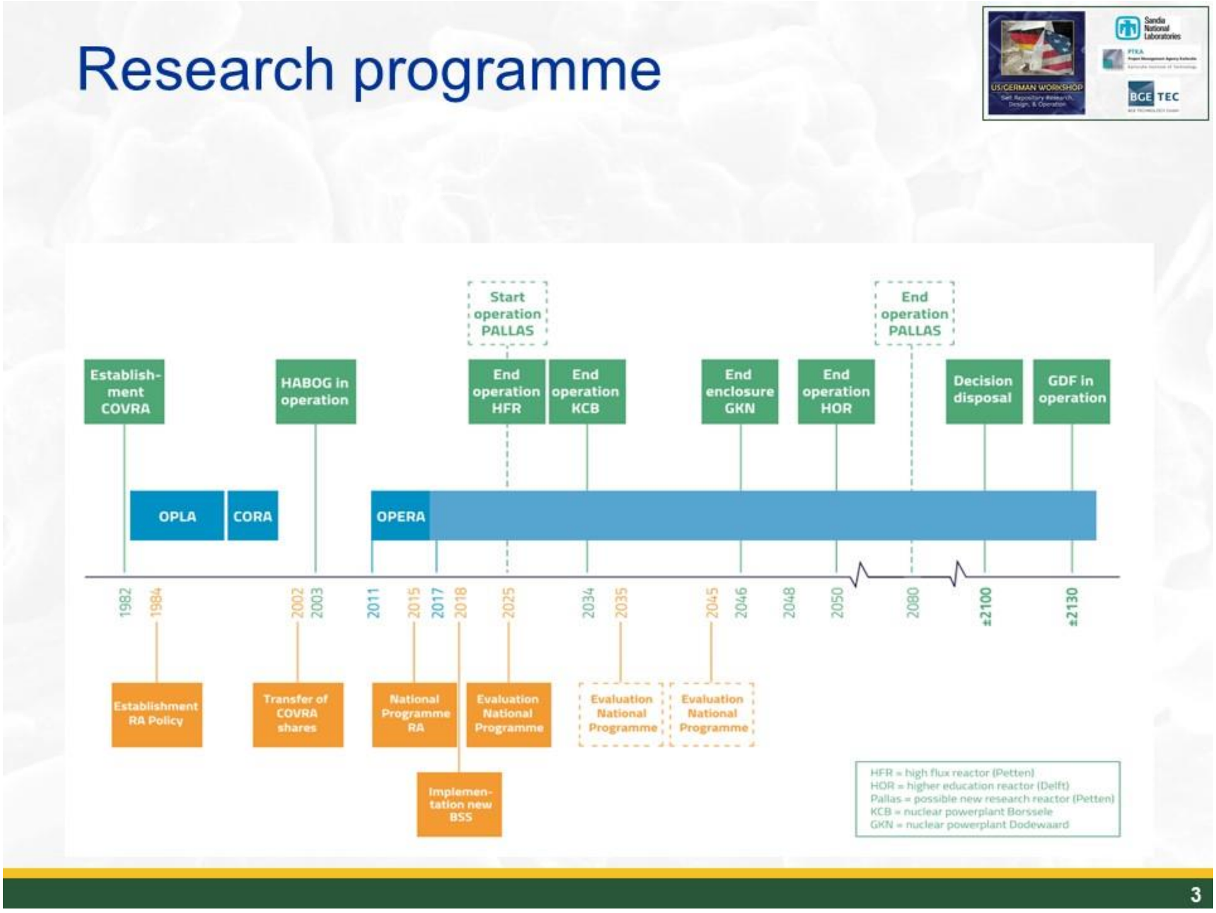
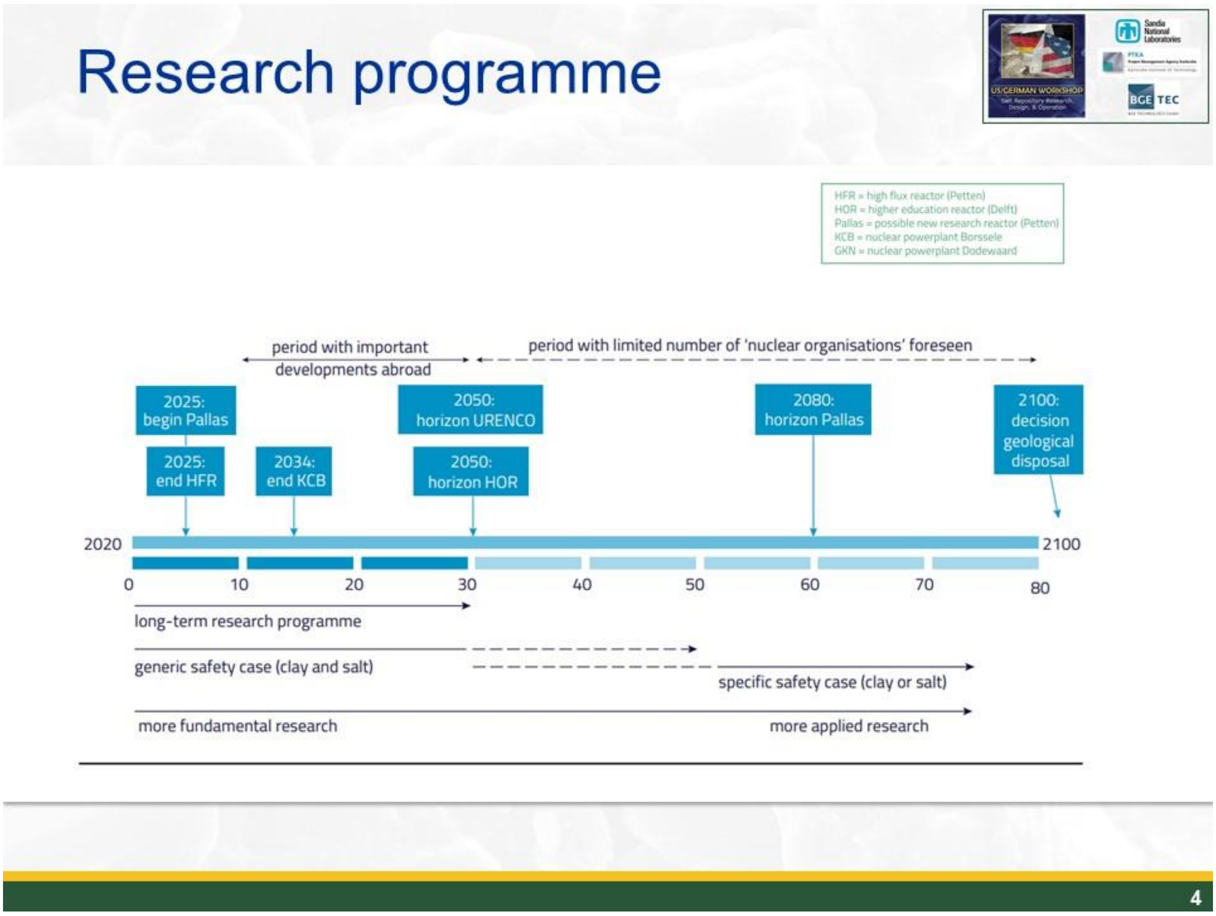
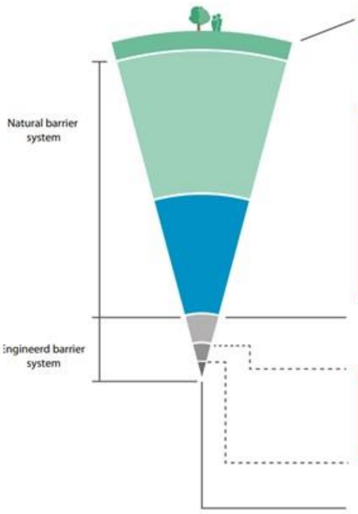
11th US/German Workshop on Salt Repository Research, Design, and Operation
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH
Jeroen Bartol
COVRA, the Netherlands
Part X of the online workshop
02 02, 2021


Content
Long term research programme
Overview of the new long-term programme
Research questions
Disposal concept
Overview of the disposal concept
HLW disposal
LILW & (TE)NORM
2


Research programme
US/GERMAN WORKSHOP
BGE TEC
Start operation PALLAS
End operation PALLAS
Establish-ment COVRA
HABOG in operation
End operation HFR
End operation KCB
End enclosure GKN
End operation HOR
Decision disposal
GDF in operation
OPLA
CORA
OPERA
1982
1984
2002
2003
2011
2015
2017
2018
2025
2034
2035
2045
2046
2048
2050
2080
±2100
±2130
Establishment RA Policy
Transfer of COVRA shares
National Programme RA
Evaluation National Programme
Evaluation National Programme
Evaluation National Programme
Implementation new BSS
HFR = high flux reactor (Petten)
HOR = higher education reactor (Delft)
Pallas = possible new research reactor (Petten)
KCB = nuclear powerplant Borssele
GKN = nuclear powerplant Dodewaard
3


Research programme
US/GERMAN WORKSHOP
BGE TEC
HFR = high flux reactor (Petten)
HOR = higher education reactor (Delft)
Pallas = possible new research reactor (Petten)
KCB = nuclear powerplant Borssele
GKN = nuclear powerplant Dodewaard
period with important developments abroad
period with limited number of 'nuclear organisations' foreseen
2025: begin Pallas
2025: end HFR
2034: end KCB
2050: horizon URENCO
2050: horizon HOR
2080: horizon Pallas
2100: decision geological disposal
2020
2100
0
10
20
30
40
50
60
70
80
long-term research programme
generic safety case (clay and salt)
specific safety case (clay or salt)
more fundamental research
more applied research
4

Research programme



Component	R&D effort for the next safety case
Biosphere	Very limited R&D effort. Integration of available information of the IAEA will be used for the safety assessment.
Surrounding rock formations	Limited R&D effort. Integration of the available knowledge on the formation of tunnel valleys potentially disturbing a GDF and changes in ground water that could effect the rate of subrosion and transport from host rock to the biosphere.
Host rock: Rock salt	**Geotechnical properties** Large R&D effort: More data on rock salt increase understanding of itslong term evolution and decreases the uncertainties. **Evolution of the permeability-porosity in rock salt** Large R&D effort: There is still a large uncertainty on the long-term evolution of the granular backfill. Provides input for the requirements on the engineered barriers / waste package. **Radionuclide Solubility in Brine** Large R&D effort: Brine is a potential transport medium for radionuclide but limited information is available on its availability. **Geological setting** Moderate R&D effort. More information on bedded salt of the Röt formation will focus research in the future.
Repository	Limited R&D effort: Relevant information is available in the Germany and USA on seals that could be used in the Dutch case.
Waste package	Waste package for HLW: Moderate R&D effort. Repackaging of HLW waste possibly needed to provide containment when backfill and EDZ still have a significant permeability. Waste package for TE(NORM): Moderate R&D effort: epackaging of waste possibly needed for to have a waste package suited for high - saline environment.
Waste form	Limited R&D effort. Integration of available information from different sources

5

Research programme

Task 4A.1: Geotechnical properties

Setting up a (rock) salt THM database. The focus will be on rock salt of the Zechstein formation, but other types of salts and formations can also be included.

Utrecht University

KOMPASS

Compaction of crushed Salt for the safe Containment

Task 4B.2: Evolution of the permeability-porosity in rock salt

What is the long-term evolution (10^3 -10^6 years) of the permeability-porosity of rock salt (backfill and EDZ) under in-situ conditions?

Task 4B.2.2: Gas-Rock Salt interaction

How does the build-up of gas pressure affect the long-term evolution of permeability and porosity of rock salt and how does it, in turn, affect the closure of the GDF?

6

Research programme

DECOVALEX 2023

Task 4B.2.3: Brine availability

What is the availability of brine in a rock salt repository, which processes influence this availability, and can a numerical model be developed to predict the brine availability?

Task 4B.4.1: Bedded salt of the Röt formation

Mapping and characterizing the Röt formation, and more specifically the rock salt within this formation in the Netherlands.

Utrecht University

Task 4B.4.2: Understanding past, present and future subrosion rates in the Netherlands

What have the subrosion rates been in the Netherlands in the past, what are they currently and what subrosion rates can be predicted for the future using numerical models?

7

Research programme

Task 4B.4.3: Diapirism rates in the Netherlands (Past – Present - Future)

What have the diapirism rates been in the Netherlands in the past, what are they currently and what diapirism rates can be predicted for the future?

Task 5.1: Impact of tunnel valleys

What is the radiological consequence of deep glacial erosion?

Task 4B.2.1: Gas Production

How much gas is produced and how will (through time) gas pressure build up in the repository after closure based on the new repository concept including the overpacks?

8

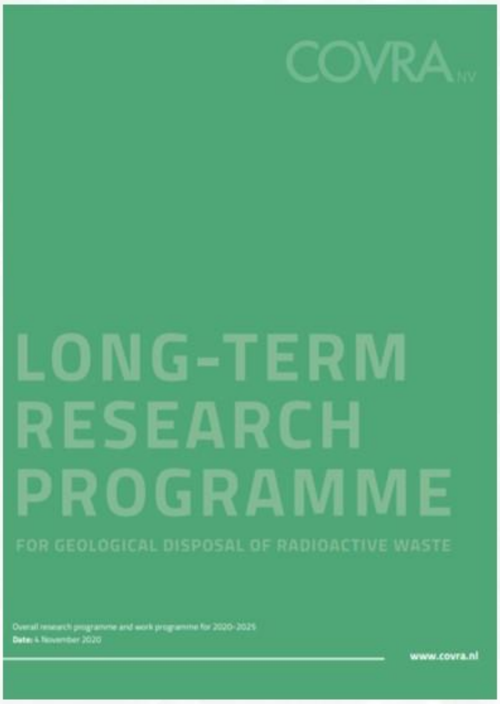
Research programme

Task 3.3.1: Waste package for HLW

What are the (dis)advantages of the use of a self-shielded "super" container? When it has clear advantages: design a self-shielded "super" container that provides complete containment during the period that the backfill and EDZ still have permeability.

Cost estimate **Initial safety case** **Performance Assessment model**

Research programme



More information on the long-term research programme can be found on our website www.covra.nl

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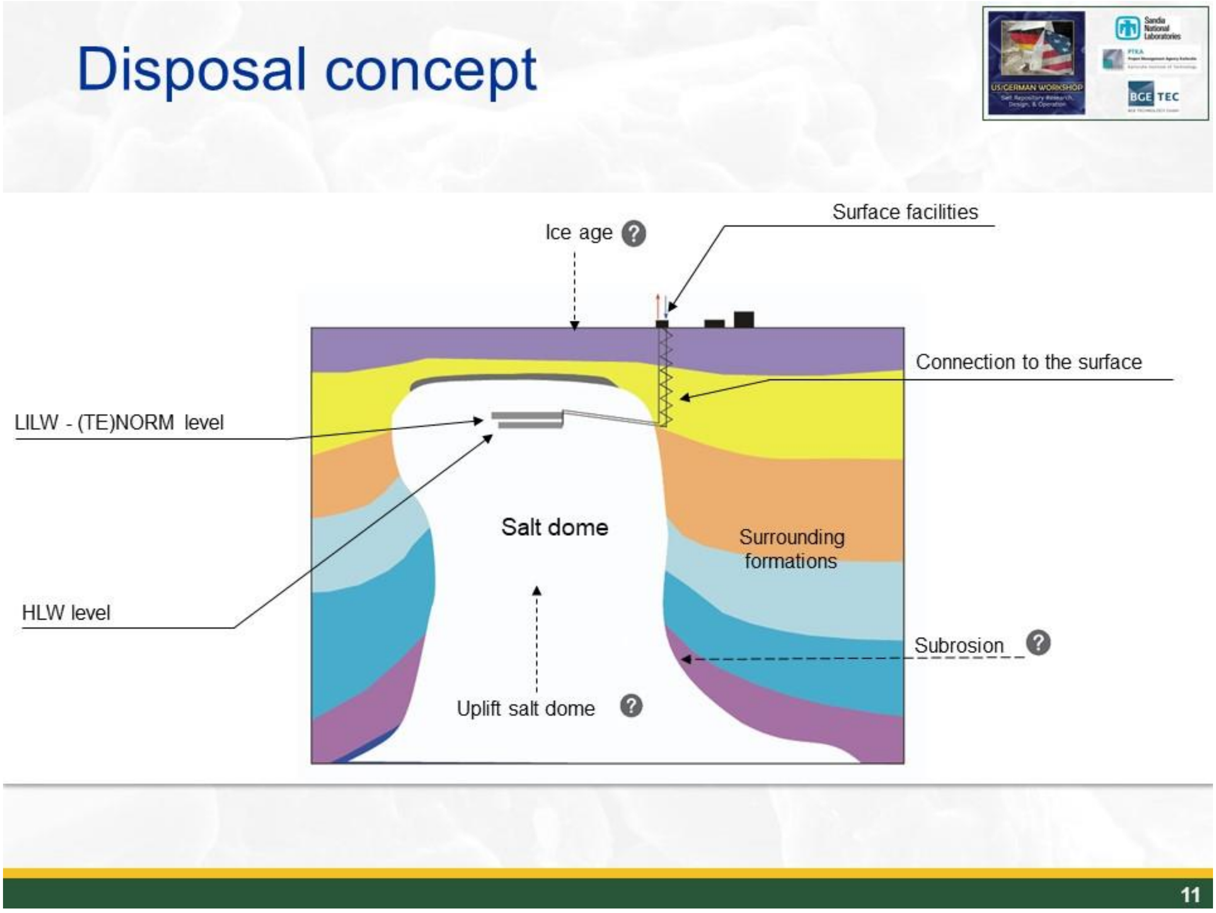
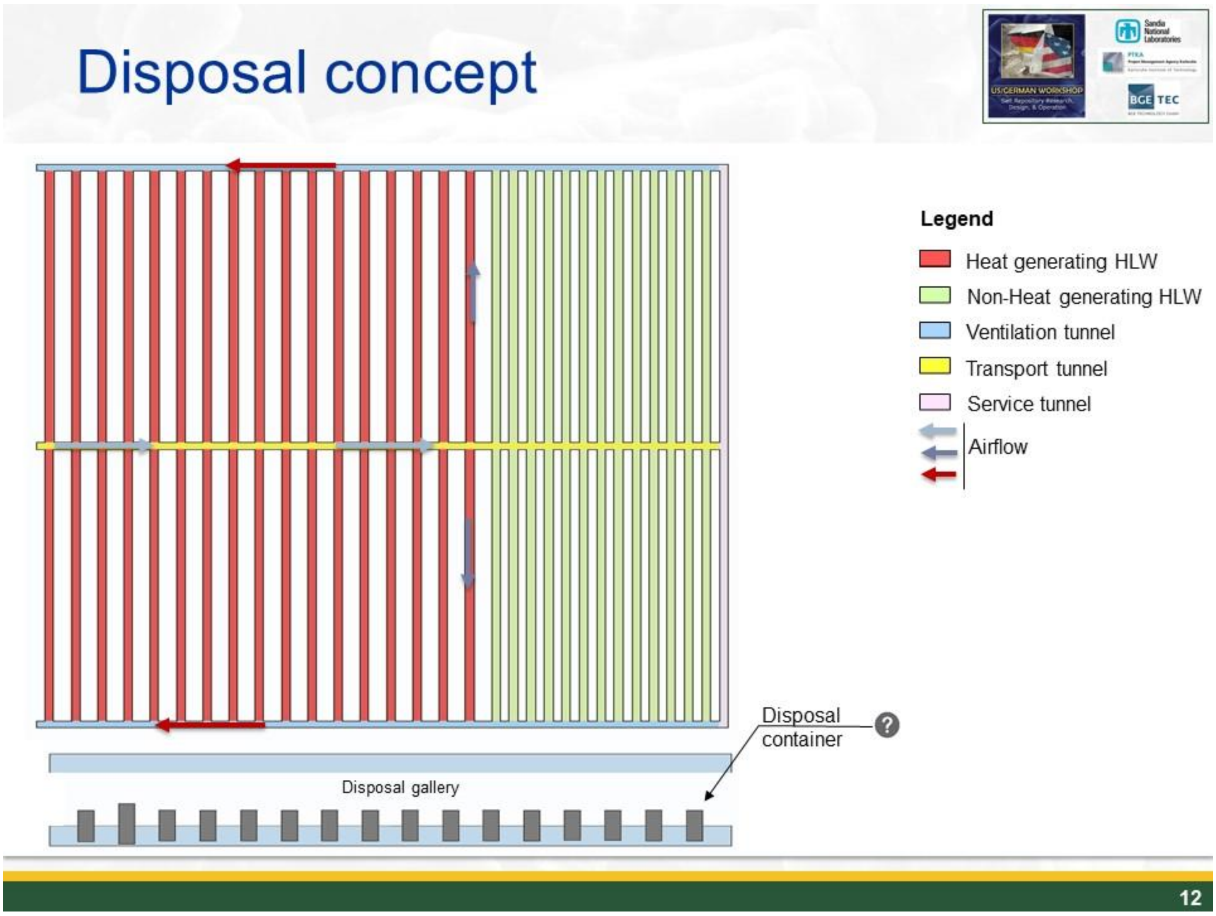
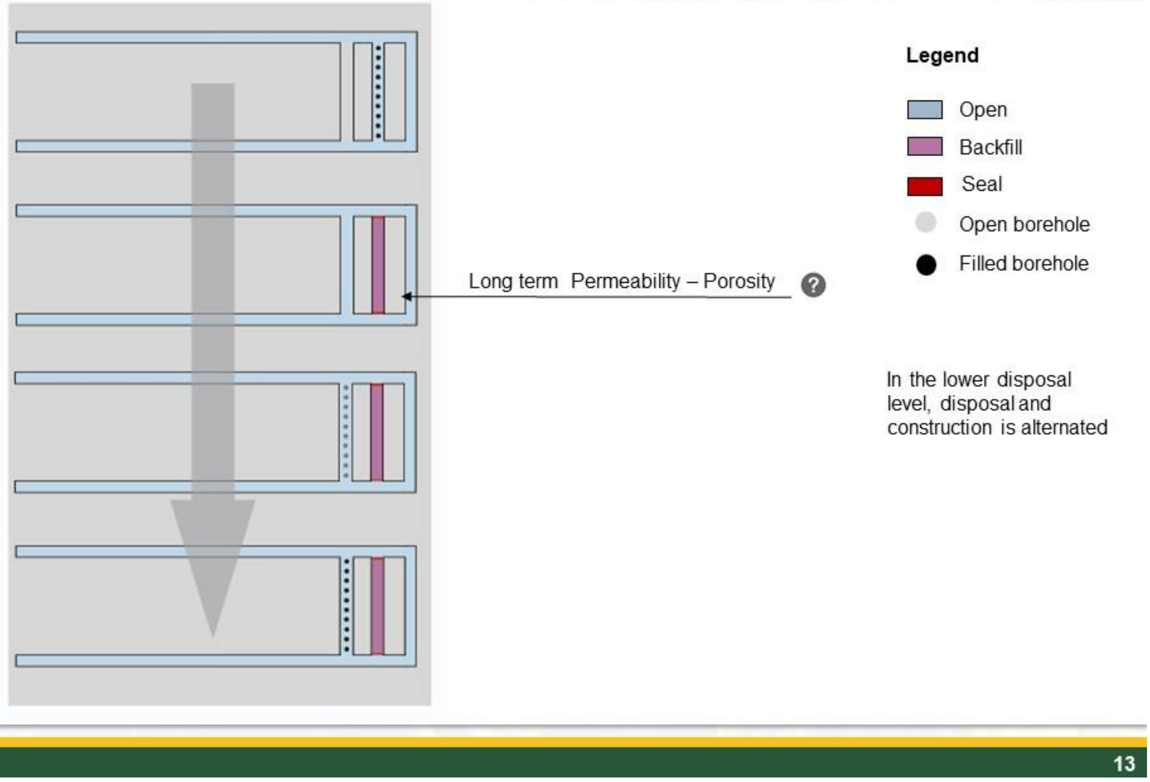
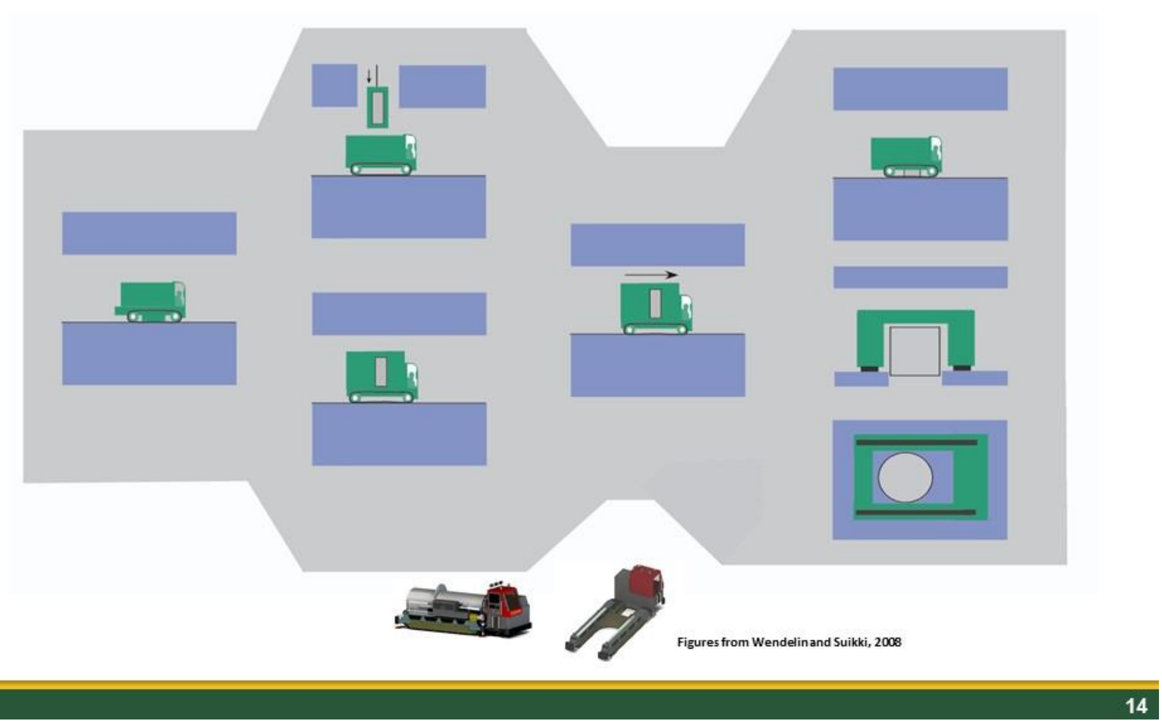

Disposal concept
Ice age
Surface facilities
Connection to the surface
LILW - (TE)NORM level
Salt dome
Surrounding formations
HLW level
Subrosion
Uplift salt dome
11

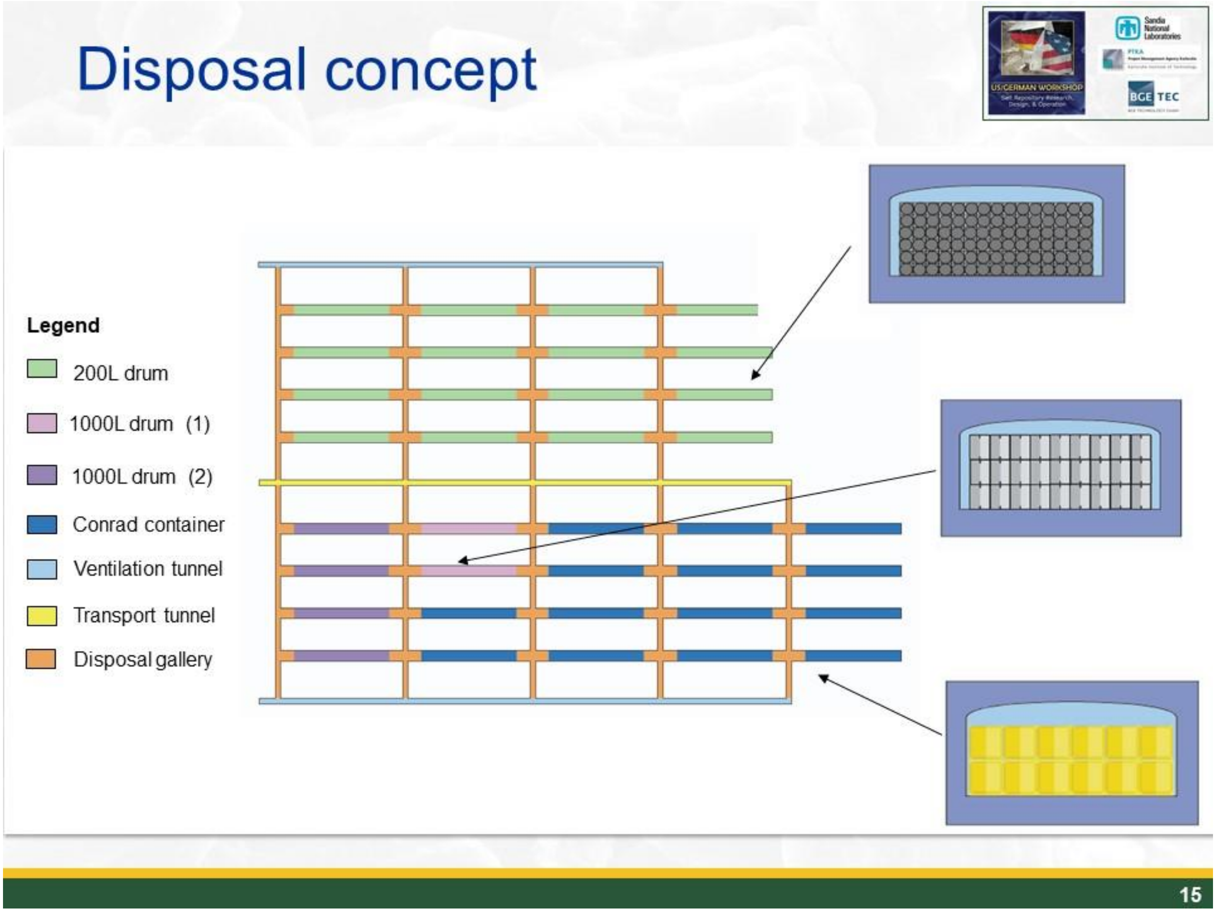

Disposal concept
Legend
Heat generating HLW
Non-Heat generating HLW
Ventilation tunnel
Transport tunnel
Service tunnel
Airflow
Disposal container
Disposal gallery
12

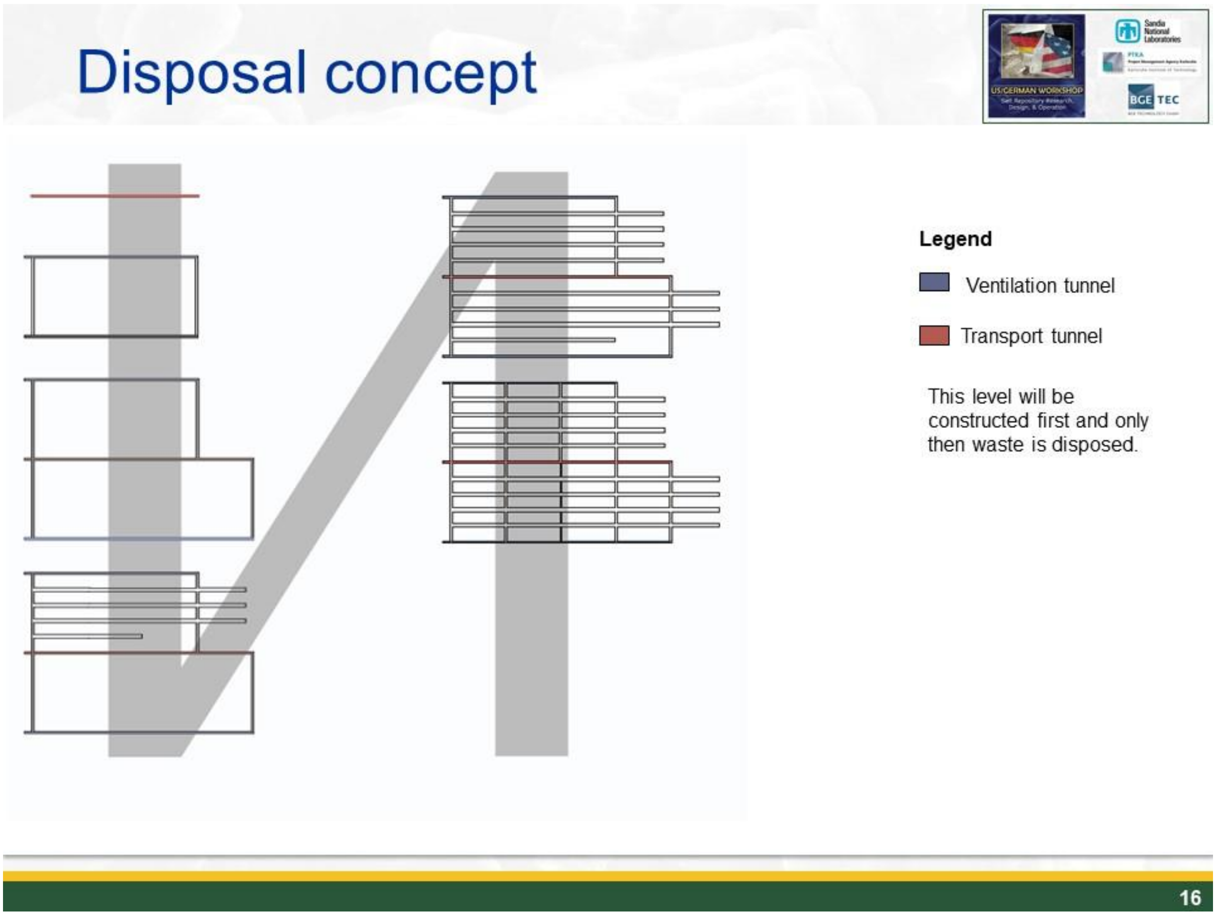
Disposal concept

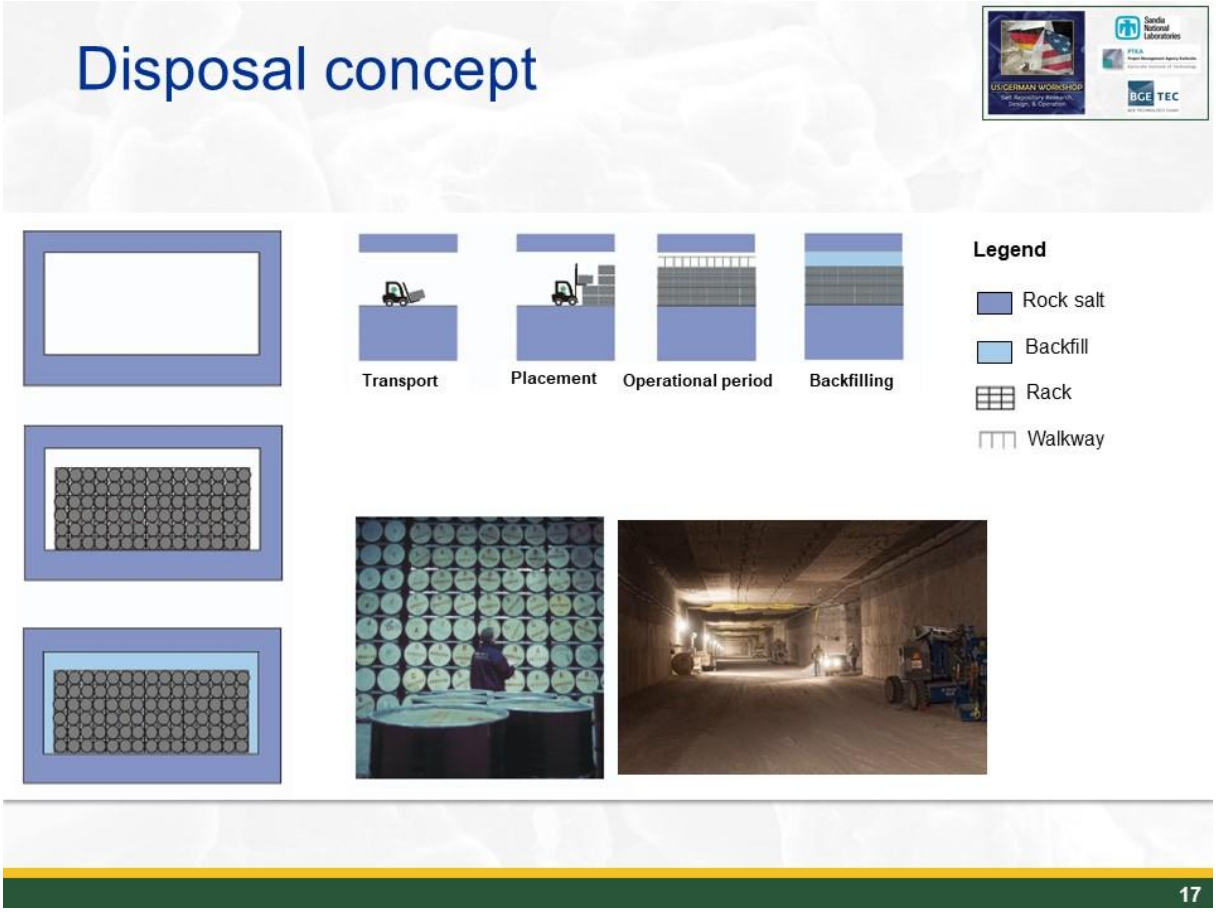


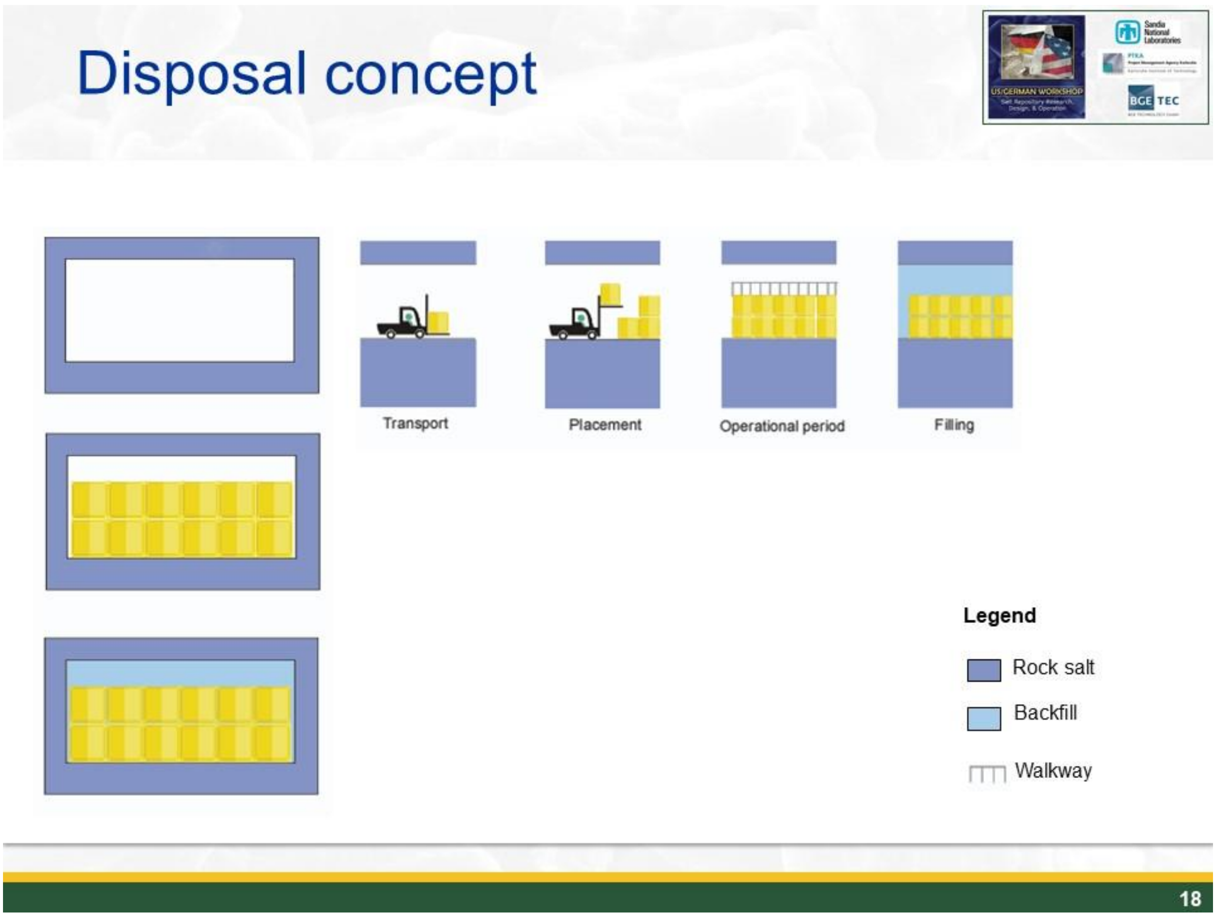
Disposal concept



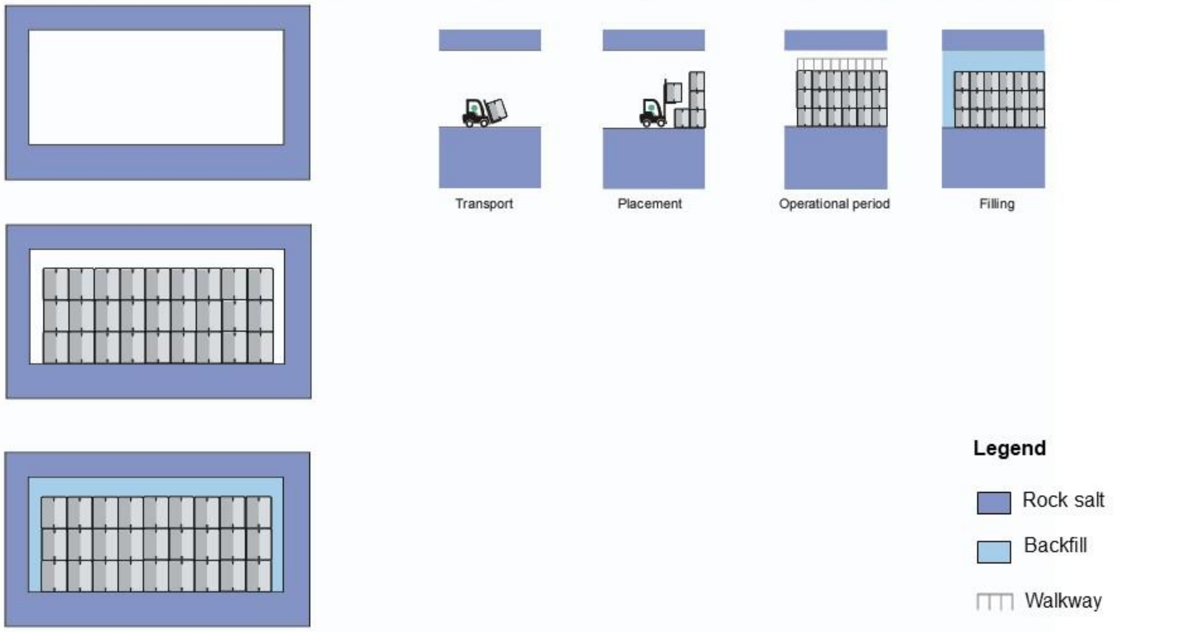

Disposal concept
Legend
200L drum
1000L drum (1)
1000L drum (2)
Conrad container
Ventilation tunnel
Transport tunnel
Disposal gallery
15


Disposal concept
Legend
Ventilation tunnel
Transport tunnel
This level will be constructed first and only then waste is disposed.
16


Disposal concept
Transport
Placement
Operational period
Backfilling
Legend
Rock salt
Backfill
Rack
Walkway
17


Disposal concept
Transport
Placement
Operational period
Filling
Legend
Rock salt
Backfill
Walkway
18

Disposal concept



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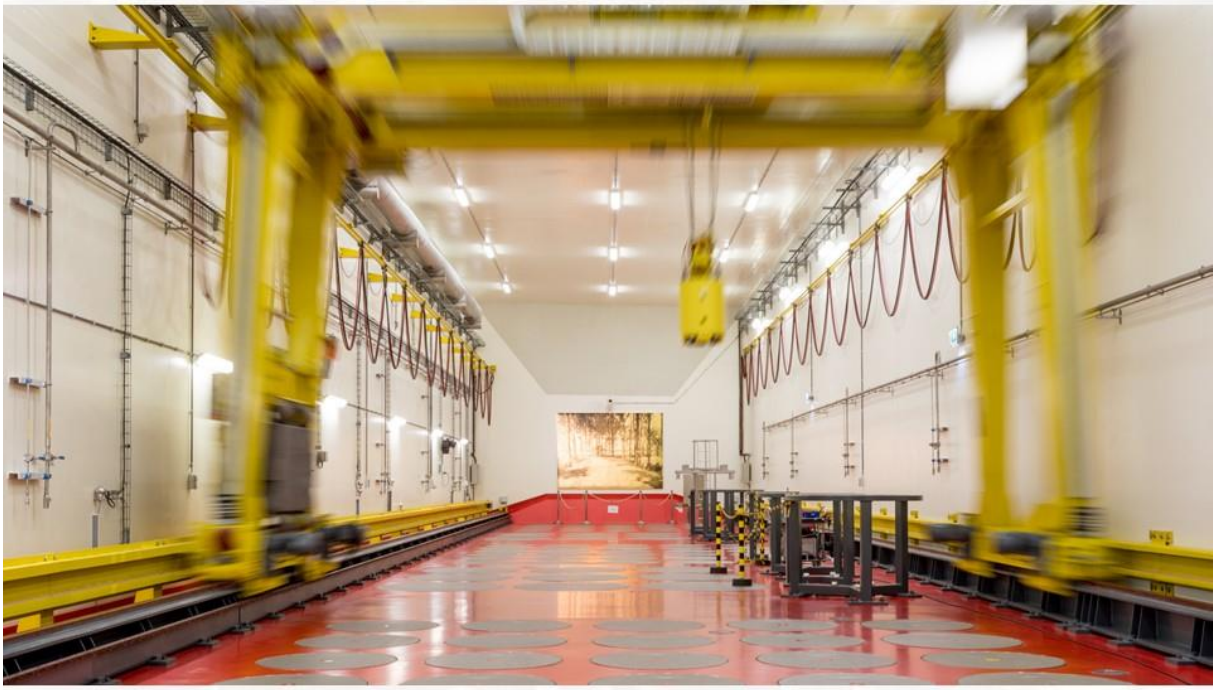
Questions



20


Geological Disposal
Delivering the nation's largest environmental project
Status of Site Selection in UK – Presentation to 11th US/German Workshop on Salt Repository Research, Design, and Operations 2021
2nd February 2020
Dr Simon Norris
Radioactive Waste Management
Working together to protect the future


Finding a willing community and a suitable site
Interested party
Working group
Community Partnership
Up to £1M per year per community
Up to £2.5M per year per community
Talking
Forming Groups
Local Studies
Drilling Boreholes
Right of Withdrawal
Test of Public Support
5 Years
10 - 15 Years
Radioactive Waste Management
2

What makes up a suitable site?

We will evaluate potential areas and sites according to six siting factors:

- **Safety and security** – safety and security must be assured and endorsed by independent regulators. A GDF will not be built unless we, and they, are satisfied it is safe.
- **Community** – communities are at the heart of the process, and we will consider social and economic opportunities, community wellbeing, and how a GDF can align with the potential host community's vision.
- **Environment** – a GDF is a major environmental protection endeavour. Construction of a GDF will need to meet independent regulatory requirements.
- **Engineering feasibility** – we will need to ensure there is scope for sustainable design and the ability to construct and operate a GDF in a given location.
- **Transport** – the safe and secure transport of waste, people and other materials.
- **Value for money** – we have a duty to ensure that value for money is delivered.

Radioactive Waste Management 3

Range of community benefits

Jobs and skills

Long-term, sustainable employment, skilled, well paid, construction & supply chain, local and regional, training, apprenticeships, etc.

Infrastructure investment

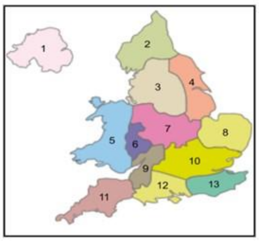
Transport, health, education, connectivity, etc.

Community support

Local projects, facilities, environment protection, land remediation, civil facilities, etc.

Radioactive Waste Management 4

GDF geology

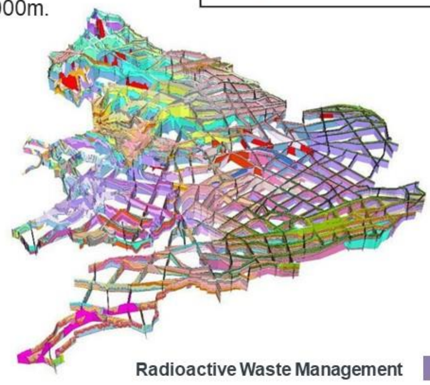


- To help communities to start discussions with us – we've summarised information about geology across the country into the National Geological Screening (NGS) reports.
- We can potentially construct a GDF in any one of three rock types, commonly found all over the UK: Higher strength rock, Lower strength sedimentary rock, Evaporite.
- We will be looking to build a GDF at depths of between 200m – 1000m.
- This could be under the seabed or under the land.

Higher strength rocks
for example Granite

Lower strength sedimentary rocks
for example Clay

Evaporite rocks
for example Rock Salt



Radioactive Waste Management 5

The Siting Process and Site Evaluation

Initial Discussions
- Interested parties engage with RWM
- Evaluations focus on safety
- Short and concise qualitative evaluation based on existing information

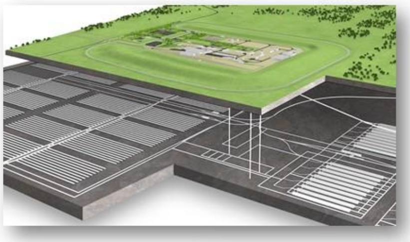
Working Group
- Search Area identified
- High level qualitative evaluation based on existing information
- Identify data gaps and what additional information is required

Community Partnership
- New surveys and studies commissioned
- Search Area refined
- Potential sites identified
- Potential sites evaluated
- Greater certainty around implications of developing a GDF
- Recommendation for site(s) to be characterised

- Multi-year programme of site characterisation by drilling boreholes
- Detailed understanding of sub-surface environment enabling designs to be developed
- Potential host community identified to enable Test of Public Support
- Recommendation for a preferred site

Radioactive Waste Management 6

What could a GDF look like?



- Surface facility c1km^2 but could be as small as 0.6km^2.
- Underground vaults between 200m and 1,000m deep.
- Surface connected to underground by shafts or inclined tunnels called "drifts".
- Underground can be directly below surface facility or can be latterly displaced by 10-15km.

- Surface facilities built onshore.
- Underground vaults can be positioned under the land surface or under the sea in the inshore zone which extends up to 22km from the shoreline.
- Coastal locations open up the possibility to establish sea transport for construction and other materials.
- Spoil from construction can be used to screen the facility or other beneficial uses.

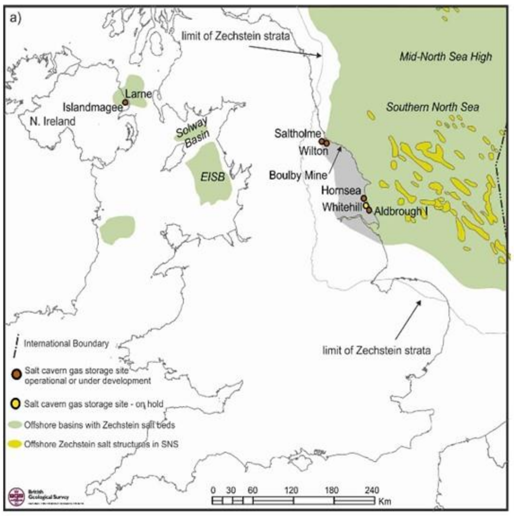
Radioactive Waste Management 7

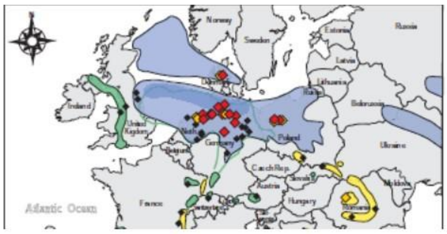
GDF: facts and figures

- **Size** – While the underground part of a GDF may cover an area of up to 20km^2, the surface facilities will occupy around 1 square kilometre of land - typically the size of a small industrial estate.
- **Cost** – A GDF is projected to cost £££ multi-billions. As with any major infrastructure project at this early stage, the cost range is wide due to the current levels of uncertainty. It will be narrowed down as we develop greater certainty on issues like final site geology, facility design and the eventual waste inventory for disposal.
- **Volume** – We are currently planning to dispose of around 750,000 cubic metres of packaged waste in total. This would include all of the materials (like spent fuel and plutonium) that are not currently classified as waste and all the waste and fuel from a future 16GWe programme of new nuclear power stations.
- **Radioactivity** – Whilst 99% of the radioactivity will decay naturally in less than 1,000 years, some of the radioactive waste will remain hazardous for over 100,000 years.
- **Timescale** – A GDF will operate for over 100 years to receive all of the legacy waste and waste arising from new nuclear stations.

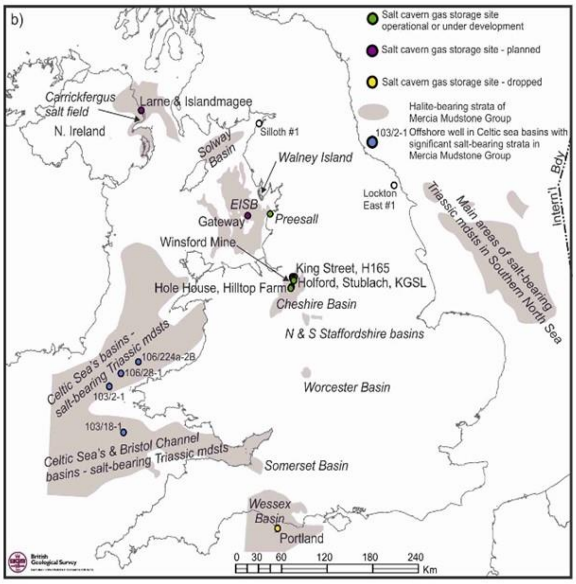
Radioactive Waste Management 8

Permian - summary



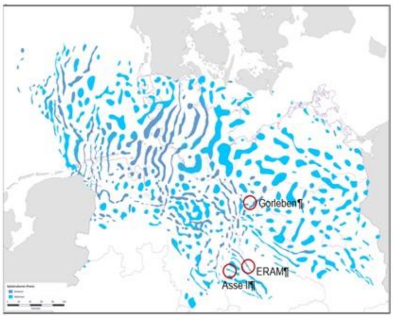


Triassic - summary



Knowledge Base

- RWM report "UK Halite Deposits - Structure, Stratigraphy, Properties and Post-closure Performance – a lot of information, experience, knowledge available, acquired via non-radwaste originated activities
- International precedents, e.g. USA (WIPP) and Germany (Gorleben, Morsleben (ERAM) and Asse)
- Specific international collaborations, e.g. "US/German workshop on Salt Repository Research, Design and Operation"
- OECD NEA Salt Club



Salt deposits of northern Germany – from BGR (2008). Pale blue colour shows salt pillows (precursors to salt domes – dark blue)

Site	Age	Depth range (top, m)
Gorleben	Permian	Approx 800 m
Asse II	Permian	LLW 725 m to 750 m ILW 511 m
Morsleben	Permian	At least 480 metres below the surface

Radioactive Waste Management

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RWM Halite Work

- UK halites considered in recent RWM geosphere and gas work, and routinely considered in ongoing / to-commence work.
- Borehole sealing work will consider sealing a borehole penetrating halite, as a 'can do' demonstration (likely to be in Germany).
- PhD ongoing – gas migration in halite (BP Institute University of Cambridge).
- DECOVALEX project - coupled THMC processes relating to the availability of heating, mechanical deformation, and water to flow into heated excavations in bedded salt.
- Benefitting from international participation and experience key for RWM.

Radioactive Waste Management

12

GDF: roles and responsibilities

HM Government

- **Government** – sets the policy on dealing with higher-activity radioactive waste (see slide 2).

NDA

- **NDA** – sets the strategy for the management of radioactive waste.

Radioactive Waste Management

- **RWM** – responsible for designing, siting, building, operating and closing a GDF safely.

CORWM

- **CoRWM** – provides independent scrutiny and advice to government.

Environment Agency

ONR Office for Nuclear Regulation

Cyfoeth Naturiol Cymru
Natural Resources Wales

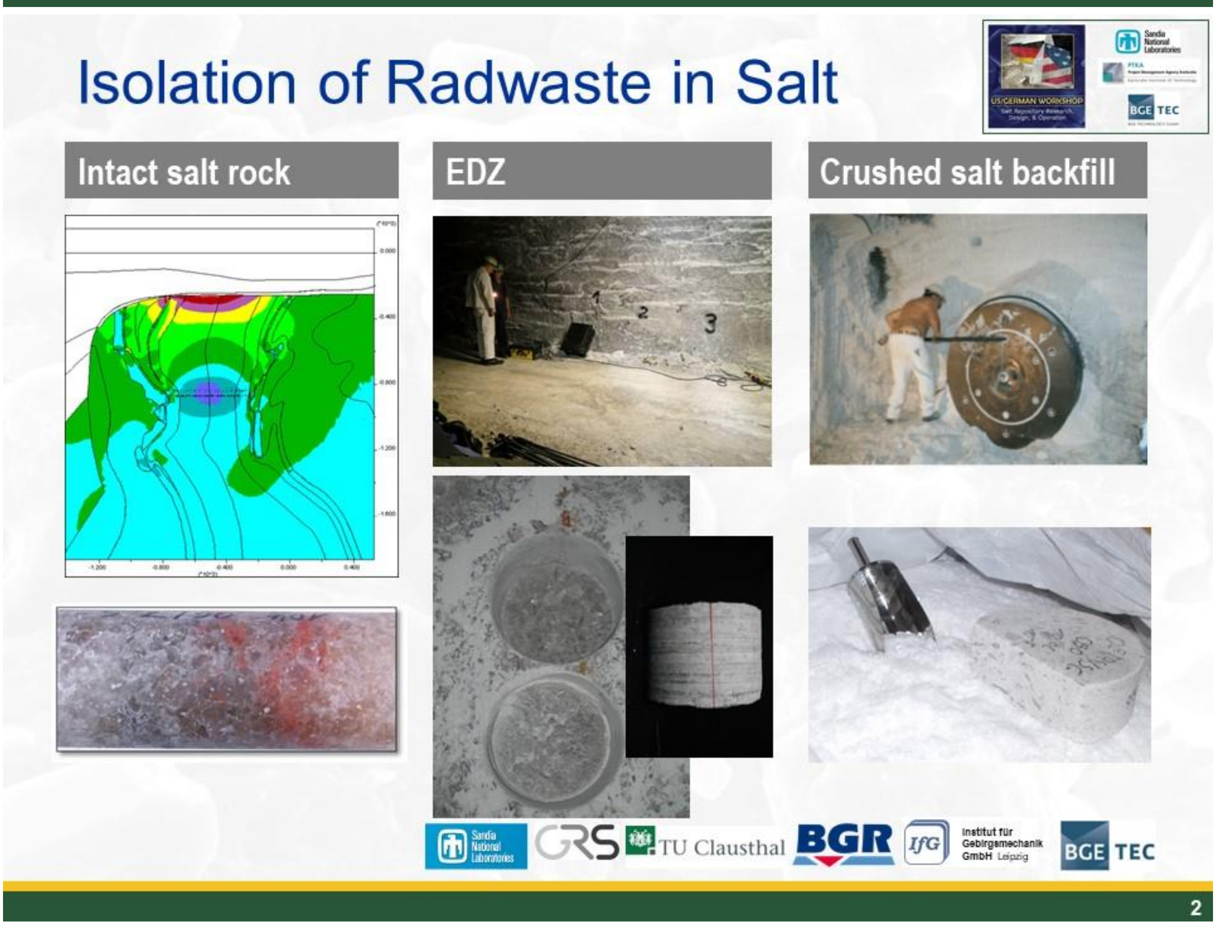
- **Regulators** – responsible for ensuring GDF safety and for granting permits and licences.

Radioactive Waste Management 13

Appendix B – Program and Presentations of Part 2 (17th June 2021)

Berlin time		17th June 2021	
16:00	16:10	Welcome by the organizers	M. Bühler/PTKA W. Bollingerfehr/BGE TEC
Crushed salt – testing and modelling Chair: M. Bühler			
16:10	16:40	Role of crushed salt in the repository concept	N. Müller-Hoeppe/BGE TEC
16:40	17:20	The KOMPASS project – Microstructural investigations presentation	M. Mills/Sandia K. Svensson/BGR
17:20	17:40	The KOMPASS project – Natural technical analogues	D. Naumann /IfG
17:40	17:50	10 min Break / Group Photo	
17:50	18:10	The KOMPASS project – Modelling related experimental aspects	S. Lerche/TUC
18:10	18:20	The KOMPASS project – Future work of relevance for LTS	L. Friedenberg/GRS
18:20	18:50	Investigations on in-situ material behavior of matrix-stabilized crushed rock salt backfill under consideration of different filling technologies – Review of the GESAV II Project	S. Pötzsch/TUBAF
18:50	19:00	Summary and Outlook	M. Bühler/PTKA W. Bollingerfehr/BGE TEC


11th US/German Workshop on Salt Repository Research, Design, and Operation
Role of crushed salt in the repository concept
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH
Nina Müller-Hoeppe
Christian Lerch
BGE TECHOLOGY GmbH
Part 2 of the online workshop
June 17, 2021


Isolation of Radwaste in Salt
Intact salt rock
EDZ
Crushed salt backfill
Sandia National Laboratories
GRS
TU Clausthal
BGR
IfG
Institut für Gebirgsmechanik GmbH Leipzig
BGE TEC
2

Role of crushed salt

- In the operational phase
  - (1) Radiation protection
  - (2) Fire and explosion protection (prevents propagation)
- In the operational and post operational phase
  - (3) Transfer of decay heat from the heat generating waste to the host rock
  - (4) Improving stability of repository mine and supporting integrity of geological barrier
- Post closure phase
  - (5) Reduction of void volume in the repository mine (limiting amount of brine and constituting a barrier of $k \sim 1 \cdot 10^{-14}$ m²)
  - **(6) New: Recovery of the salt barrier´s tightness comparable to the host rock in order to achieve isolation of radwaste**

3

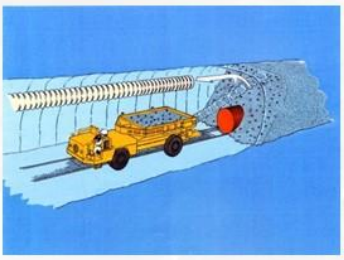
Functional Requirements

- High initial density and placeable without gap in the roof is sufficient to fulfil functions (1) to (5)

Furthermore

- Dry crushed salt close to the metallic containers to limit corrosion effects (natural moisture content ~ 0.02 M%)
- Possible emplacement technologies to achieve this goal considering additionally staff´s radiation protection (neutrons!)

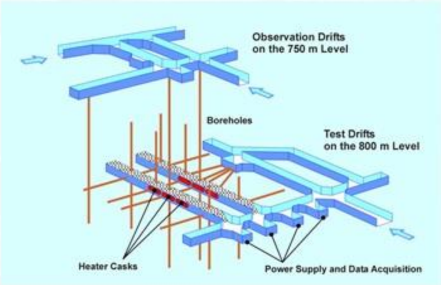
- Slinger truck technology appeared to be the best option

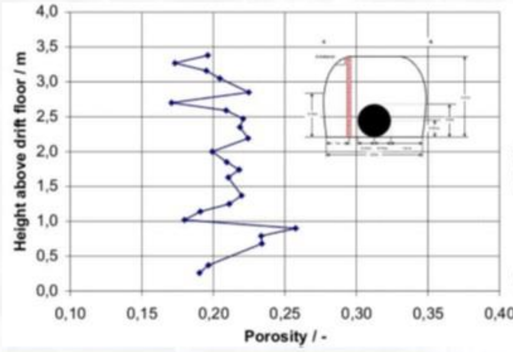


4

Functional Requirements

- ➢ Compliance with functional requirements (1) – (5) was demonstrated by the TSS/BAMBUS R&D projects
- ➢ No gap in the roof (1), (2), (4)



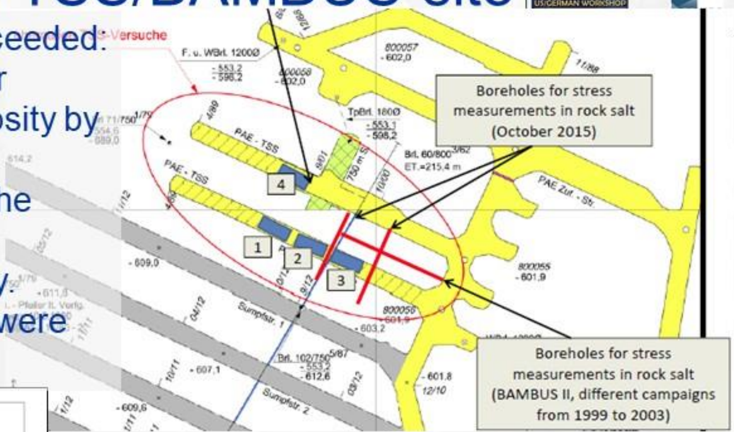


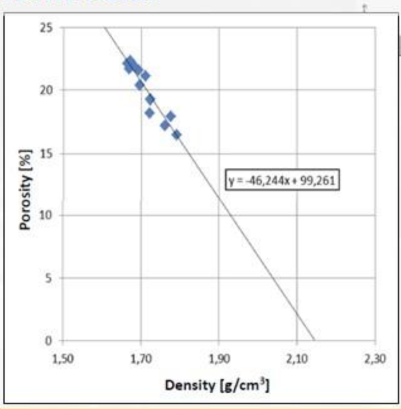
(Source: GRS)

5

Revisitation of TSS/BAMBUS site

- Backfill compaction proceeded.
- Within 15 years a further reduction of backfill porosity by 3 – 5% was observed (~ drift convergence at the 800-m-level).
- The backfill was very dry.
- The working conditions were warm-cold.



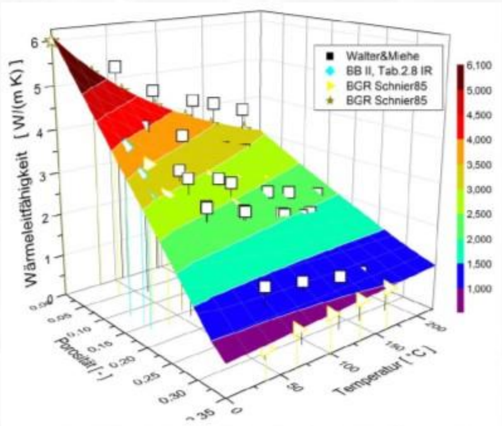


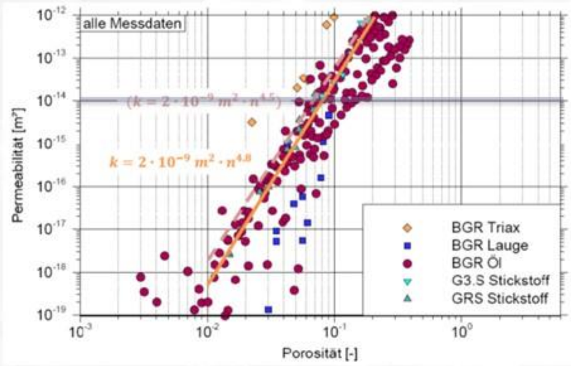
- Porosity: 23 – 17%
- Thermal conductivity: 2.3 W/(m·K)
- Gas permeability: ca. 5 · 10^{-13} m²

SANDIA, 2016
IfG, 2016

Functional Requirements

- Compliance with functional requirements (1) – (5) was demonstrated by the TSS/BAMBUS R&D projects
- Considering heat transfer properties (3) and limitation of void volume (5) early stage at high porosity is decisive



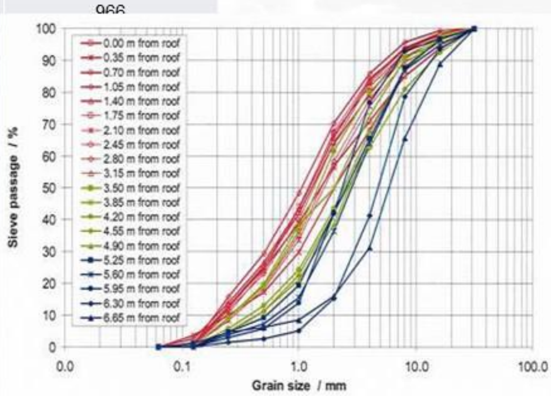


7

QA-measures

- QA-measures considering functions (1) to (5)
  - Initial porosity by recording mass of emplaced crushed salt and volume of cavity
  - Grain size distribution within a drift´s cross-section

	Southern drift	Northern drift
Backfill material [10^3 kg]	1,347	1,363
Drift volume [m³]	963	966
Initial bulk density [kg/m³]	1,399	
Specified deviation [%]	+2 … -2.6	
Range of initial density [kg/m³]	1,363 … 1,427	
Porosity [-]	0.34 … (0.35) … 0.37	
Void ratio [-]	0.52 … (0.54) … 0.58	



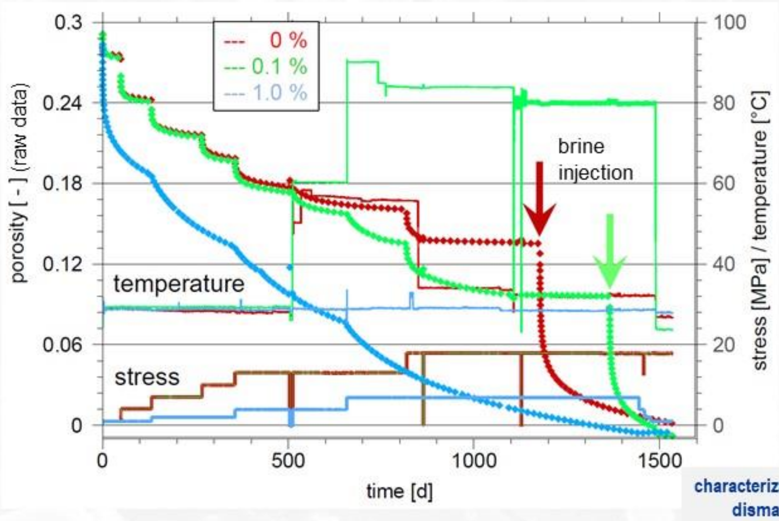
BAMBUS II project (2004)

8

Functional Requirement (6)

BMU 2010

➢ From limited release to isolation of radionuclides



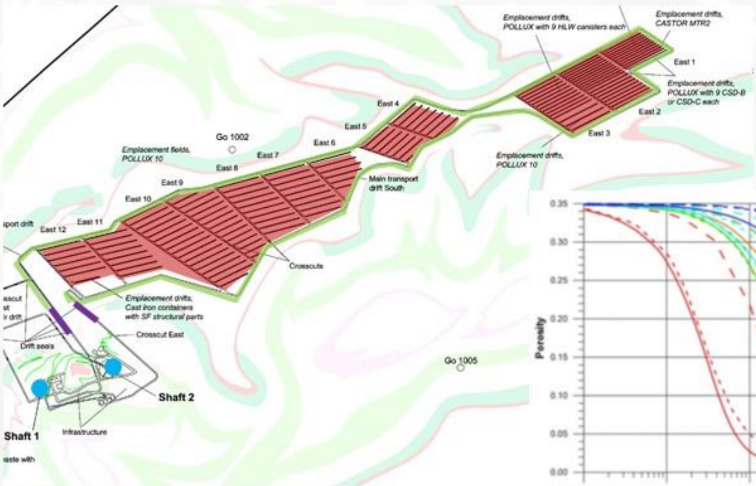
Current knowledge gives confidence that granular salt will compact to a final porosity in the order of 1±1 % within less than 1000 a, but this has to be demonstrated, reliably

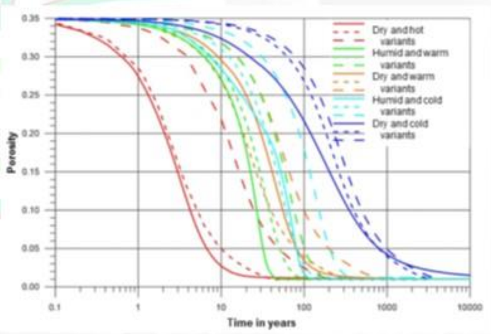
characterization after dismantling yields porosities of 1 – 2%

REPOPERM II, 2017

9

First Application of BMU 2010 Requirements - VSG





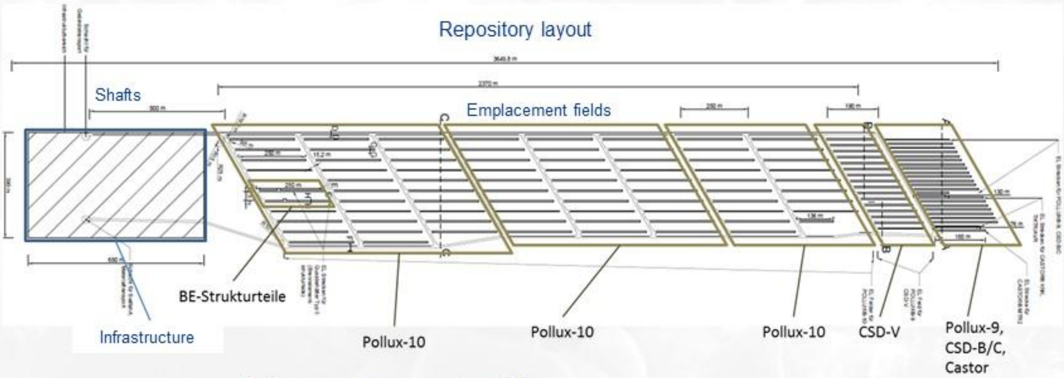
Backfill and seals:

- Dry crushed salt in emplacement drifts and cross-cuts
- Humid crushed salt in access drifts
- Drift seals (made of MgO-concrete)
- Shaft seals include humid crushed salt sealing elements

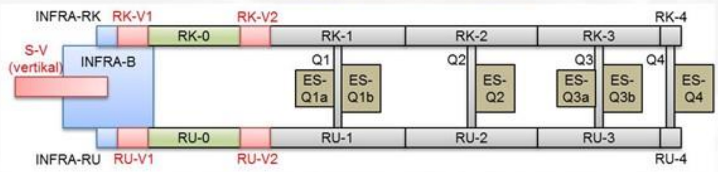
Result
Safe confinement of radionuclides within 1 million years!

Application to Bedded Salt Formation - KOSINA

Repository layout



Performance assessment model



- Dry crushed salt in emplacement drifts, cross-cuts, access drifts
- Humid crushed salt in selected parts of access drifts
- Drift seals, shaft seals

<u>Result</u>
Safe confinement of radionuclides within 1 million years!

11

Functional Requirement (6) – Knowledge Gaps

- Current knowledge gives confidence that granular salt will compact to a final porosity in the order of 1±1 % within less than 1000 a
  - but this has reliably to be demonstrated in order to show salt barrier´s recovery
- Scientific challenge
  - long lasting processes must be accelerated in order to achieve results within a reasonable time span
  - Consequently, it must be demonstrated as well that accelerated results are equivalent to that of long lasting processes
- Furthermore, to predict long-term behaviour of a repository verified and validated numerical models are required

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The KOMPASS Project – Closing Knowledge Gaps

KOMPASS –

Compaction of Crushed Salt for the Safe Containment

(„Kompaktion von Salzgrus für den sicheren Einschluss“)

- The overall objective of the project is to reduce the knowledge gaps to enhance the safety case for a repository in rock salt

- This includes
  - the completion of the experimental database
  - the improvement of process understanding
  - and the enhancement and calibration of models to enable a reliable prediction of crushed salt reconsolidation

13

The KOMPASS Project - Phase I

- KOMPASS – Phase I (01.09.2018 – 31.08.2020) was funded by the Federal Ministry for Economic Affairs and Energy (**BMWi**) under support code 02E11708. Results of phase I are presented here
- The authors are sincerely thankful for the financial support
- The project partners would also like to express their special thanks to our colleagues from **Sandia** for fruitful cooperation

Partners

BGE TEC:	Christian Lerch, Nina Müller-Hoeppe
BGR:	Ralf Eickemeier, Ben Laurich, Wenting Liu, Dieter Stührenberg, Kristoff Svensson, Kornelia Zemke
GRS:	Larissa Friedenberg, Klaus Wieczorek, Oliver Czaikowski (Coordinator)
IfG:	Christoph Lüdeling, Till Popp
TUC:	Uwe Düsterloh, Svetlana Lerche, Juan Zhao

PTKA Projektträger Karlsruhe
Karlsruher Institut für Technologie

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

BGE TEC BGR GRS IfG Institut für Gebirgsmechanik GmbH Leipzig TU Clausthal

10th US/German Workshop on Salt Repository Research, Design, and Operation, May 2019, SD 14

The KOMPASS Project – Phase II

- KOMPASS – Phase II (01.07.2021 – 30.06.2023) is also funded by the Federal Ministry for Economic Affairs and Energy (**BMWi**) under support code 02E11951
- A joint project of BGE TEC, BGR, GRS, IfG, and TUC
- Cooperation with Sandia and Utrecht University as associated partners is planned
- The overall objective of the project is to reduce furthermore the knowledge gaps to enhance the safety case for a repository in rock salt
- This includes
    - Advanced experimental investigations based on results of KOMPASS I
    - Advanced microstructure investigations based on results of KOMPASS I
    - Numerical modelling aiming at to establish a virtual demonstrator
    - Evaluating of numerical models referring to the requirements of long-term safety

PTKA Projektträger Karlsruhe
Karlsruher Institut für Technologie

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

BGE TEC BGR GRS IfG Institut für Gebirgsmechanik GmbH Leipzig TU Clausthal

10th US/German Workshop on Salt Repository Research, Design, and Operation, May 2019, SD 15

Remarks and Outlook

- Keep in mind that crushed salt must be emplaced by mining techniques
- Knowledge on initial conditions relies on presently available QA-measures
    - Initial porosity by recording mass of emplaced crushed salt and volume of cavity
    - Grain size distribution
    - (Surface) moisture content
    - Mineral composition
    - Temperature
- If humid backfill is used preservation of humidity distribution over time is a research issue – clay salt may act as a natural analogue

16

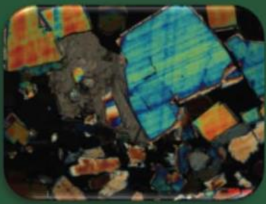
Acknowledgement

The projects are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and managed by the Project Management Agency Karlsruhe (PTKA)

Thank you for your attention!

ELSA II

17

Microstructural Investigations of Pre-Compacted Samples from IfG

Melissa Mills
Sandia National Laboratories
Albuquerque, NM, USA

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

Sandia National Laboratories
PTKA Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH

Part 2 of the online workshop
June 17, 2021
SAND2021-6966 PE

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.

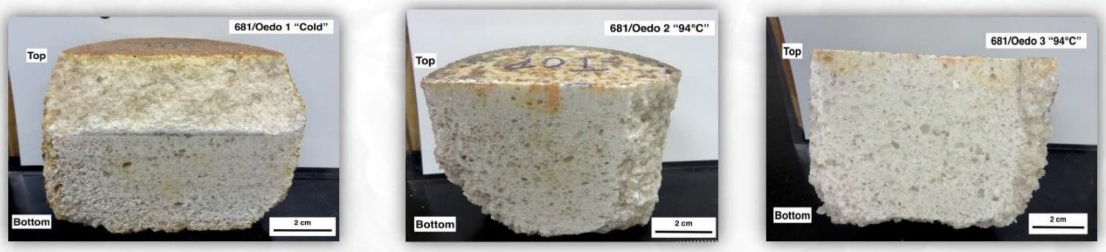
KOMPASS Project Pre-Compacted Samples

Technique	Resulting sample size	Controlled by strain rate / load	Stress regime	Runtime	Remaining porosity	Material	Number of tests
Plain Strain (TUC)	d = 90 mm h = 180 mm	Radial load (σ_{max} = 5/10/15 MPa)	Plain strain (longest axis fixed)	3 d	2 – 11 %	Preliminary tests on not classified crushed salt w = 0.5/1/2/3 %	8
		Radial load (σ_{max} = 2/4/5/10/15 MPa)		2 – 7 d	2 – 19 %	KOMPASS reference material w = 0.1/0.3/0.5/1 %	23
Small Cell (IfG)	d = 80 mm h = 100 mm	Axial load, stepwise (σ_{max} = 20 MPa)	Oedometric	1 – 5 d	10 – 20 %	KOMPASS reference material	3
Big Cell (IfG)	d = 500 mm h = 620 mm	Axial load, stepwise (σ_{max} = 20 MPa)	Oedometric	< 28 d	10 – 20 %	KOMPASS reference material w = dry/1 %	2
BGR	d = 100 mm h = 200 mm	Strain rate, stepwise ($\dot{\varepsilon}_{max}$ = 9.1*10^{-6} 1/s) (σ_{max} = 20 MPa)	Oedometric	< 28 d	~ 15 %	Various (shown in this study: ASSE/DEBORA)	> 40 (2 shown in this study)

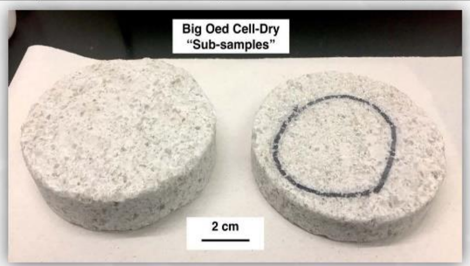
- Sandia received small and big cell samples from IfG in late 2019, and two samples from TUC in late 2020

2

Pre-Compacted Samples (IfG)

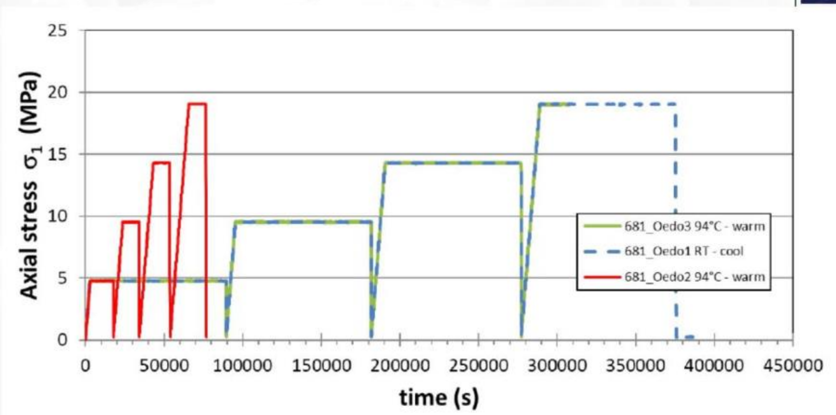


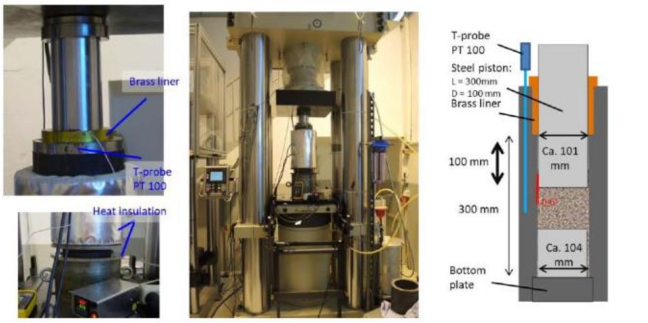
Sample ID	Oedometer Inner Diameter (m)	Temperature (°C)	Axial Stress (MPa)	Duration (days)	Final Relative Porosity (%)
681/Oed 1	0.1	Ambient	20	5	14.8
681/Oed 2	0.1	94	20	1	10.5
681/Oed 3	0.1	94	20	5	10
Big Oed cell Dry (sub-sampled)	0.514	Ambient	20	28	13.6



3

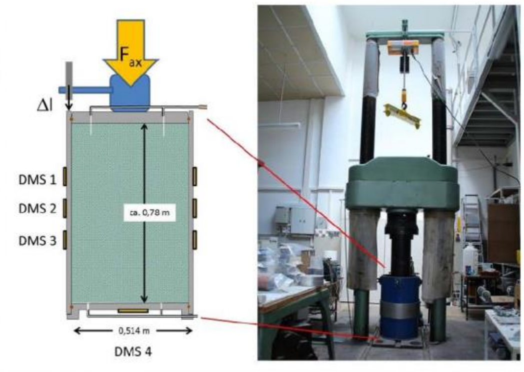
Pre-Compacted Samples (IfG): Small



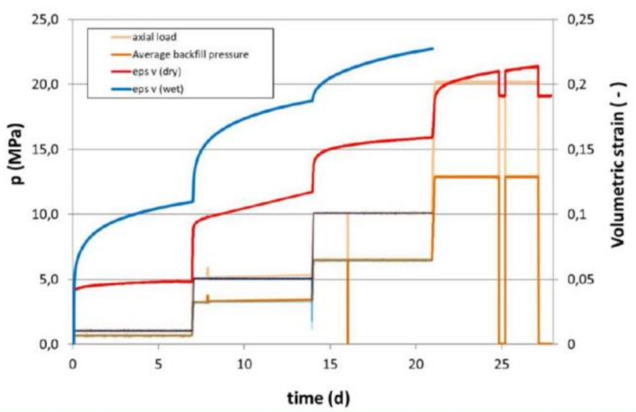


4

Pre-Compacted Samples (IfG): Big

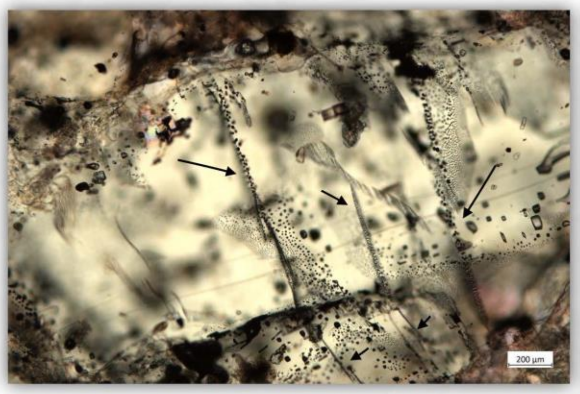


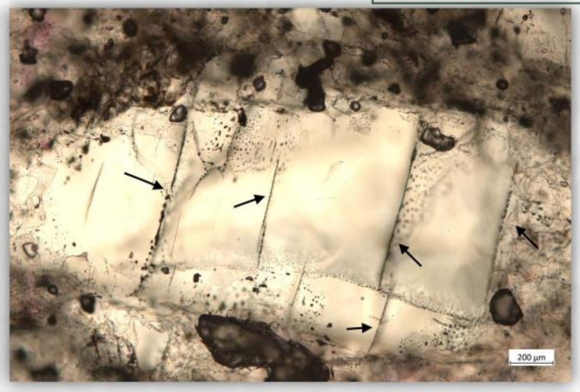
- Stepwise sample preparation
- Multistep load test
- Desired sub-samples to be more uniform



5

Microstructures: Oed 1 (Ambient, 5 days)

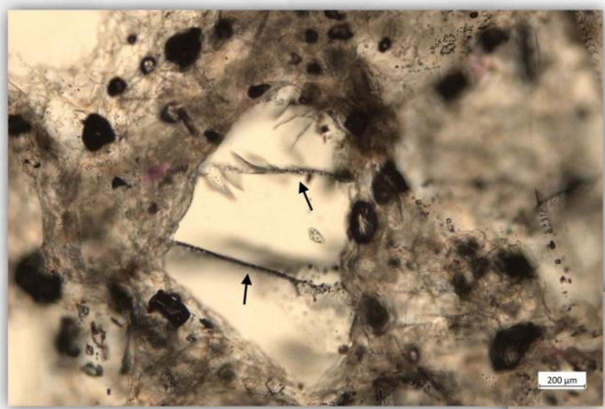


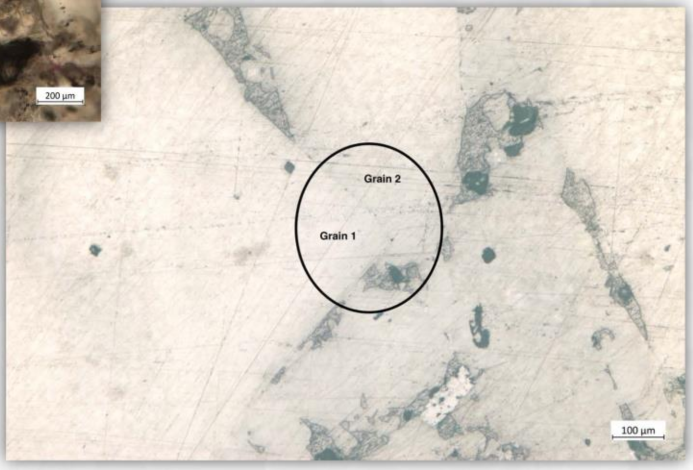


- Microcracks with planes of fluid inclusions; cataclastic grain rearrangement by intragranular cracks

6

Microstructures: Oed 2 (94°C, 1 day)

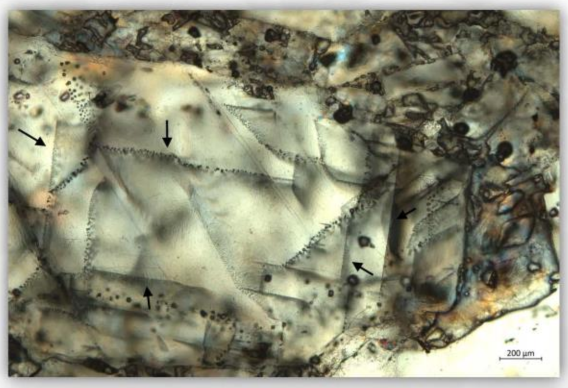




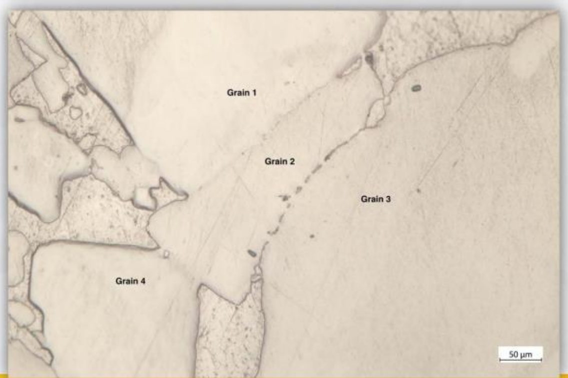
- Microcracks; cohered contact points between grains likely assisted from temperature

7

Microstructures: Oed 3 (94°C, 5 days)

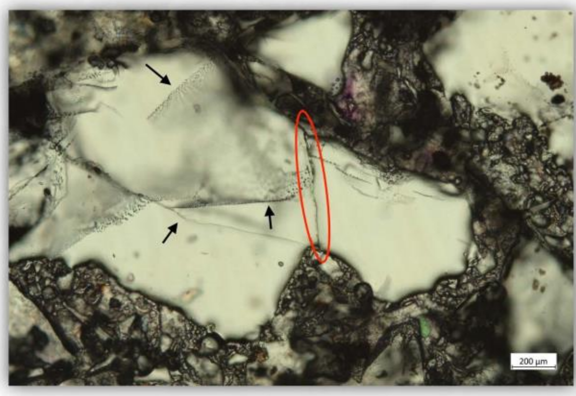


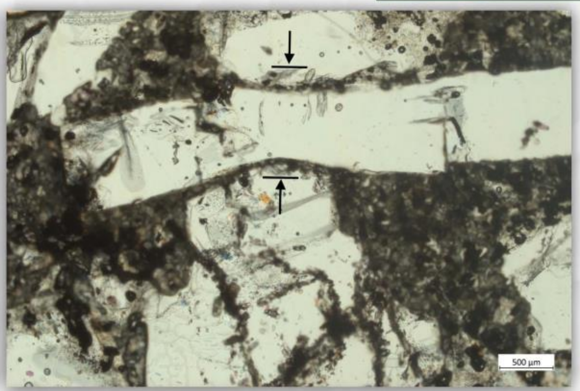
- Fluid inclusion planes; plastic deformation seen at grain contacts; possible pressure solution redisposition and/or dislocation motion



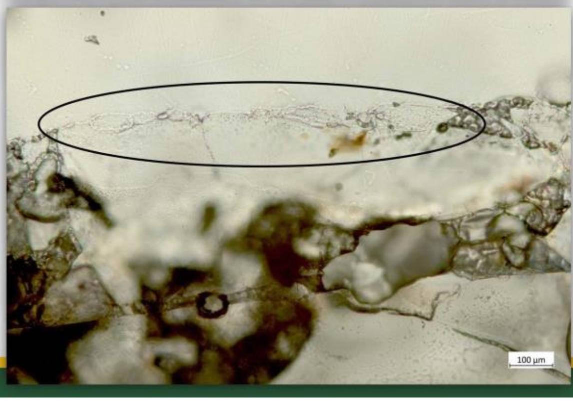
8

Microstructures: Big Oed (ambient, 28 days)



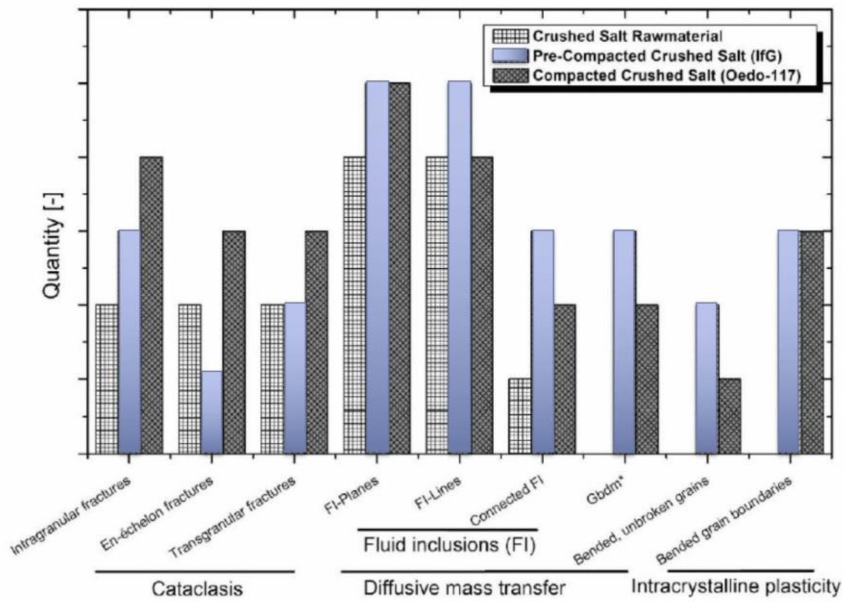


- Microcracks with transgranular crack; cataclastic deformation; mechanically abraded surface between grains



9

Comparison



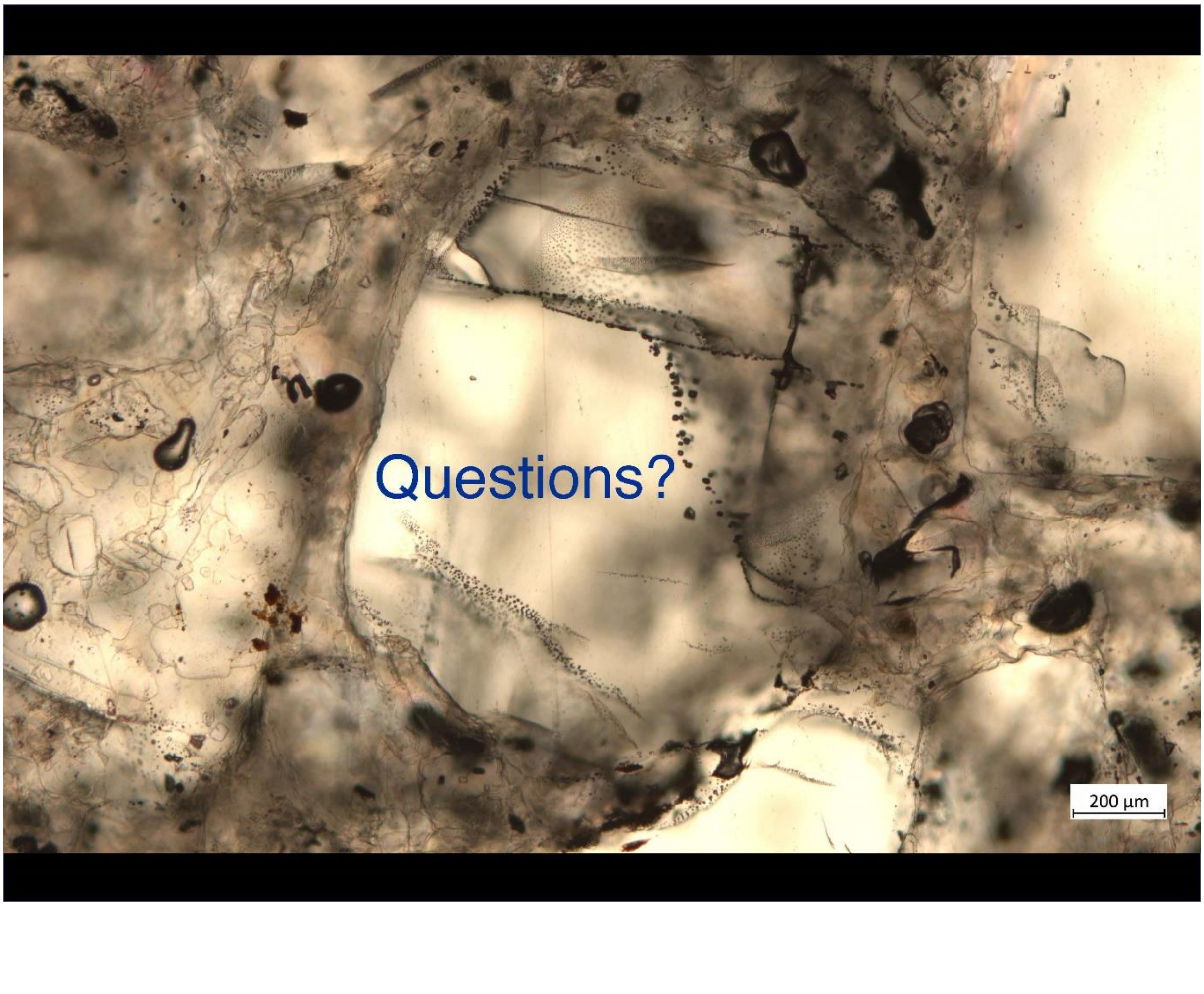
10

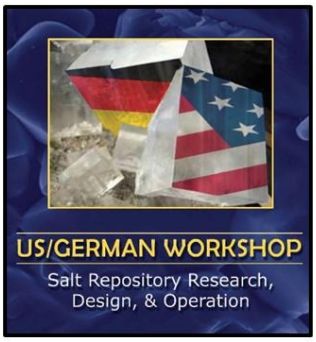
Future

- Subgrain analysis by SEM
- Preparation and analysis of additional pre-compacted samples from TUC, with varying conditions
  - Received samples #14 & #15 (15MPa, 2 days, w=0.5%)
- Examination of fully compacted samples

*Extra time for any unanticipated shipping delays ☺

11





Microstructural indicators for deformation mechanisms

Kristoff Svensson

BGR

US-German Workshop

Part 2 of the online workshop

June 17, 2021

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

Why should we study microstructures?

- **Microstructures are indicators for deformation mechanisms**
  - **Which deformation mechanism was active and what were the circumstances?**
- **Microstructures help to quantify the deformation mechanism**
- **Comparing microstructures in differently compacted samples can reveal the dominant deformation mechanisms for numerical modeling**

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2

Microstructures and correlated deformation mechanisms

MICROSTRUCTURES *General*	*Specific*		MECHANISMS *Specific*	*General*
MICROFRACTURES, RIGID PARTICLE DISPLACEMENT AND ROTATION *Chapter 2*	**Microcracks**	*2.3*	Microcracking	CATACLASIS *(2.2)*
	Microfaults	*2.4*		
	Deformation bands	*2.5*		
	Distributed cataclasis	*2.6*		
	Gouge zones	*2.7*		
	Microfracture surface features	*2.8*		
	Crystallographic fabrics	*2.9*		
	Pre-lithification microstructures	*2.10*	IPF	
	Pseudotachylite	*2.11*	Melting	
MATERIAL REMOVAL, TRANSPORT AND DEPOSITION *Chapter 3*	**Grain surface solution textures**	*3.3*	Dissolution	DIFFUSIVE MASS TRANSFER BY SOLUTION *(3.2)*
	Indenting, truncating, and interpenetrating grains	*3.4*		
	Strain caps	*3.5*		
	Microstylolites	*3.6*		
	Cleavage	*3.7*		
	Surface deposition textures	*3.8*	Precipitation	
	Overgrowths, pressure shadows and fringes, mica beards	*3.9*		
	Grain shape fabrics	*3.10*		
	Fluid inclusion planes	*3.11*		
	Microveins	*3.12*		
PERMANENT DISTORTION OF THE CRYSTAL LATTICE *Chapter 4*	**Deformation twins**	*4.3*	Twinning	INTRACRYSTALLINE PLASTICITY *(4.2)*
	Undulatory extinction	*4.4*		
	Intracrystalline deformation bands, kink bands & subgrains	*4.5*	Recovery	
	Deformation lamellae	*4.6*		
	Grain shape fabrics & ribbons	*4.7*		
	New grains, core and mantle structure	*4.8*	Re-crystallization	
	Crystallographic fabrics	*4.9*		
MATERIAL REMOVAL, TRANSPORT AND DEPOSITION, PHASE TRANSFORMATIONS *Chapter 5*	Grain shape fabrics & ribbons	*5.3*		SOLID STATE DIFFUSIVE MASS TRANSFER, PHASE TRANSFORMATIONS *(5.2)*
	Foam texture	*5.4*		
	Decussate texture	*5.5*		
	Porphyroblasts	*5.6*		
	Reaction rims, relict minerals, coronas, symplectites	*5.7*		
	Chemical zoning	*5.8*		
	Phase transformation microstructures	*5.9*	Phase Transformation	

Blenkinsop, T. **2002**, Deformation Microstructures and Mechanisms in Minerals and Rocks, Book, Kluwer Academic Publishers, ISBN: 0-412-73480-X

Three types of deformation mechanisms in rock salt:

- Plasticity, microcracking
  - Cataclasis
  - Dilatancy
- Dislocation creep
  - Dislocations
  - Subgrains
  - Recrystallization
- Solution-precipitation creep
  - Grain boundary sliding and rotation
  - Dissolution
  - Precipitation

Jackson, M. P. A., Hudec, M. R. **2017**, Salt Tectonics – Principles and Practice, Book, Cambridge University Press, ISBN: 978-1-107-01331-5

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3

Deformation mechanisms and respective indicators

deformation mechanism	indicators	quantification
cataclasis	microcracks microfaults breaking-index	statistical
dislocation creep	bended grains	subjective
	subgrain size and subgrain orientation	statistical
solution-precipitation creep	recrystallization overgrows	subjective
	fluid inclusions	statistical

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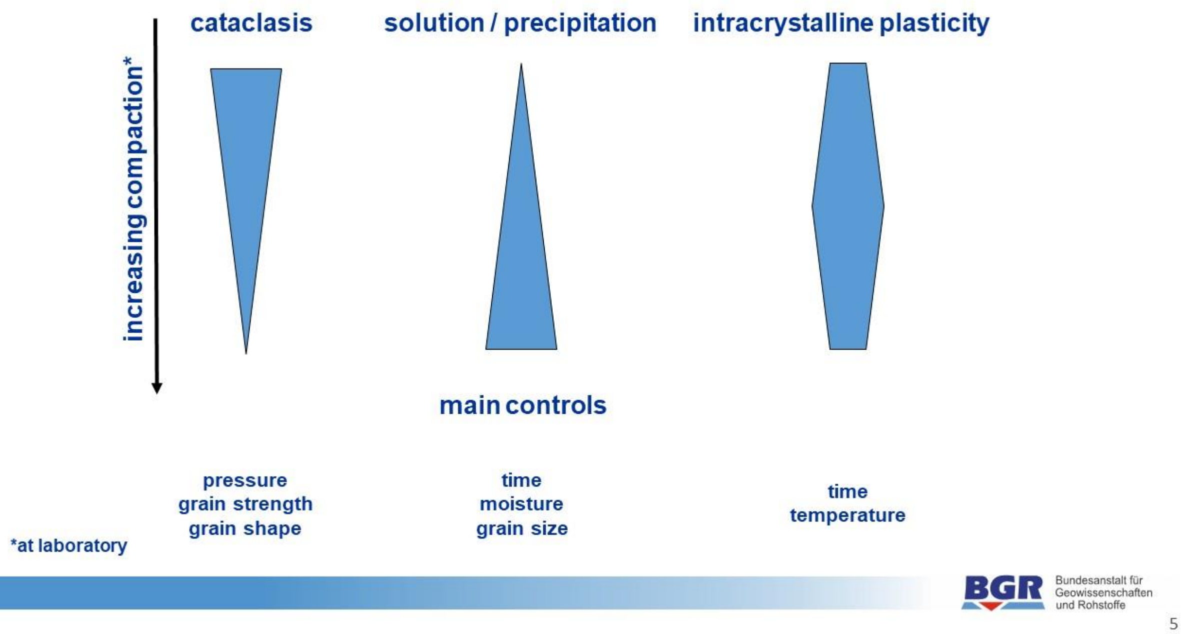
4


cataclasis
solution / precipitation
intracrystalline plasticity
increasing compaction*
main controls
pressure
grain strength
grain shape
time
moisture
grain size
time
temperature
*at laboratory
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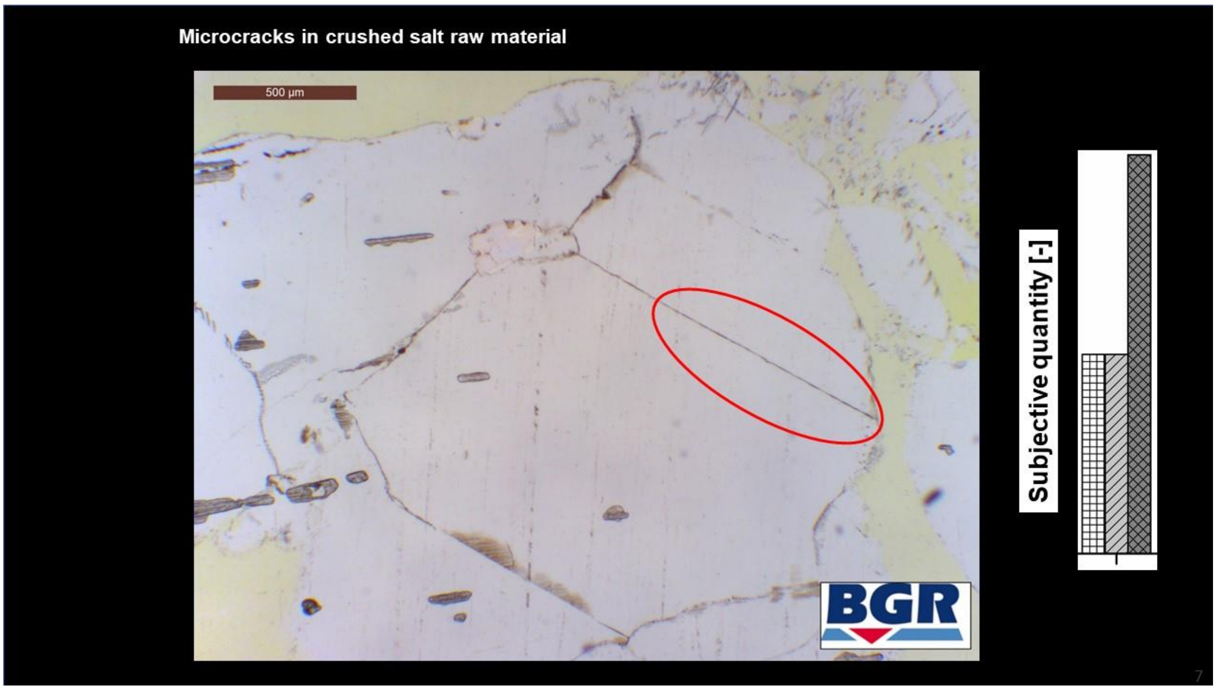
und Rohstoffe
5

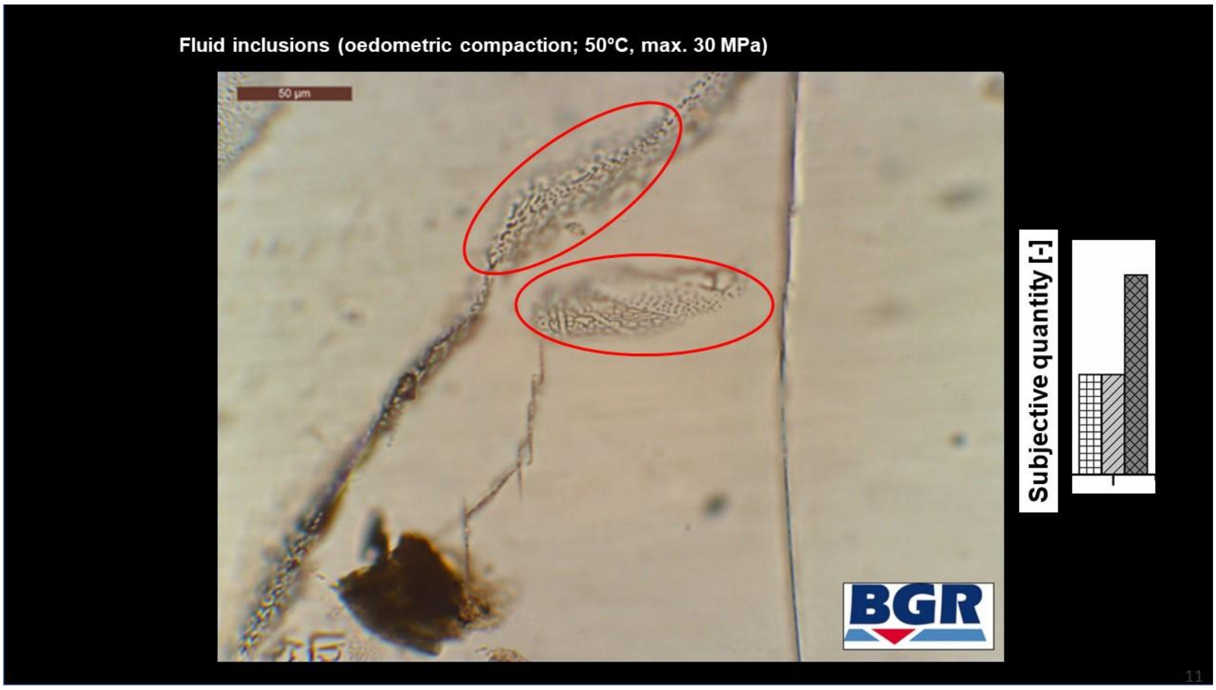

Microcracks in compacted crushed salt (oedometric compaction; 50°C, max. 30 MPa)
50 µm
BGR
Subjective quantity [-]

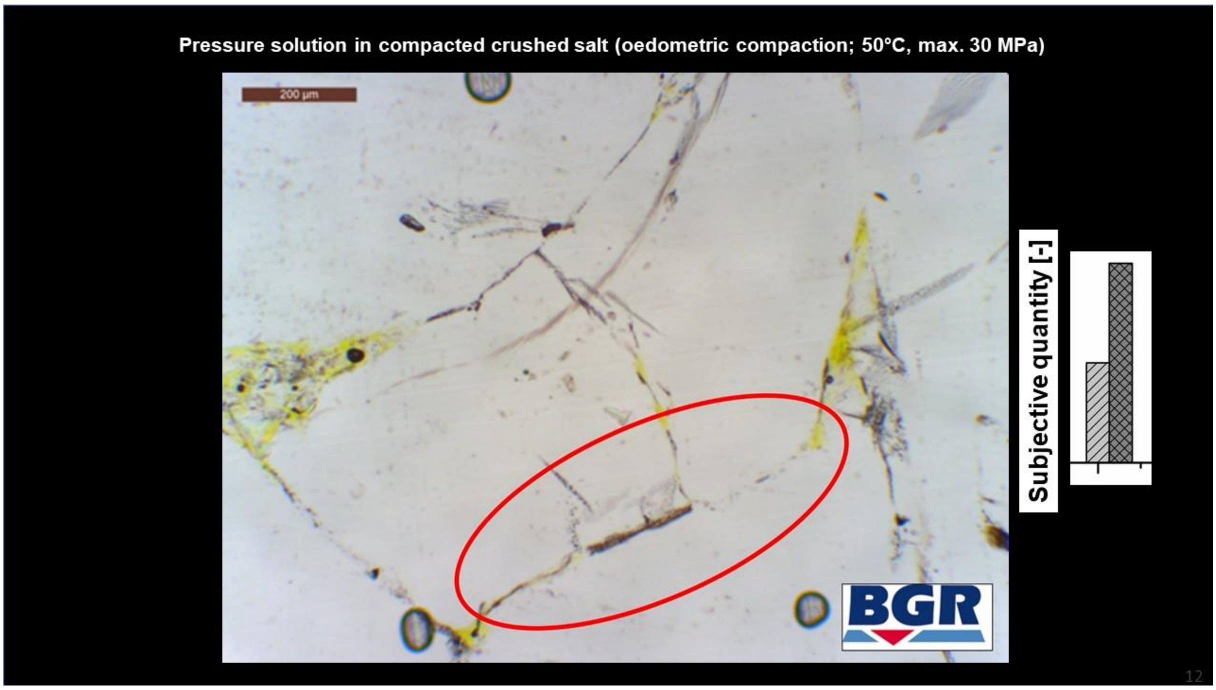

Microcracks in crushed salt raw material
500 µm
Subjective quantity [-]
BGR

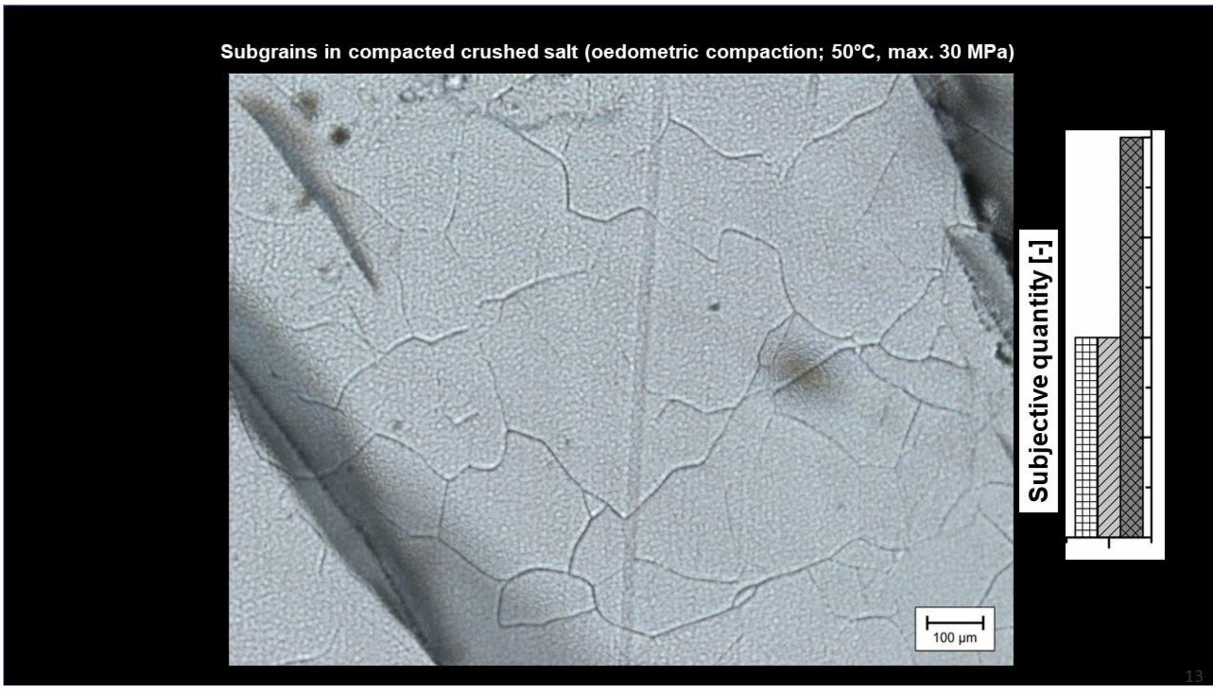

En-échelon structures in crushed salt raw material
200 µm
Subjective quantity [-]
BGR


En-échelon structures in compacted crushed salt (oedometric compaction; 50°C, max. 30 MPa)
200 µm
Subjective quantity [-]
BGR
9

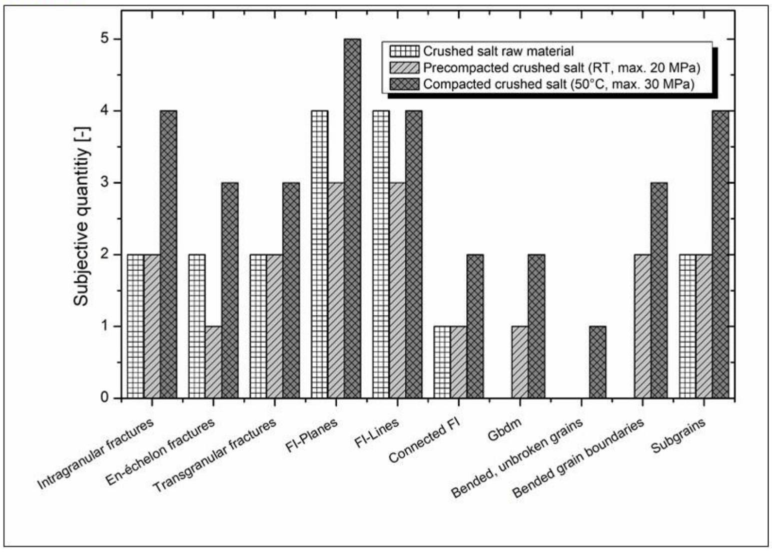

Fluid inclusions in crushed salt raw material
100 µm
Subjective quantity [-]
BGR
10


Fluid inclusions (oedometric compaction; 50°C, max. 30 MPa)
50 µm
Subjective quantity [-]
BGR
11


Pressure solution in compacted crushed salt (oedometric compaction; 50°C, max. 30 MPa)
200 µm
Subjective quantity [-]
BGR
12



Preliminary results



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Preliminary conclusions

- Compacting the sample increases the quantity of the observed microstructures
- Precompaction shows only minor influence on the abundance of observed microstructures compared to uncompacted crushed salt
- Compacting samples (<6% porosity) increases the abundancy of both:
    - plastic and cataclastic indicators

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Future work

- Preliminary results showed differences in the investigated samples but further investigations are necessary
- Assign deformation indicators to certain compaction states
- Ongoing comparison of differently compacted crushed salt (KOMPASS II)
- Comparison of real-used backfill material with laboratory material
- Isolated generation of deformation indicators

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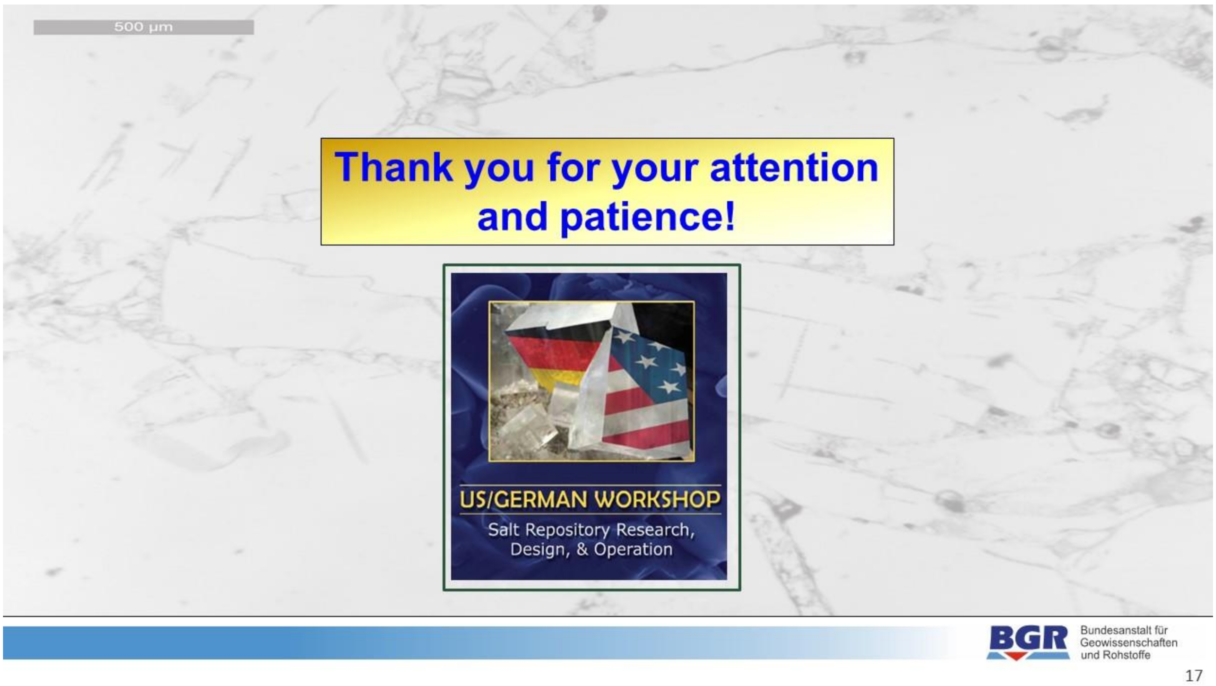
16


500 µm
Thank you for your attention and patience!
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
BGR
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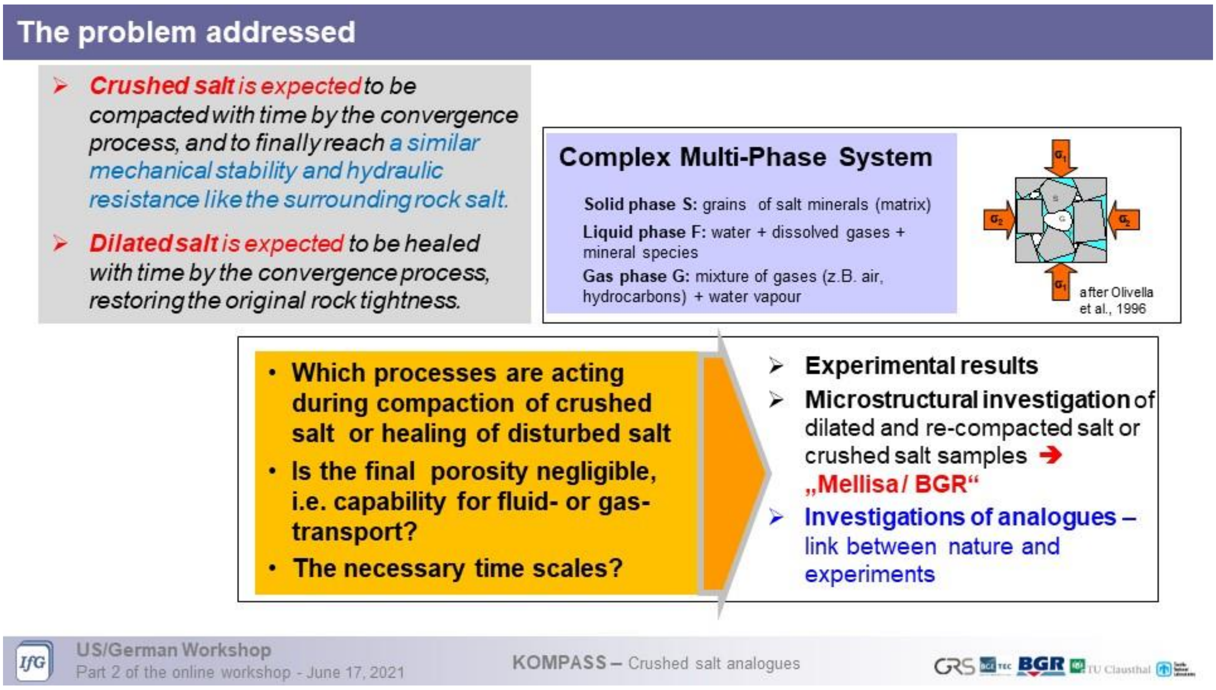
17


Granular salt compaction and healing
Natural and Technical analogues
Dirk Naumann / Till Popp (IfG Leipzig)
Outline
• Background
• Natural and technical analogues
• Fundamental micro-structural processes
• Summary / Open questions
HLW
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
BGE TEC


The problem addressed
➢ Crushed salt is expected to be compacted with time by the convergence process, and to finally reach a similar mechanical stability and hydraulic resistance like the surrounding rock salt.
➢ Dilated salt is expected to be healed with time by the convergence process, restoring the original rock tightness.
Complex Multi-Phase System
Solid phase S: grains of salt minerals (matrix)
Liquid phase F: water + dissolved gases + mineral species
Gas phase G: mixture of gases (z.B. air, hydrocarbons) + water vapour
after Olivella et al., 1996
• Which processes are acting during compaction of crushed salt or healing of disturbed salt
• Is the final porosity negligible, i.e. capability for fluid- or gas-transport?
• The necessary time scales?
➢ Experimental results
➢ Microstructural investigation of dilated and re-compacted salt or crushed salt samples ➔ „Mellisa / BGR“
➢ Investigations of analogues – link between nature and experiments
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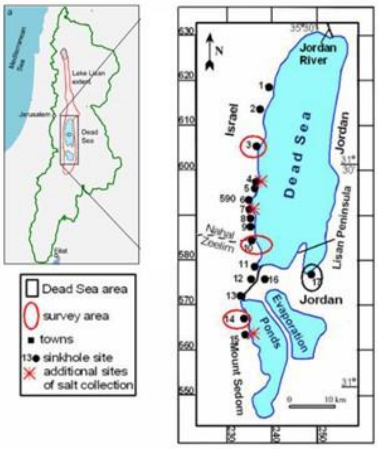
GRS
BGR
TU Clausthal

Dead Sea salt sediments (crushed salt)

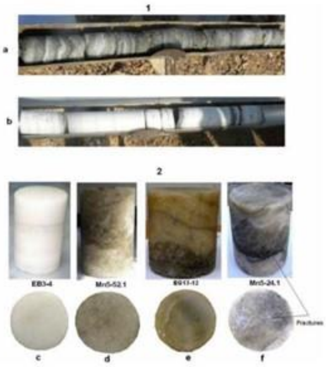


(after Goretsky, personal commun.)

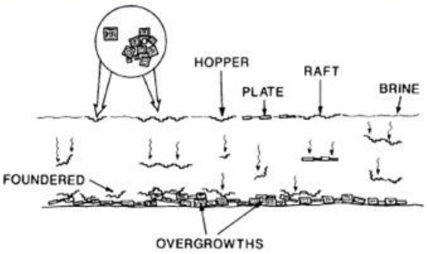
Shallow salt layers buried within the Dead Sea fill during several quartenary time periods:

- Duration of compaction processes of several hundreds up to some thousands of years
  = comparable to our time scales
- Low vertical stresses due to low depth (up to 100 metres)

Presentation of literature findings from boreholes and seismic investigations on core sample

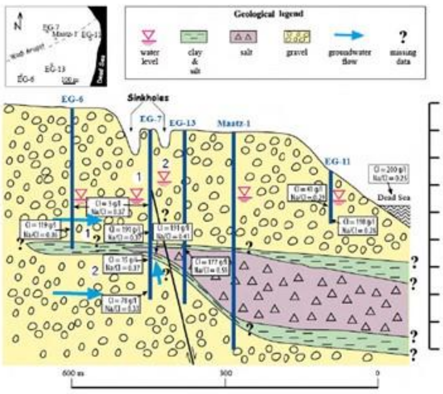


Syndepositional and postdepoptional diagenesis of salt rocks (crushed salt)



Salt crust of salt at the Dead Sea (from Melanie Lidman/Times of Israel)

(1) Formation of halite cumulates begins with crystal nucleation at the brine/air interface (e.g. hopper crystals). At the bottom loosely packed layers of cumulates with halite cement as overgrowths (after Handford, 1991).



(2) Diagenesis: Schematic cross section across the Deap Sea

(Yechieli et al., 2006).

Porosity decrease during diagenesis – core investigations

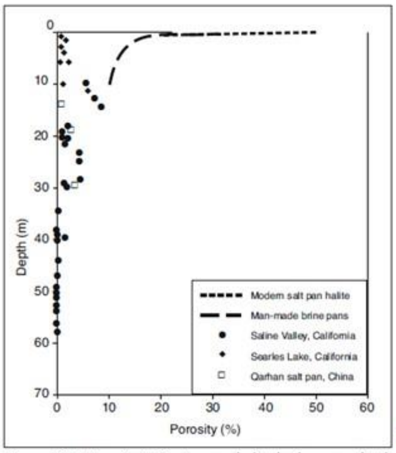


Figure 1.31. Porosity in Quaternary halite beds versus depth (after Casas and Lowenstein, 1989). All effective porosity is lost by 70 m burial.

- Quaternary halite layers at about 10 m have porosities of 10%, and layers at depths below about 45 m are tightly cemented and contain no visible porosity.
- Casas and Lowenstein (1989) showed that the porosity loss was entirely due to early post-depositional diagenetic cementation by clear halite.
- Mechanical effects on porosity reduction are of minor importance

- **All effective porosity is lost by 70 m burial**
- **Hydro-chemical effects (pore cementation) are of major importance**

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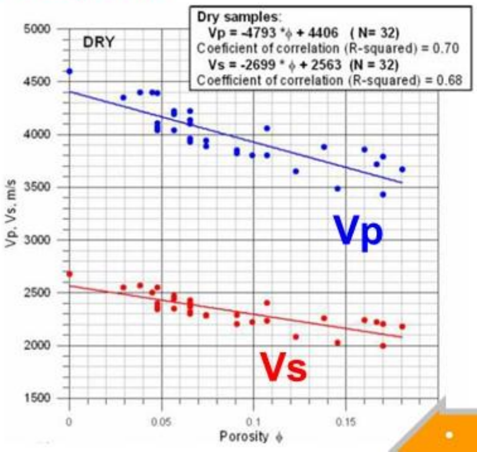
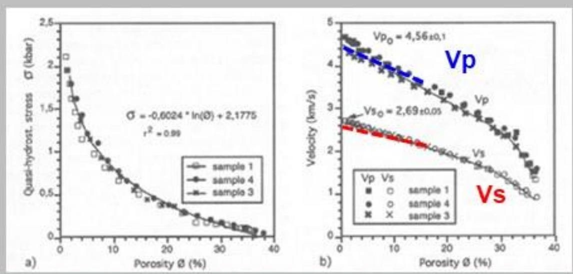
KOMPASS – Crushed salt analogues

Core investigations – ultrasonic velocity measurements

Deep Sea



(after Goretsky, personal commun.)



Compaction of crushed salt with simultaneous monitoring of Vp and Vs:
(Popp Kern, 1998):

$$\phi = (Vp - 4.56 \pm 0.1)/(-0.0698)$$

- **The lab trend is confirmed for the natural salt samples from swallow depth**

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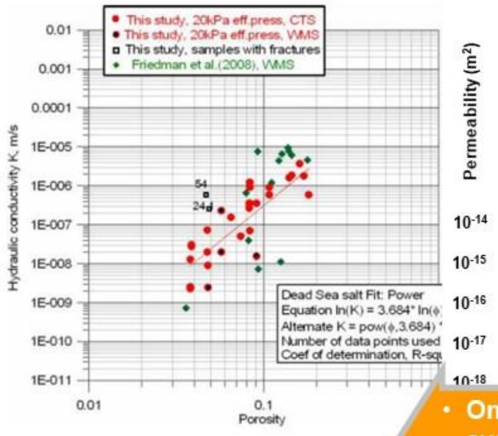
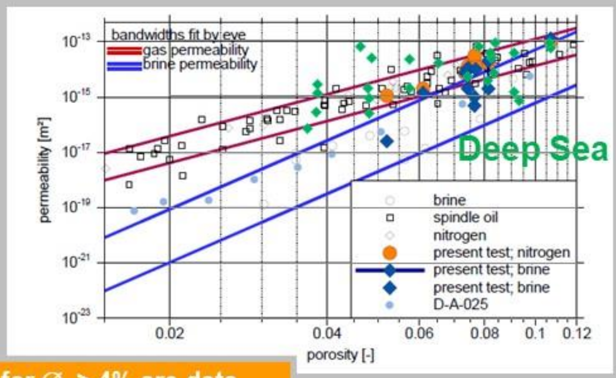
Core investigations – permeability measurements

Deep Sea



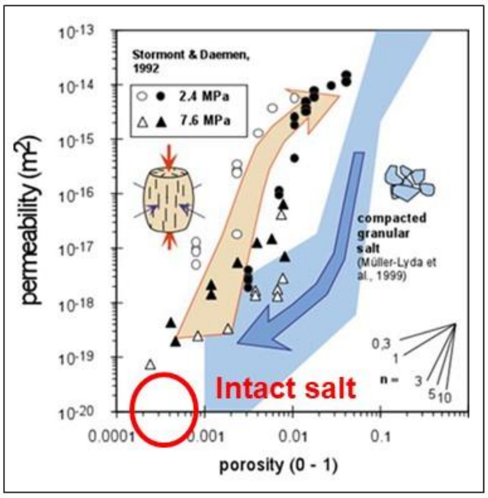
(after Goretsky, personal commun.)

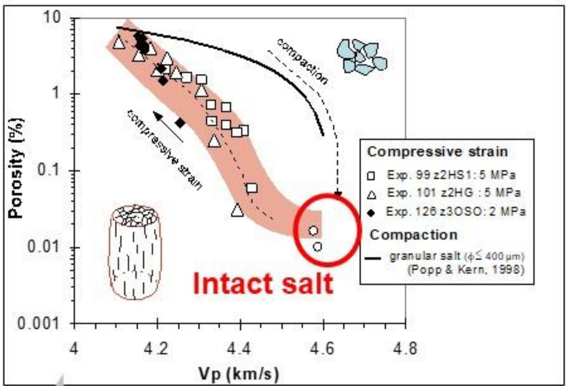
- REPOPERM II: permeability testing with various fluids



- Only for ∅ > 4% are data available (sign. Scattering)
- Gas vs. brine: Which permeability trend is true?

Reliability of „porosity“ estimates: - Dilatancy vs. compaction



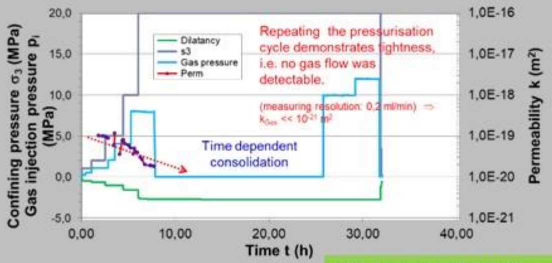


- No unique permeability-porosity or – velocity relation in the low porosity range ➔ pore space connectivity
- Change of inclination – final porosity?

Re-compaction of dilated salt – Case study Teutschenthal

Main access drift 2. level between the cavities 345/445; View to the East (originally mined: 10/1962).

- Permeability testing of re-consolidated self-backfill-material (heavily damaged salt)



The reconsolidated material behaves like the virgin rock

☺ Low permeability

➢ **Lessons learned at the Teutschenthal site:**

- Natural closure of underground openings due to salt creep is a fact, **but take into account: it's carnallite**
- Despite room closure of underground openings is a long-lasting process, it will happen within periods of up to 1000 years depending on, e.g. the salt type, repository depth …
- During re-consolidation the natural salt properties (e.g. strength, tightness) of the crushed salt will be restored
- Humidity will accelerate this process

- **Humidity – associated healing seems to be most relevant**
- **How does it work?**

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Underlying mechanisms: Volumetric creep of salt – Long term

$$\dot{\varepsilon}_v = A(T).f_A(\phi).\sigma^{5.5} + B(T).f_B(\phi).\frac{\sigma}{d^3} + \dots ?$$

Dislocation creep (BGR)	Pressure solution creep (Utrecht)	Plasticity coupled solution transfer

High stress, high strain-rate, coarse grain size	Low stress, low strain-rate, fine grain size	High stress conditions

(Spiers et al. 2005)

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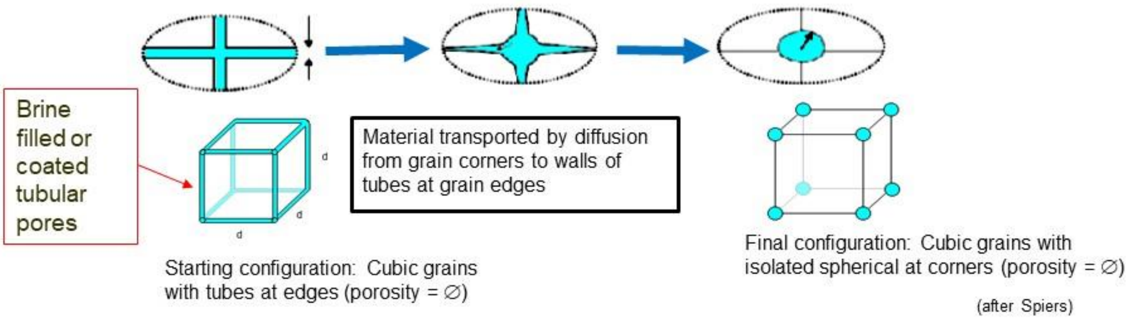
Microphysical model for pore disconnection – Fluid transport

Driving force for material transport by diffusion = surface energy !!

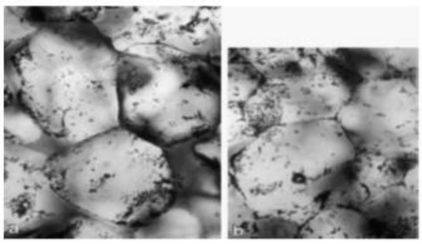


Time for pore disconnection:

$$t = \frac{3\phi d^3 RT}{32\,\pi DC\,\Omega\,\gamma F(\phi)}$$

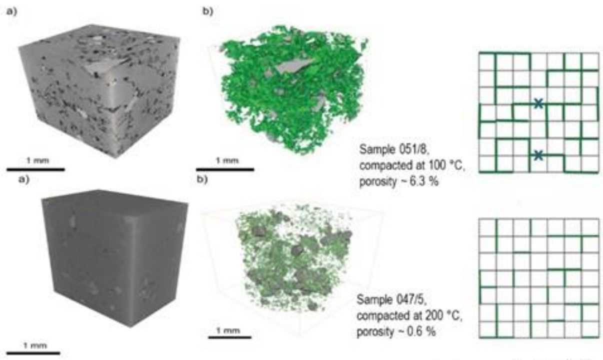
ϕ is porosity, d grain size, T temperature, $\gamma = 0.2$ J/m^2,
$D = 5\times10^{-9} m^2 s^{-1}$ (70 °C) (diffusion coefficient),
$C = 0.2$ m^3/m^3 (solubility of salt),
$\Omega = 2.7\times10^{-5}$ m^3/mol (molar volume of salt) **and** $F(\phi) = \frac{3}{2}\left(\frac{\phi}{3\pi}\right)^{\frac{1}{2}} - \left(\frac{3\phi}{4\pi}\right)^{\frac{2}{3}}$

Closure of interconnecting pore space – crushed salt



Very intense indentation and grain boundary straightening by pressure solution showing presence of 120º 'equilibrium' grain boundary triple junctions (grain size 180–212 µm; bulk compaction strain 27%; wet compaction stress 5 MPa)

B. den Brok et al. / Tectonophysics 307 (1999) 297–312



Jobmann et al. (2014)

Percolation network model

In the porosity range of 6 – 3 % the **connectivity** of the pore space decreases rapidly

Summary / open questions

- Natural analogues of Dead Sea salt sediments show that all effective porosity is lost by 70 m burial
- Direct measurements of **porosity and permeability** resp. **ultrasonic wave velocities** demonstrate recovery of a low porosity = hydraulic tightness,
- The Teutschenthal-example confirms healing / consolidation in situ, i.e. crushed salt approaches intact salt properties with time

but

- ➢ Mechanical-induced crack/pore closure is not sufficient to explain healing, i.e. development of cohesion!
- ➢ Humidity-assisted deformation mechanisms are the key-factor for healing and crushed salt consolidation!

Despite a significant process understanding exists sufficient experimental data and appropriate modelling approaches are still missing ….

Follow-Up R&D-Project „KOMPASS II“

US/German Workshop
Part 2 of the online workshop - June 17, 2021
KOMPASS – Crushed salt analogues

11th US/German Workshop on Salt Repository Research, Design, and Operation

The KOMPASS project
Modelling related experimental aspects

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

Sandia National Laboratories

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

BGE TEC
BGE TECHNOLOGY GmbH

Svetlana Lerche
Uwe Düsterloh
Juan Zhao
TUC

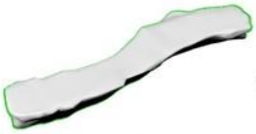
Part 2 of the online workshop
Juni 17, 2021

Overview

1. General reasons for need in modelling related lab tests
2. Modelling related lab program design for crushed salt
3. Results and next steps: KOMPASS I and KOMPASS II

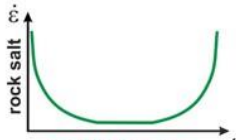
2

General reasons for need in modelling related lab tests



real geometry

What? Basic task in the numerical analyses
Idealized/simplified reproduction of reality
Geomechanics: underground system with antropogenic consturction and geogenic structure



real behavior

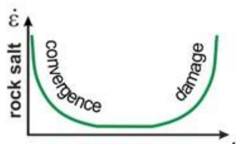
3

General reasons for need in modelling related lab tests

real geometry

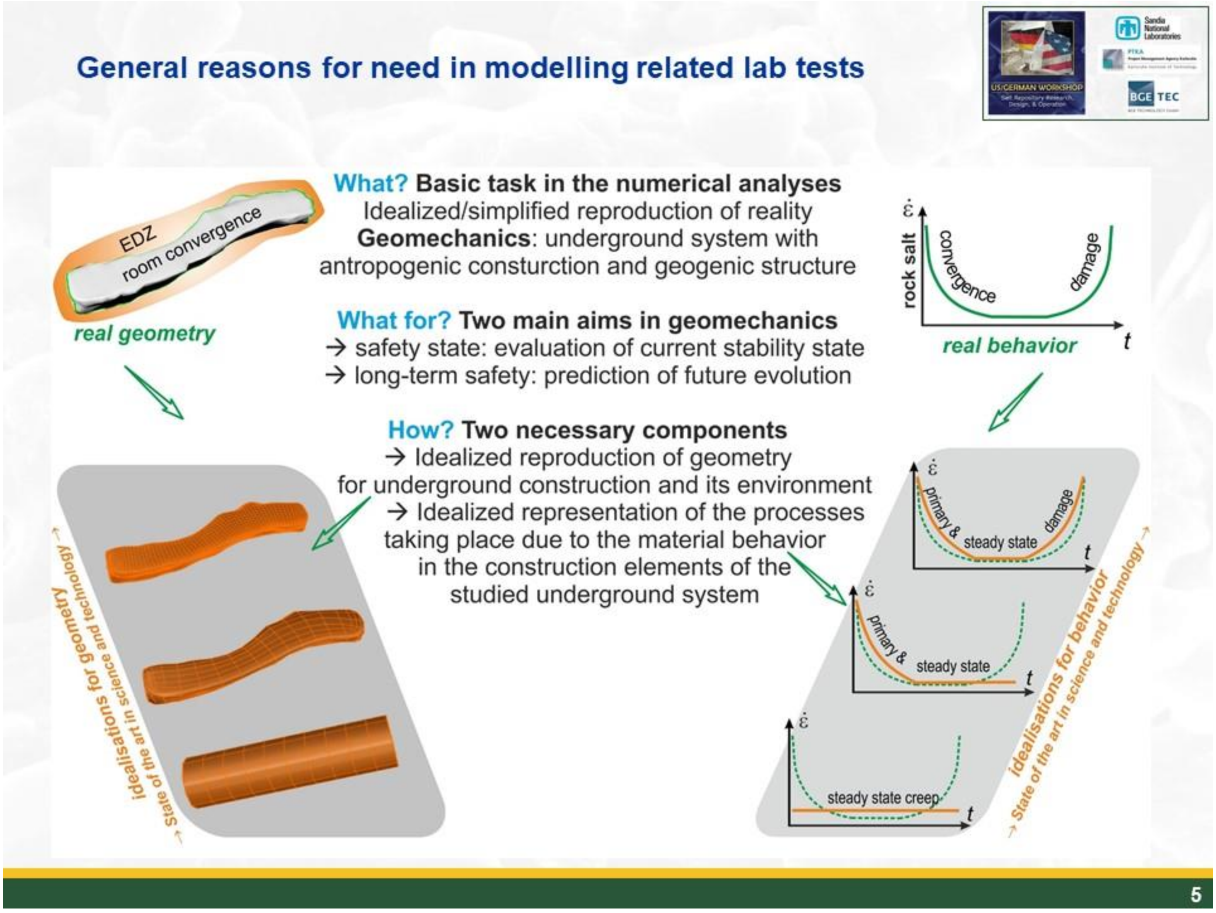
What? Basic task in the numerical analyses
Idealized/simplified reproduction of reality
Geomechanics: underground system with antropogenic consturction and geogenic structure

What for? Two main aims in geomechanics
→ safety state: evaluation of current stability state
→ long-term safety: prediction of future evolution



real behavior

4


General reasons for need in modelling related lab tests
US/GERMAN WORKSHOP
Sandia National Laboratories
PTKA
BGE TEC
EDZ
room convergence
real geometry
What? Basic task in the numerical analyses
Idealized/simplified reproduction of reality
Geomechanics: underground system with
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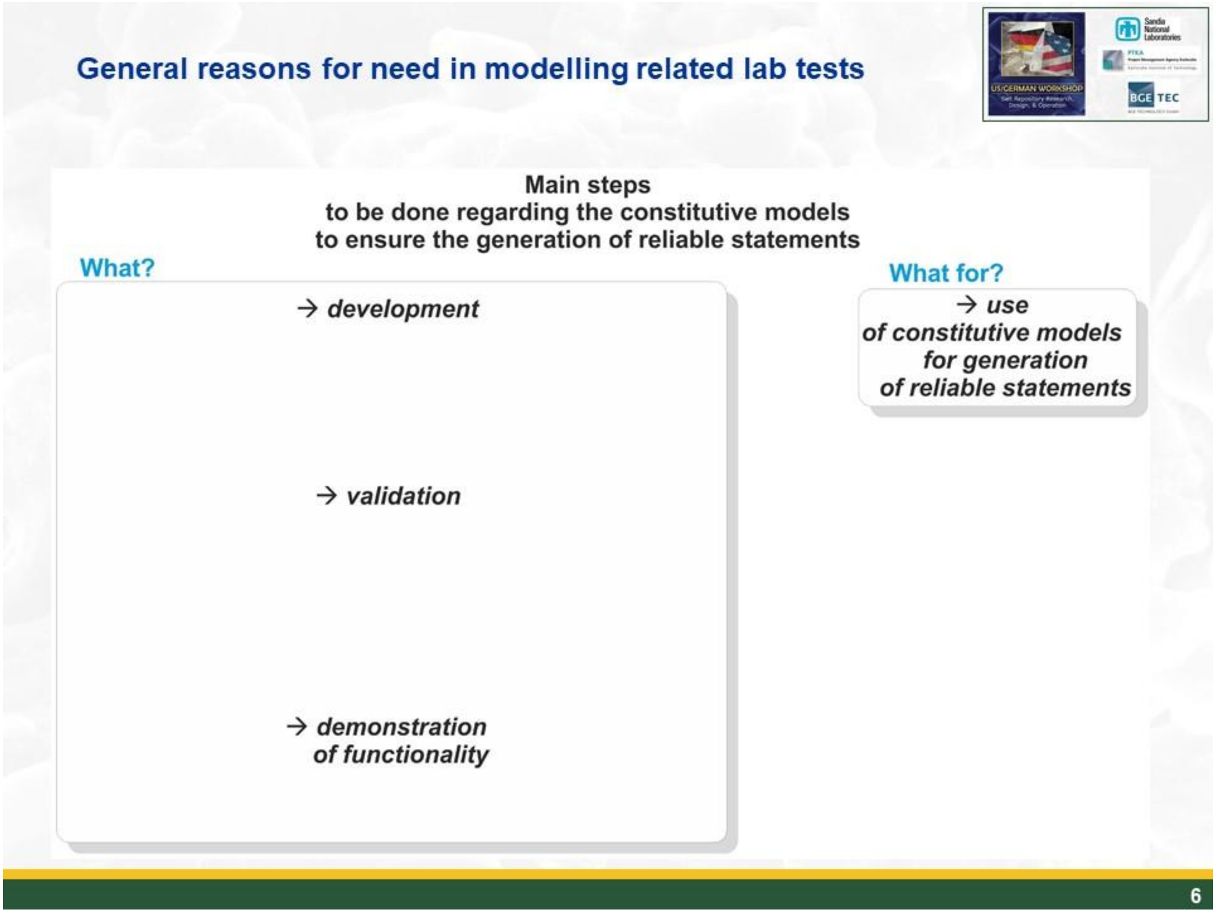
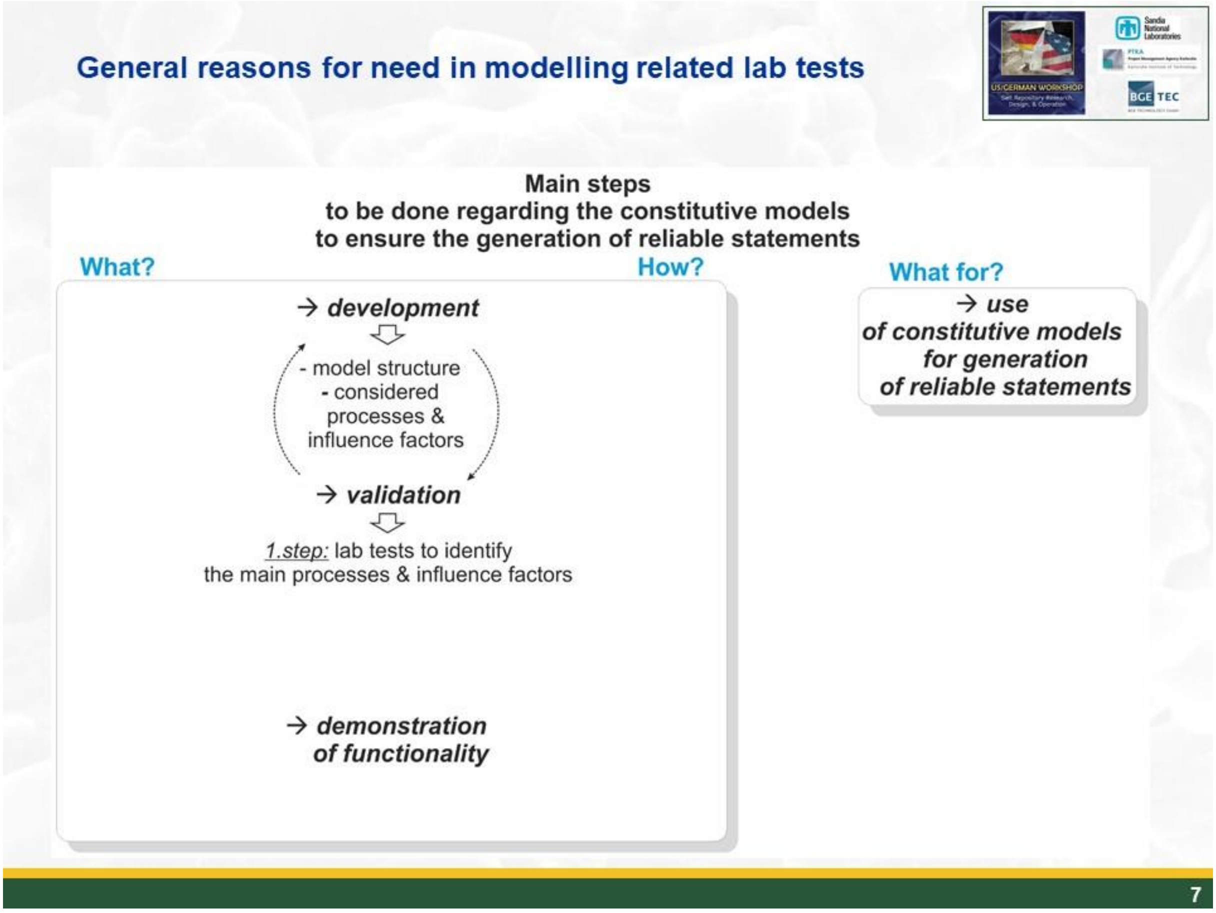
What for? Two main aims in geomechanics
→ safety state: evaluation of current stability state
→ long-term safety: prediction of future evolution
How? Two necessary components
→ Idealized reproduction of geometry
for underground construction and its environment
→ Idealized representation of the processes
taking place due to the material behavior
in the construction elements of the
studied underground system
rock salt
convergence
damage
real behavior
t
primary &
steady state
damage
steady state creep
idealisations for geometry
State of the art in science and technology
idealisations for behavior
State of the art in science and technology
5


General reasons for need in modelling related lab tests
US/GERMAN WORKSHOP
Sandia National Laboratories
PTKA
BGE TEC
Main steps
to be done regarding the constitutive models
to ensure the generation of reliable statements
What?
→ development
→ validation
→ demonstration
of functionality
What for?
→ use
of constitutive models
for generation
of reliable statements
6


General reasons for need in modelling related lab tests
US/GERMAN WORKSHOP
Sandia National Laboratories
PTKA
BGE TEC
Main steps
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What?
How?
What for?
→ development
- model structure
- considered
processes &
influence factors
→ validation
1.step: lab tests to identify
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→ demonstration
of functionality
→ use
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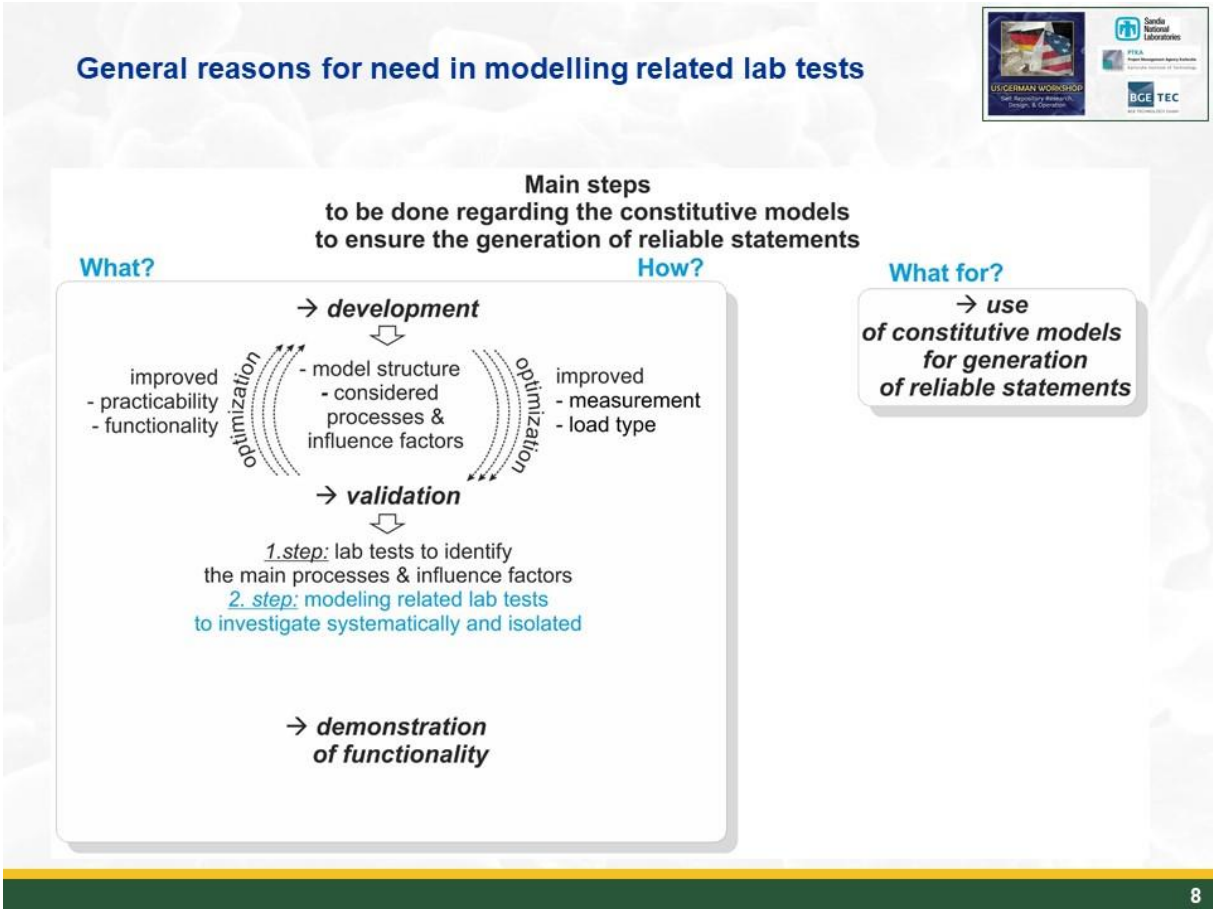
7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→ validation
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2. step: modeling related lab tests
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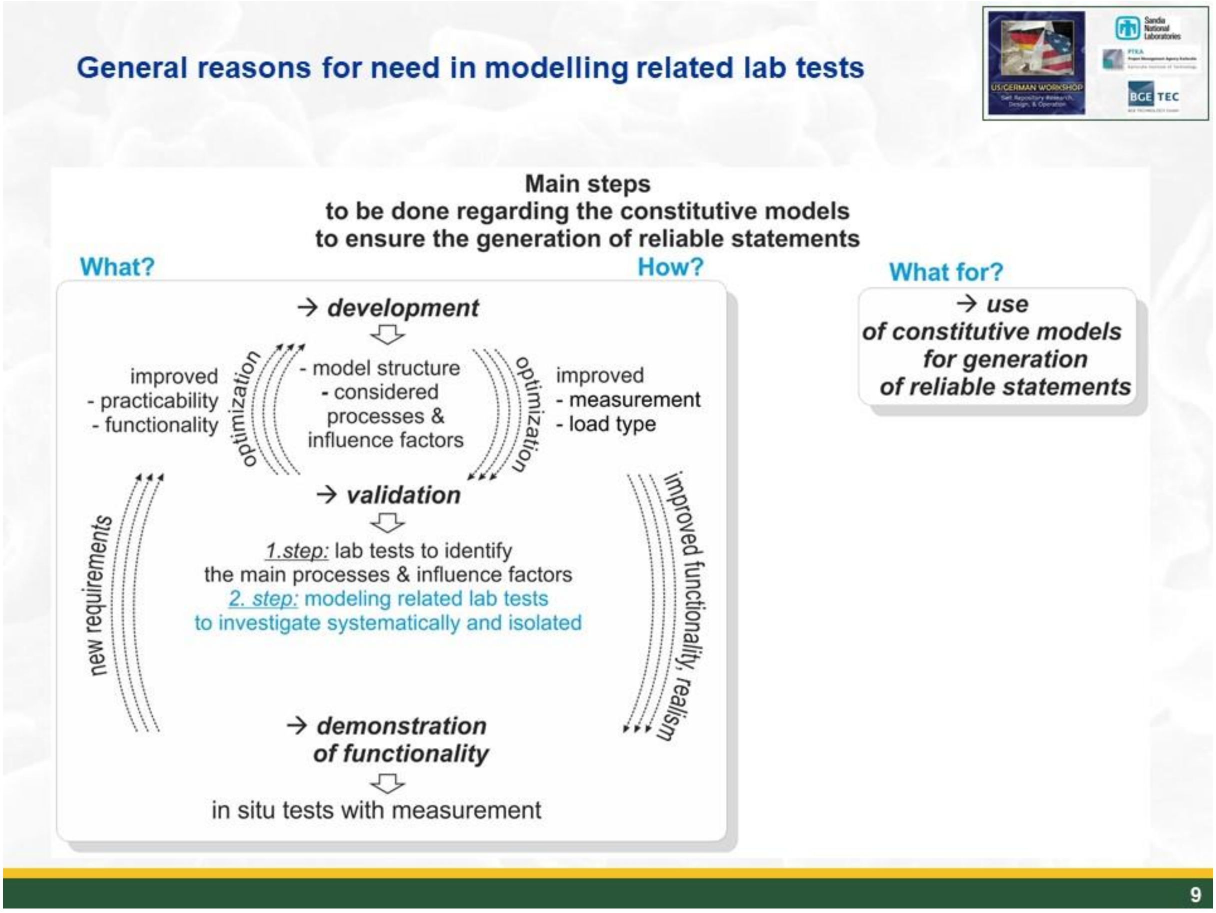
8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new requirements
1.step: lab tests to identify
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to investigate systematically and isolated
improved functionality, realism
→ demonstration
of functionality
in situ tests with measurement
→ use
of constitutive models
for generation
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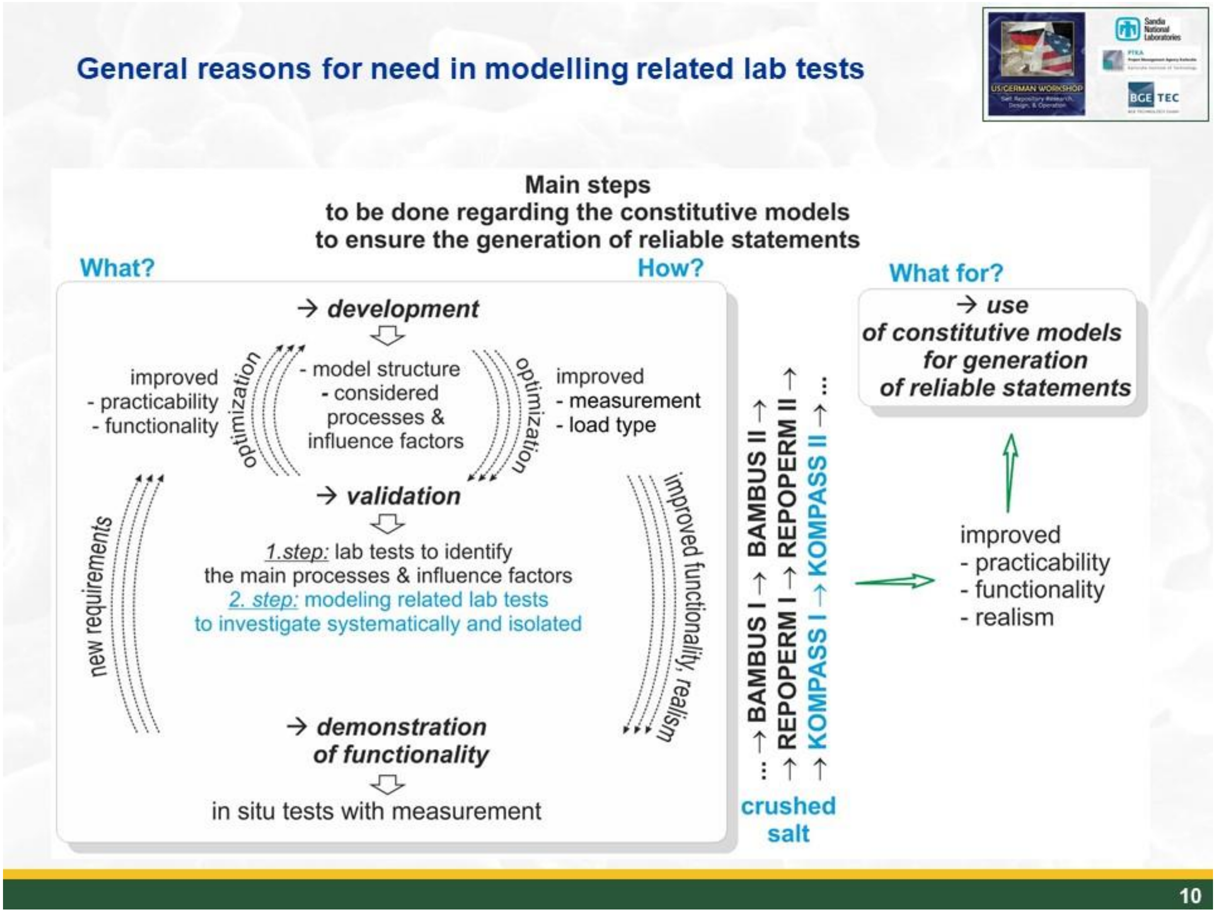
9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improved functionality, realism
→ demonstration
of functionality
in situ tests with measurement
… → BAMBUS I → BAMBUS II → …
↑ REPOPERM I → REPOPERM II ↑
↑ KOMPASS I → KOMPASS II → …
crushed
salt
→ use
of constitutive models
for generation
of reliable statements
improved
- practicability
- functionality
- realism
10

Overview

1. General reasons for need in modelling related lab tests
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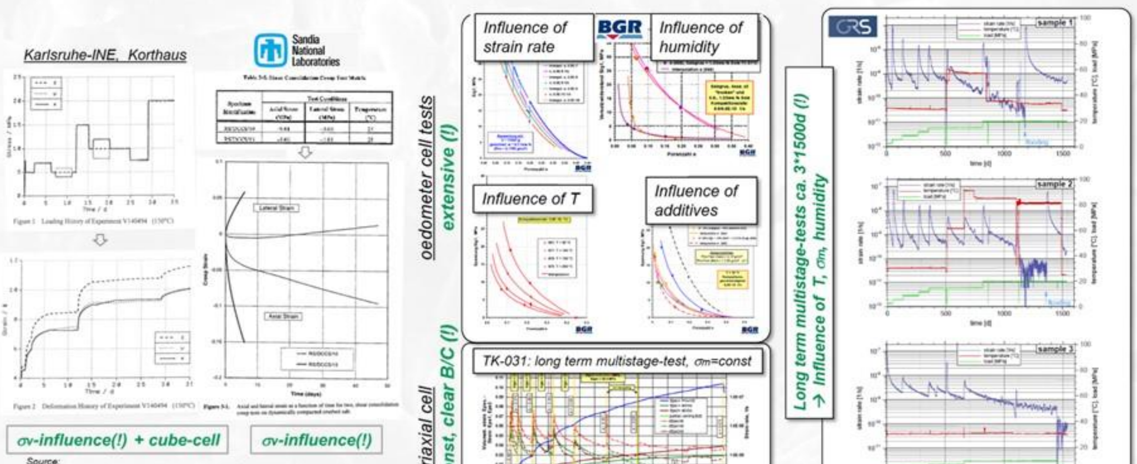
11

Modelling related lab program design for crushed salt

previous investigations



Source: Korthaus, INE, Consolidation and deviatoric deformation behaviour of dry crushed salt at temperatures up to 150°C, Montreal, 1996

Source: Callahan, Crush salt constitutive model, RESPEC, Rapid City, 1999

Sources: REPOPERM I (2009), REPOPERM II (2017)

Source: REPOPERM II (2017)

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Modelling related lab program design for crushed salt

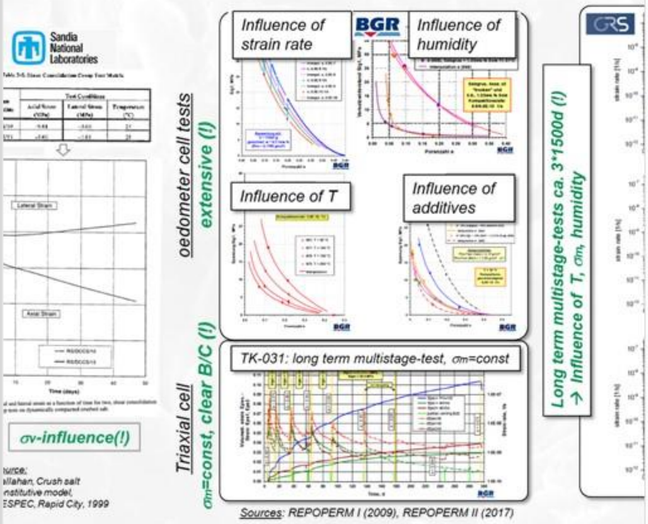
previous investigations

1. step: LAB
identification of main processes & influence factors

1. step: MODEL
- model structure
- considered processes & influence factors

2. step: LAB
modeling related: systematically and isolated investigations

2. step: MODEL
- improved functionality
- increased realism
- extended range of validity



1. step: LAB
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1. step: MODEL
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2. step: MODEL
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→ State of the art in science and technology →

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Modelling related lab program design for crushed salt

concept for modelling related lab program design

Principles/Guidelines for planning **How?**

for the system of tests

Completeness →

Systematics →

Reliability & Effectiveness →

for individual tests

Clearness/ unambiguity/ clear-cut analysis →

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Modelling related lab program design for crushed salt

concept for modelling related lab program design

Principles/Guidelines for planning **How?**

for the system of tests

Completeness →
- All known/assumed influence factors

Systematics →
- Comparability of tests: uniform material for all tests; coordinated test types (B/C) and coordinated areas/values of infulence factors
- Exclusion of material variations/scattering: multi-stage tests
- Structure - influence factors groups: M, H, T; material state internal factors; external influence factors
- Prioritization: in situ relevant factors; insufficient studied factors

Reliability & Effectiveness →
- New technoligies for more precise measurement
- Several labs with different measurement technologies and optimized B/C

for individual tests

Clearness/ unambiguity/ clear-cut analysis →
- Isolation of studied process: avoid/switch off the remaining processes
- Isolation of studied influence factor: keep all remaining factors constant due to special partly innovative B/C
- Area of the currently investigated influence factor:
  a) continuous range: in situ relevant range, broad area
  b) discrete levels: min 5 levels (for clear identification of dependency)

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Modelling related lab program design for crushed salt

concept for analysis and structural decomposition of constitutive models

methodical approach in frame of physical modeling

step 1:
current requirements
- areas of application

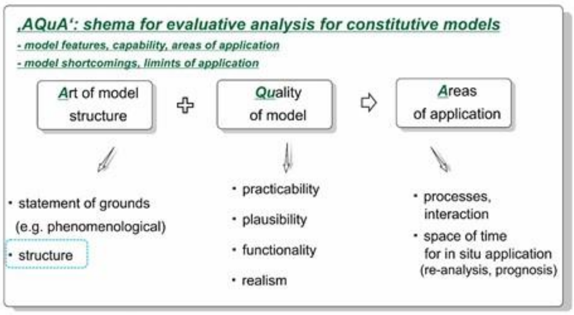
review for existing models & evaluation of current status
- Art of model strucure
- Quality
- Areas of application

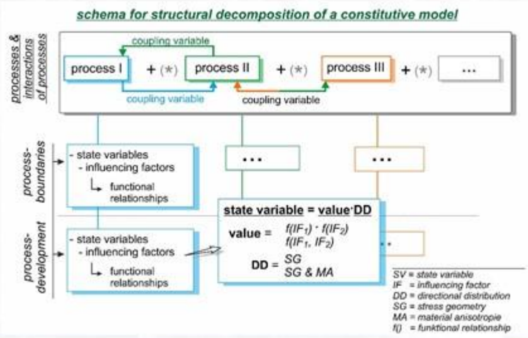
step 2:
data base/lab tests
- interpretability/clearness
- completness
- systematics

step 3:
building of model structure
hypothesis generating
- options/systematic
- ‚Occam's razor'
- dimentional analysis

hypothesis test/corroborate
- Iisolation of influencing factors

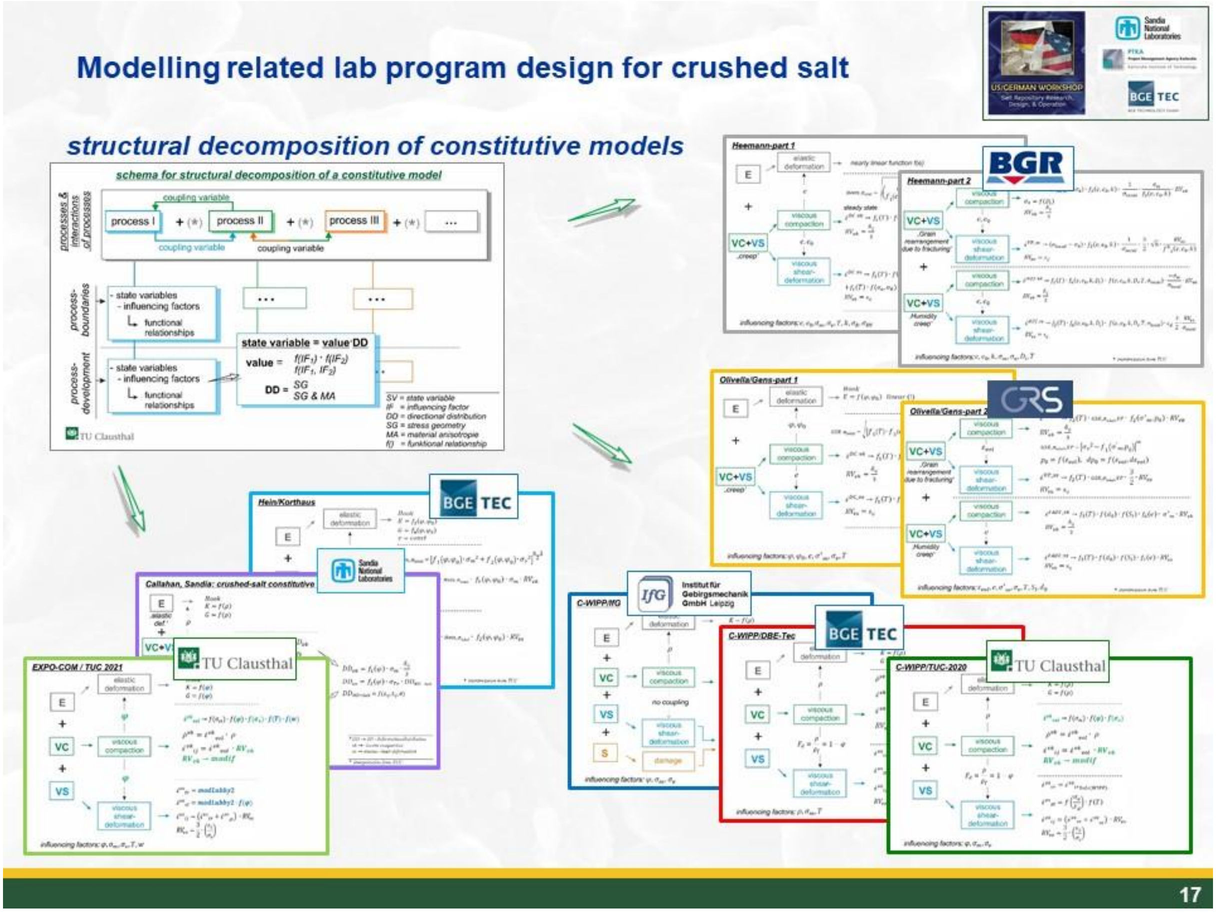
step 4:
validation
- implementation
- plausibility
- realism



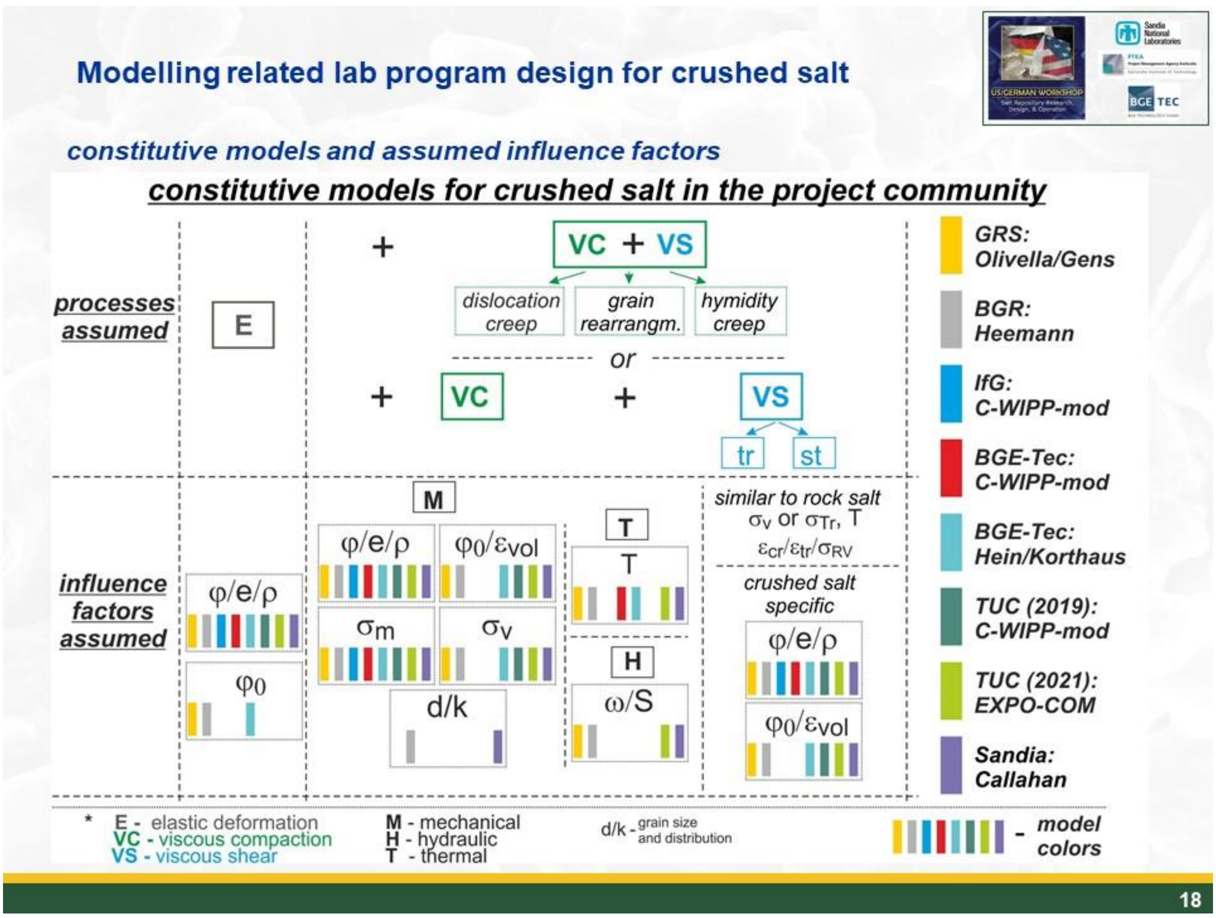


TU Clausthal

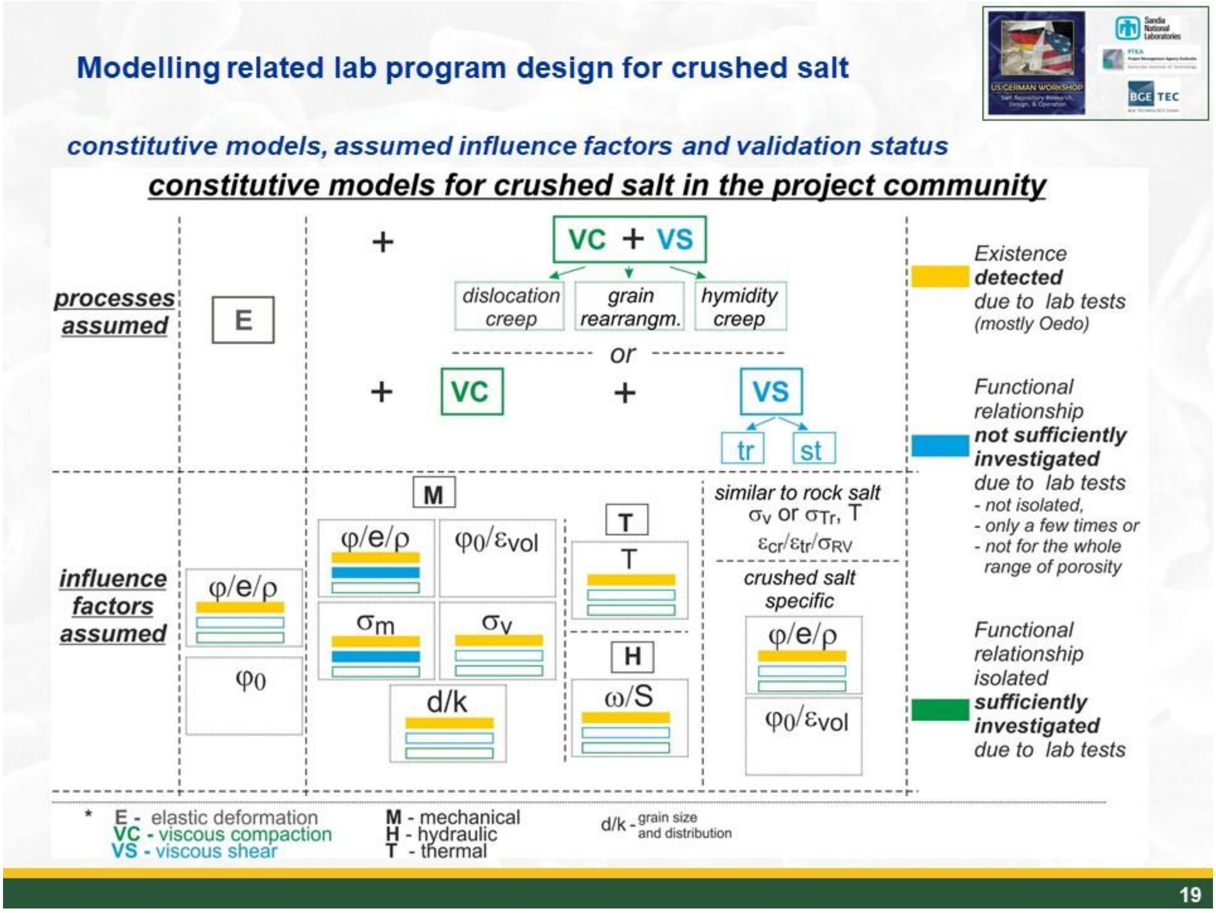
16



Modelling related lab program design for crushed salt
structural decomposition of constitutive models
schema for structural decomposition of a constitutive model
process I
process II
process III
coupling variable
state variables
- influencing factors
functional relationships
state variable = value·DD
TU Clausthal
Heemann-part 1
Heemann-part 2
BGR
Olivella/Gens-part 1
Olivella/Gens-part 2
Hein/Korthaus
BGE TEC
Callahan, Sandia: crushed-salt constitutive
EXPO-COM / TUC 2021
TU Clausthal
C-WIPP/IfG
Institut für Gebirgsmechanik GmbH Leipzig
C-WIPP/DBE-Tec
BGE TEC
C-WIPP/TUC-2020
TU Clausthal
17



Modelling related lab program design for crushed salt
constitutive models and assumed influence factors
constitutive models for crushed salt in the project community
processes assumed
E
+
VC + VS
dislocation creep
grain rearrangm.
hymidity creep
or
+
VC
+
VS
tr
st
influence factors assumed
M
T
H
φ/e/ρ
φ0/εvol
φ/e/ρ
φ0
σm
σv
d/k
T
ω/S
similar to rock salt
σv or σTr, T
εcr/εtr/σRV
crushed salt specific
φ/e/ρ
φ0/εvol
GRS: Olivella/Gens
BGR: Heemann
IfG: C-WIPP-mod
BGE-Tec: C-WIPP-mod
BGE-Tec: Hein/Korthaus
TUC (2019): C-WIPP-mod
TUC (2021): EXPO-COM
Sandia: Callahan
* E - elastic deformation
VC - viscous compaction
VS - viscous shear
M - mechanical
H - hydraulic
T - thermal
d/k - grain size and distribution
- model colors
18


Modelling related lab program design for crushed salt
constitutive models, assumed influence factors and validation status
constitutive models for crushed salt in the project community
processes assumed
E
+
VC + VS
dislocation creep
grain rearrangm.
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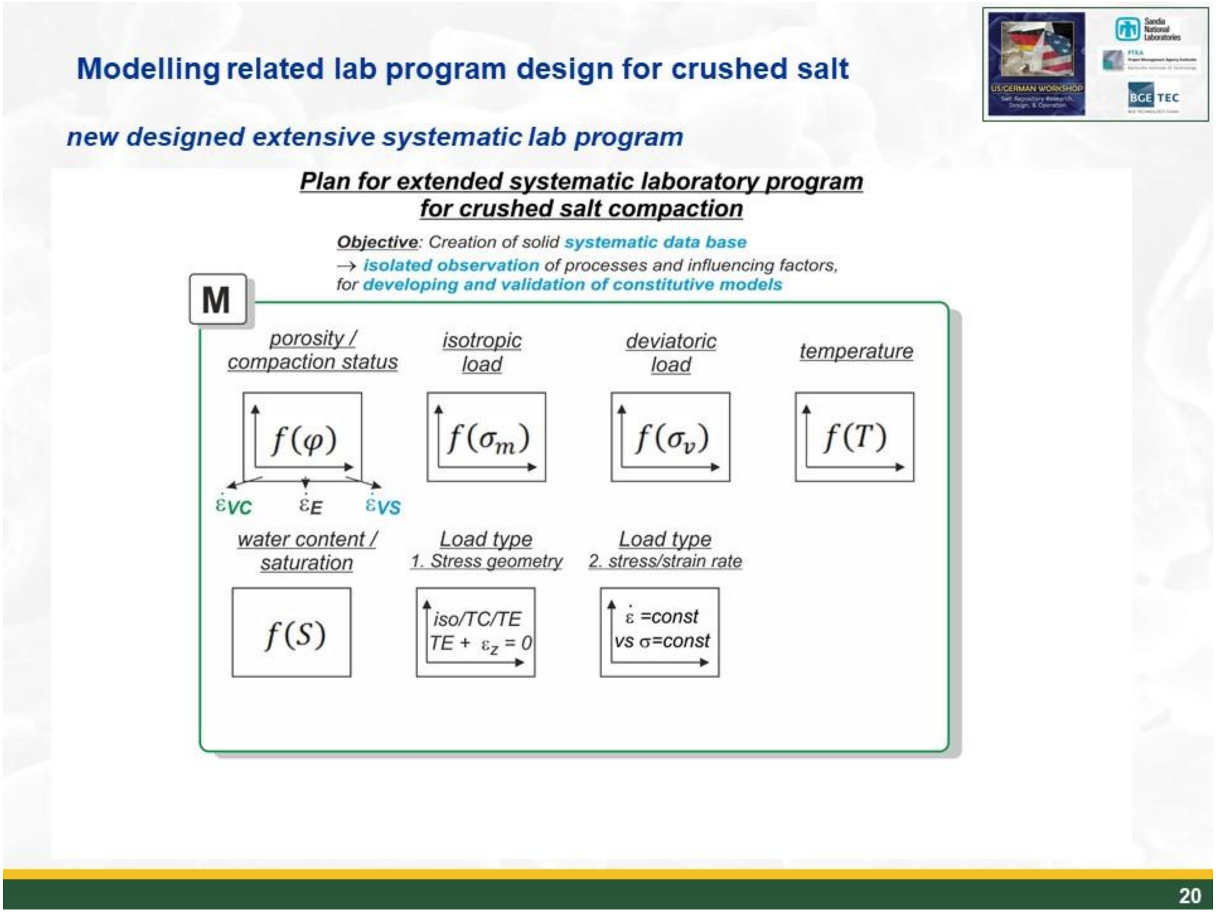
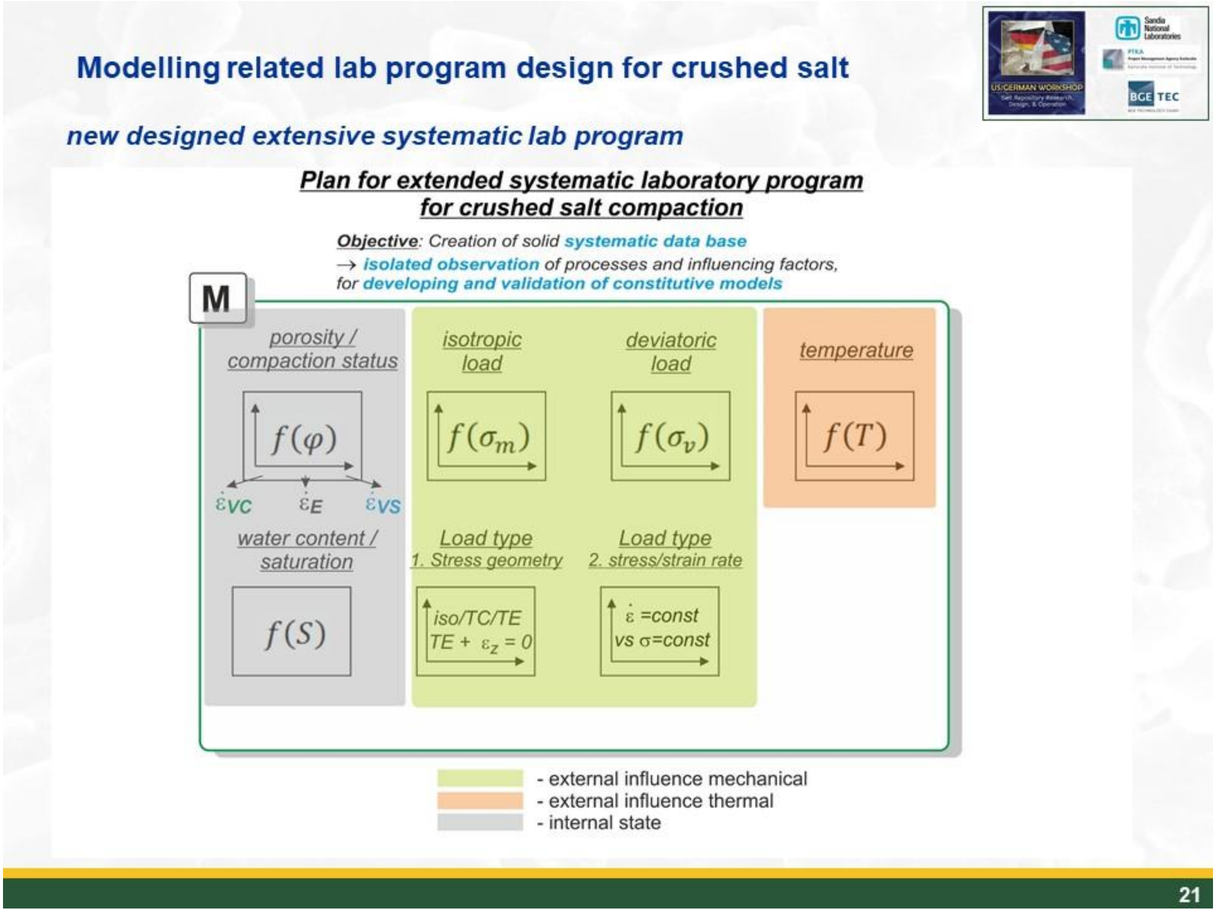
or
+ VC + VS
tr st
influence factors assumed
φ/e/ρ
φ0
M
φ/e/ρ
φ0/εvol
σm
σv
d/k
T
T
H
ω/S
similar to rock salt
σv or σTr, T
εcr/εtr/σRV
crushed salt specific
φ/e/ρ
φ0/εvol
Existence detected due to lab tests (mostly Oedo)
Functional relationship not sufficiently investigated due to lab tests
- not isolated,
- only a few times or
- not for the whole range of porosity
Functional relationship isolated sufficiently investigated due to lab tests
* E - elastic deformation
VC - viscous compaction
VS - viscous shear
M - mechanical
H - hydraulic
T - thermal
d/k - grain size and distribution
19


Modelling related lab program design for crushed salt
new designed extensive systematic lab program
Plan for extended systematic laboratory program for crushed salt compaction
Objective: Creation of solid systematic data base
→ isolated observation of processes and influencing factors,
for developing and validation of constitutive models
M
porosity / compaction status
f(φ)
εVC εE εVS
isotropic load
f(σm)
deviatoric load
f(σv)
temperature
f(T)
water content / saturation
f(S)
Load type
1. Stress geometry
iso/TC/TE
TE + εz = 0
Load type
2. stress/strain rate
ε =const
vs σ=const
20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Objective: Creation of solid systematic data base
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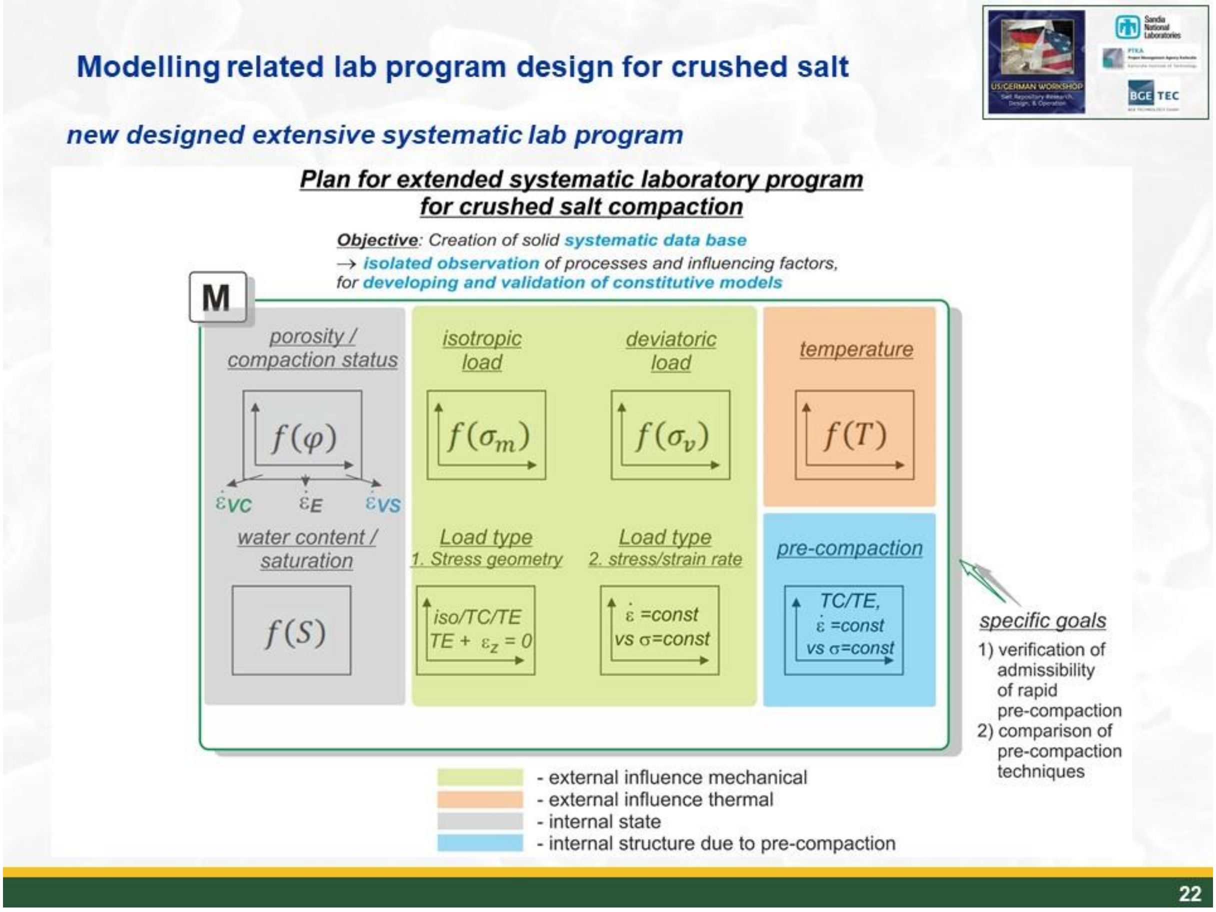
M
porosity / compaction status
$f(\varphi)$
$\dot{\varepsilon}_{VC}$ $\dot{\varepsilon}_{E}$ $\dot{\varepsilon}_{VS}$
water content / saturation
$f(S)$
isotropic load
$f(\sigma_m)$
deviatoric load
$f(\sigma_v)$
temperature
$f(T)$
Load type
1. Stress geometry
iso/TC/TE
TE + $\varepsilon_z = 0$
Load type
2. stress/strain rate
$\dot{\varepsilon}$ =const
vs σ=const
- external influence mechanical
- external influence thermal
- internal state
21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$\dot{\varepsilon}_{VC}$ $\dot{\varepsilon}_{E}$ $\dot{\varepsilon}_{VS}$
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$f(S)$
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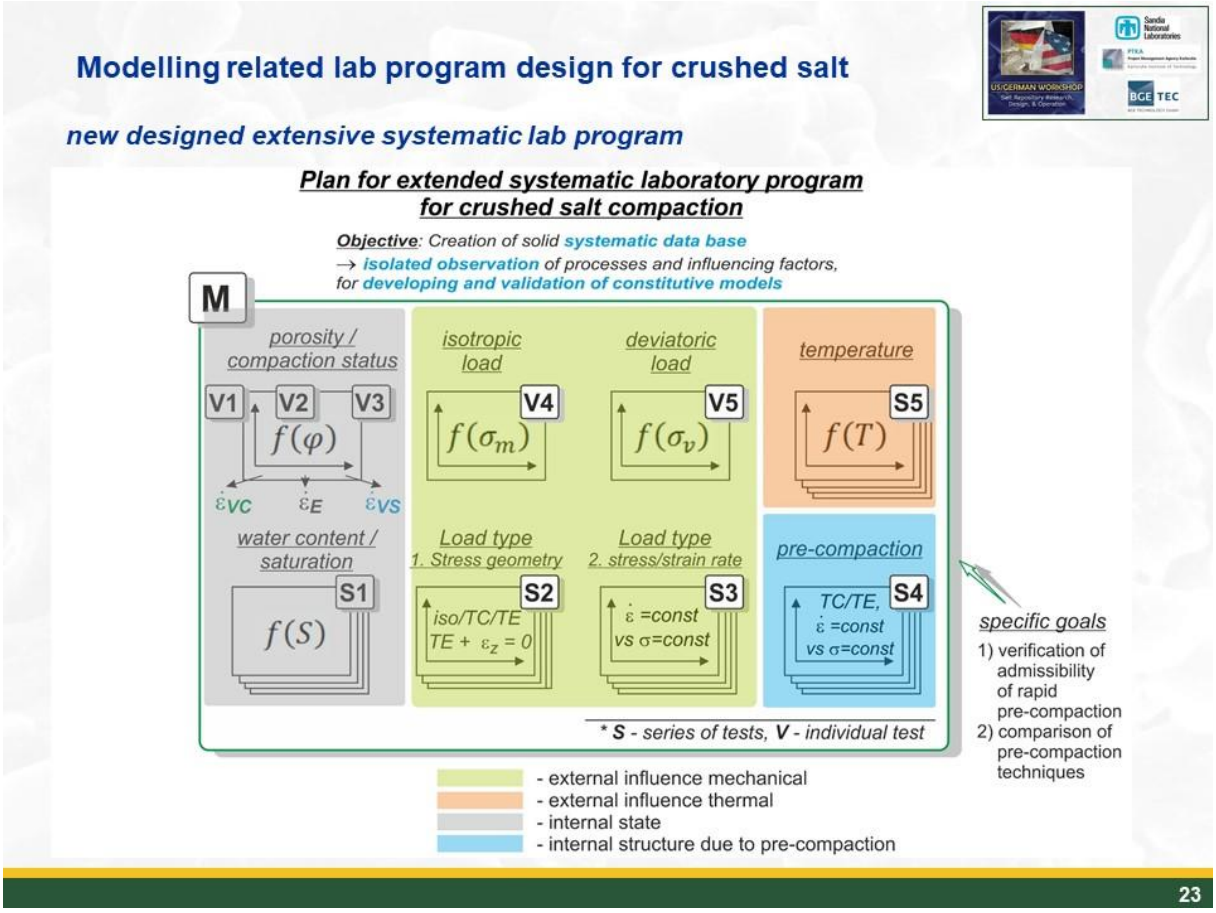
$f(\sigma_m)$
deviatoric load
$f(\sigma_v)$
temperature
$f(T)$
Load type
1. Stress geometry
iso/TC/TE
TE + $\varepsilon_z = 0$
Load type
2. stress/strain rate
$\dot{\varepsilon}$ =const
vs σ=const
pre-compaction
TC/TE,
$\dot{\varepsilon}$ =const
vs σ=const
specific goals
1) verification of admissibility of rapid pre-compaction
2) comparison of pre-compaction techniques
- external influence mechanical
- external influence thermal
- internal state
- internal structure due to pre-compaction
22


US/GERMAN WORKSHOP
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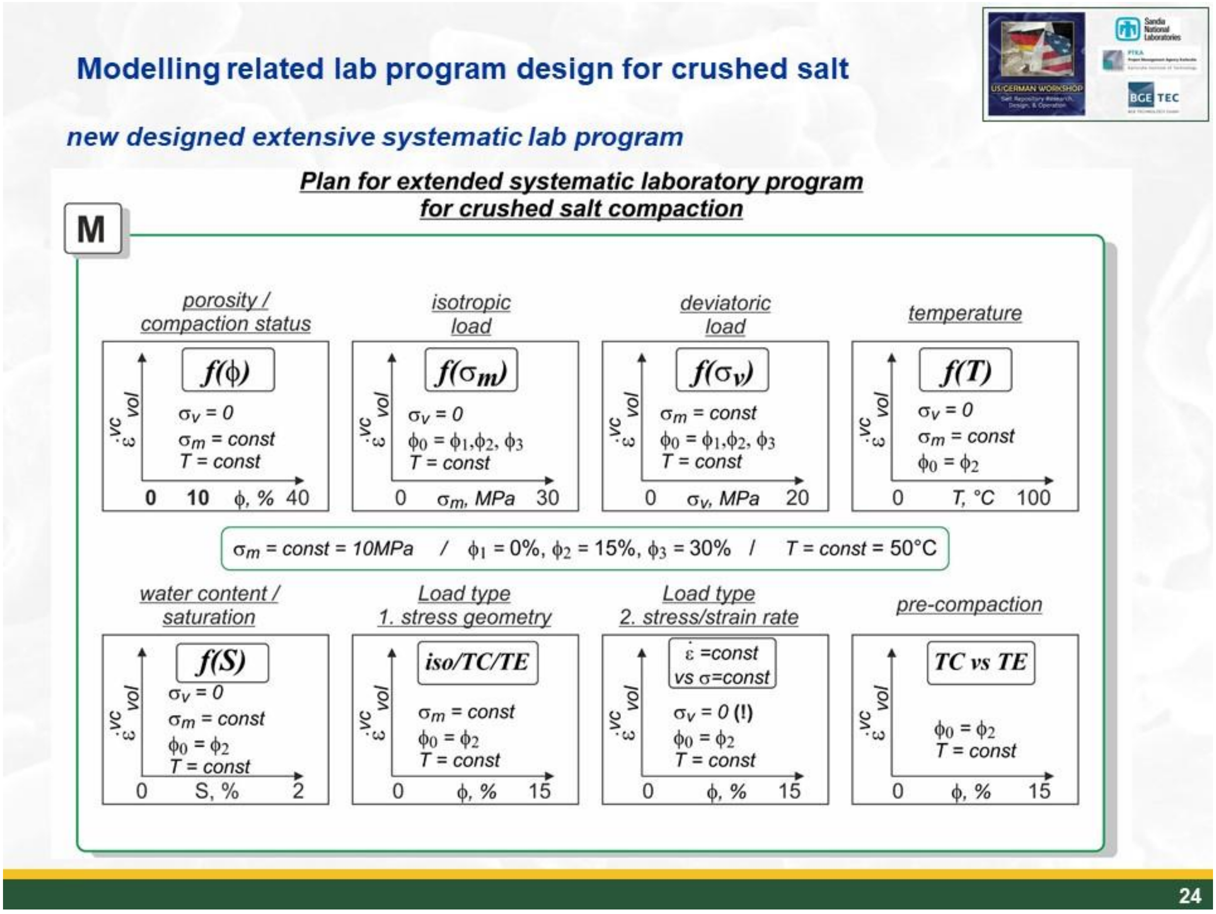
M
porosity / compaction status
V1
V2
V3
f(φ)
ε̇VC
ε̇E
ε̇VS
water content / saturation
S1
f(S)
isotropic load
V4
f(σm)
deviatoric load
V5
f(σv)
Load type
1. Stress geometry
S2
iso/TC/TE
TE + εz = 0
Load type
2. stress/strain rate
S3
ε̇ =const
vs σ=const
temperature
S5
f(T)
pre-compaction
S4
TC/TE,
ε̇ =const
vs σ=const
specific goals
1) verification of admissibility of rapid pre-compaction
2) comparison of pre-compaction techniques
* S - series of tests, V - individual test
- external influence mechanical
- external influence thermal
- internal state
- internal structure due to pre-compaction
23


US/GERMAN WORKSHOP
Modelling related lab program design for crushed salt
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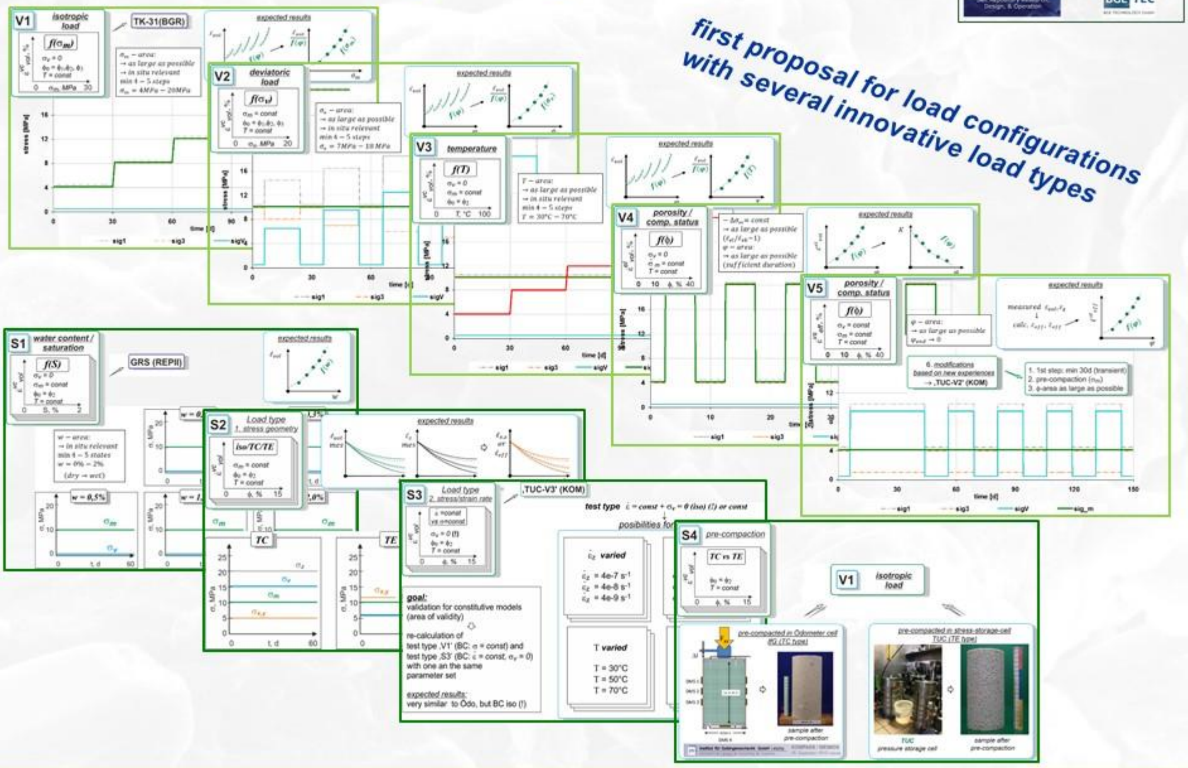
M
porosity / compaction status
f(ϕ)
σv = 0
σm = const
T = const
0 10 ϕ, % 40
isotropic load
f(σm)
σv = 0
ϕ0 = ϕ1,ϕ2, ϕ3
T = const
0 σm, MPa 30
deviatoric load
f(σv)
σm = const
ϕ0 = ϕ1,ϕ2, ϕ3
T = const
0 σv, MPa 20
temperature
f(T)
σv = 0
σm = const
ϕ0 = ϕ2
0 T, °C 100
σm = const = 10MPa / ϕ1 = 0%, ϕ2 = 15%, ϕ3 = 30% / T = const = 50°C
water content / saturation
f(S)
σv = 0
σm = const
ϕ0 = ϕ2
T = const
0 S, % 2
Load type
1. stress geometry
iso/TC/TE
σm = const
ϕ0 = ϕ2
T = const
0 ϕ, % 15
Load type
2. stress/strain rate
ε̇ =const
vs σ=const
σv = 0 (!)
ϕ0 = ϕ2
T = const
0 ϕ, % 15
pre-compaction
TC vs TE
ϕ0 = ϕ2
T = const
0 ϕ, % 15
ε̇vc, vol
24

Modelling related lab program design for crushed salt



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Overview

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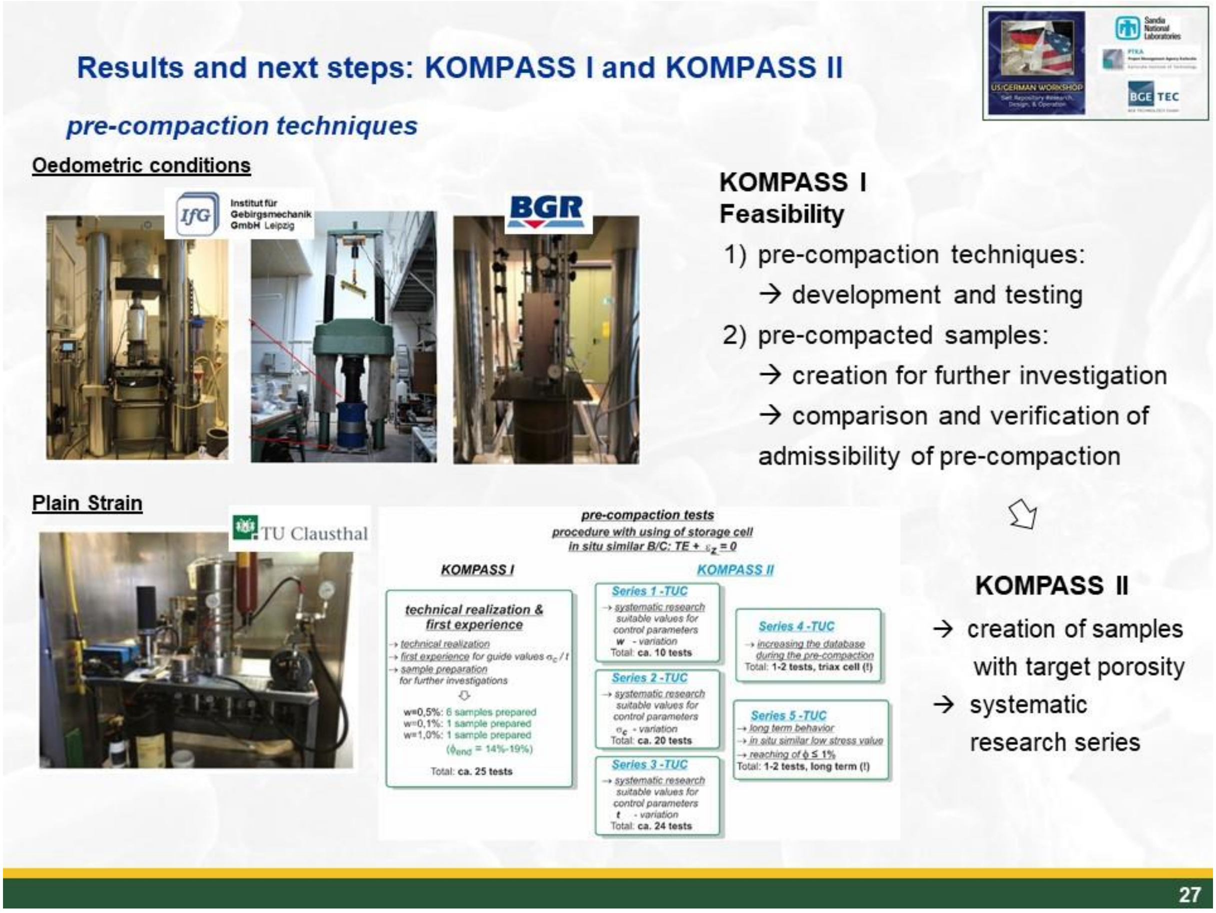
3. Results and next steps: KOMPASS I and KOMPASS II

26


Results and next steps: KOMPASS I and KOMPASS II
pre-compaction techniques
Oedometric conditions
Institut für Gebirgsmechanik GmbH Leipzig
BGR
KOMPASS I
Feasibility
1) pre-compaction techniques:
→ development and testing
2) pre-compacted samples:
→ creation for further investigation
→ comparison and verification of admissibility of pre-compaction
Plain Strain
TU Clausthal
pre-compaction tests
procedure with using of storage cell
in situ similar B/C: TE + εz = 0
KOMPASS I
KOMPASS II
technical realization & first experience
→ technical realization
→ first experience for guide values σc / t
→ sample preparation for further investigations
w=0,5%: 6 samples prepared
w=0,1%: 1 sample prepared
w=1,0%: 1 sample prepared
(φend = 14%-19%)
Total: ca. 25 tests
Series 1 -TUC
→ systematic research suitable values for control parameters
w - variation
Total: ca. 10 tests
Series 2 -TUC
→ systematic research suitable values for control parameters
σc - variation
Total: ca. 20 tests
Series 3 -TUC
→ systematic research suitable values for control parameters
t - variation
Total: ca. 24 tests
Series 4 -TUC
→ increasing the database during the pre-compaction
Total: 1-2 tests, triax cell (!)
Series 5 -TUC
→ long term behavior
→ in situ similar low stress value
→ reaching of φ ≤ 1%
Total: 1-2 tests, long term (!)
KOMPASS II
→ creation of samples with target porosity
→ systematic research series
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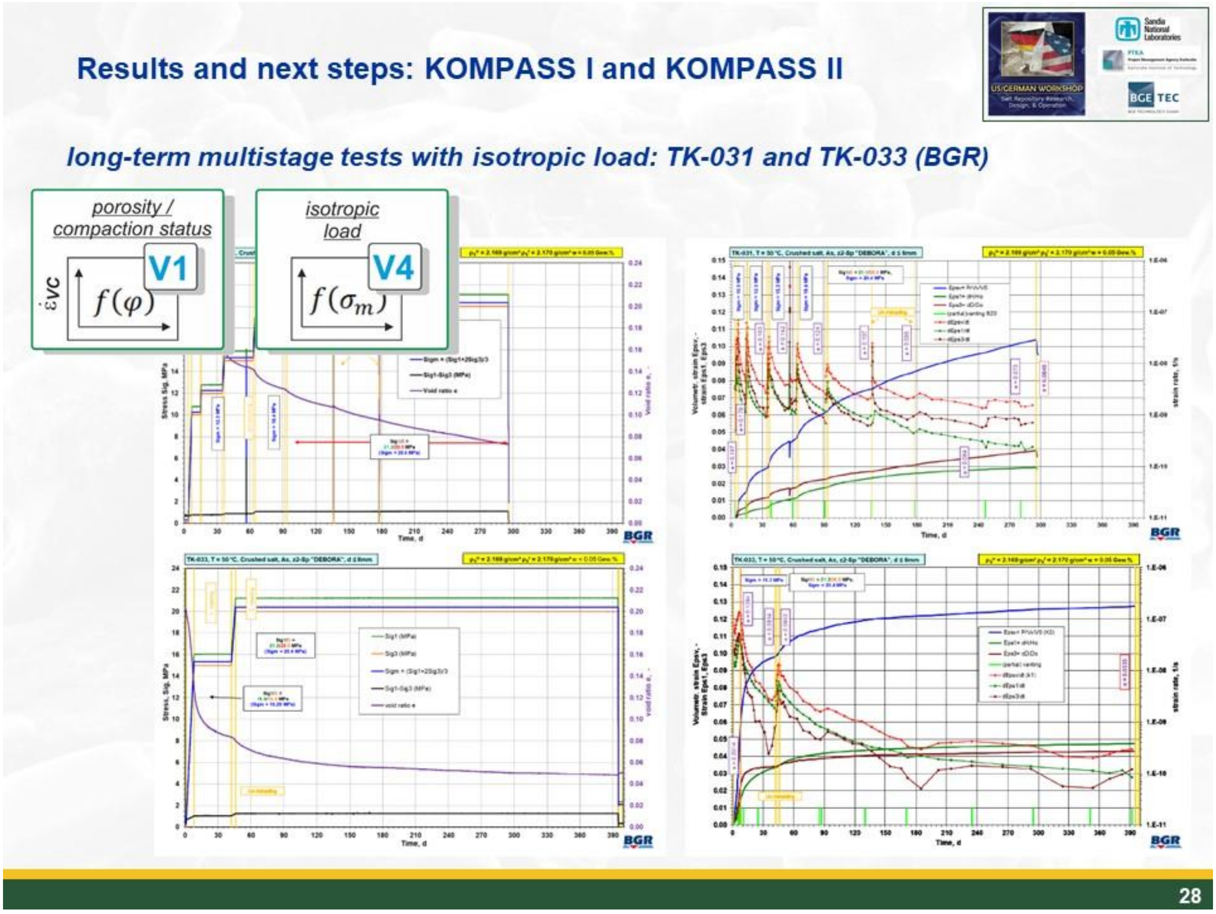
Results and next steps: KOMPASS I and KOMPASS II
long-term multistage tests with isotropic load: TK-031 and TK-033 (BGR)
porosity / compaction status
V1
ε̇vc
f(φ)
isotropic load
V4
f(σm)
Time, d
BGR
US/GERMAN WORKSHOP
Sandia National Laboratories
PTKA
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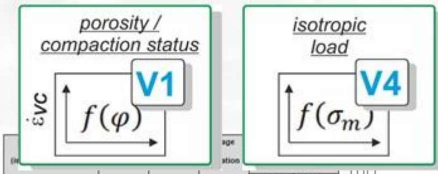
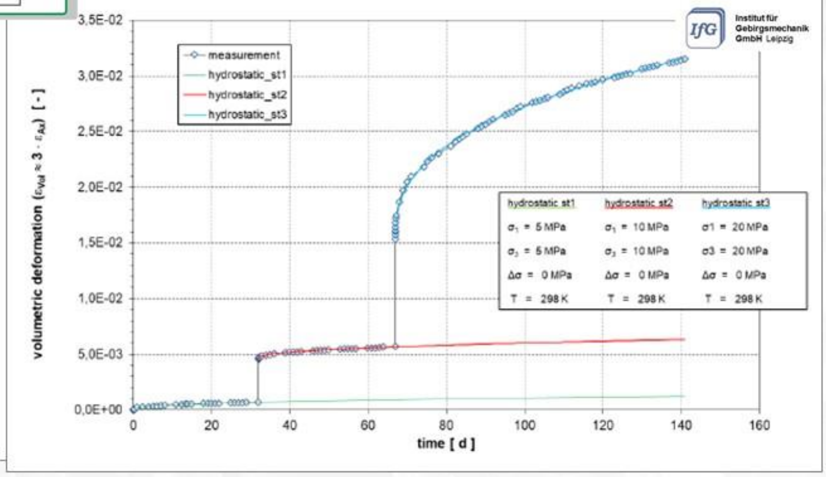
Results and next steps: KOMPASS I and KOMPASS II

long-term multistage tests with isotropic load: 5 tests (IfG)

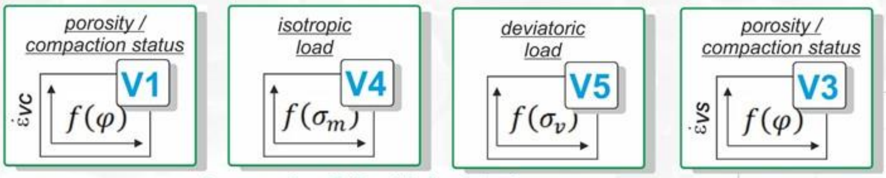


				$\Phi_{initial}$	Φ_{final}
		[MPa]	[d]	[%]	[%]
684/OEDO1/TCC1	dry	5	31.9	14.39	14.32
(25 °C)	dry	10	35.1	13.94	13.82
	dry	20	92.0	13.07	11.09
Total test time: 197 d	+T (60 °C)	20	38.0	-	-
684/OEDO1/TCC2	dry	10	31.9	15.60	15.49
(25 °C)	dry	20	35.1	14.43	12.83
	dry	30	92.0	12.03	7.77
Total test time: 197 d	+T (60 °C)	30	38.0	-	-
684/OEDO1/TCC3	dry	1	31.9	12.90	12.84
(25 °C)	dry	5	35.1	12.24	12.33
	dry	10	92.0	11.90	11.70
Total test time: 197 d	+T (60 °C)	10	38.0	-	-
684/OEDO1/TCC5	wet (1%)	5	31.9	16.00	7.82
(25 °C)	wet (1%)	10	35.1	7.66	3.98
Total test time: 197 d	wet (1%)	20	92.0	4.18	1.36
684/OEDO1/TCC6	wet (1%)	1	31.9	16.21	10.60
(25 °C)	wet (1%)	5	35.1	10.43	5.01
Total test time: 197 d	wet (1%)	10	92.0	4.71	0.88

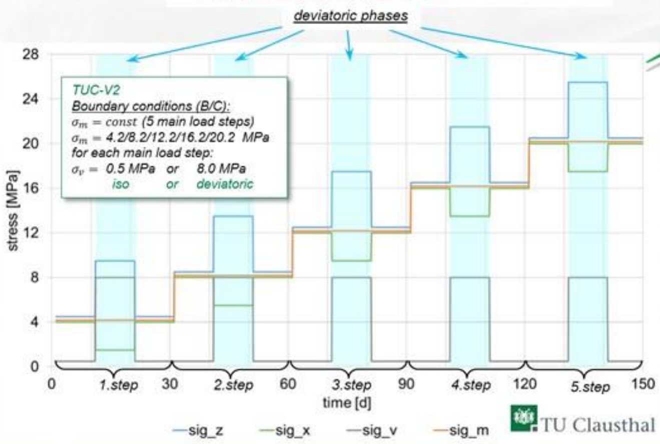


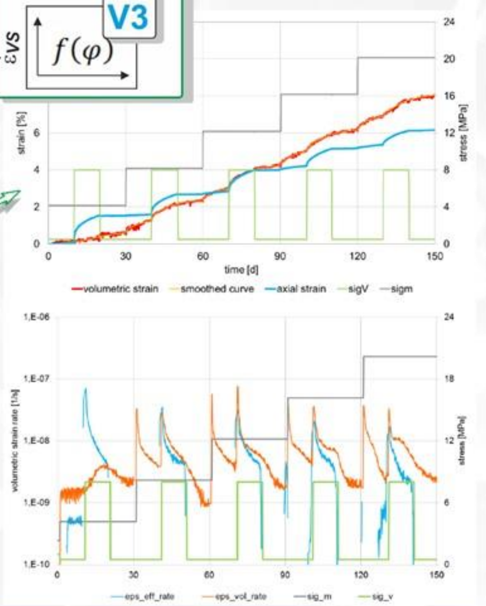
Results and next steps: KOMPASS I and KOMPASS II

long-term multistage test with isotropic and deviatoric load: TUC_V2



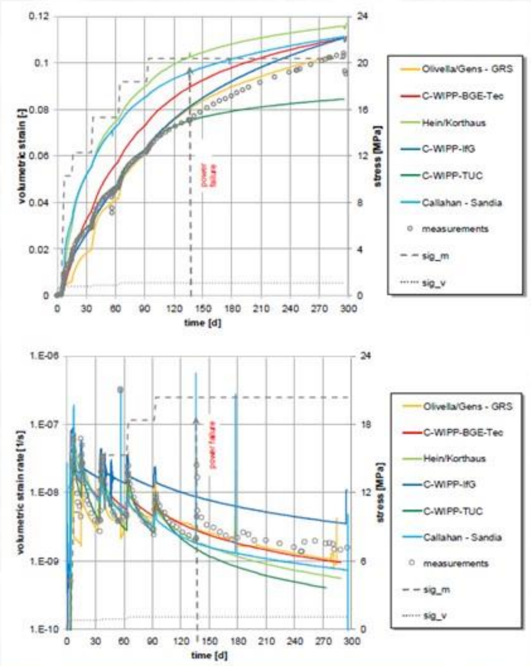
- Innovative B/C with isolated σv
- Measurable influence





Results and next steps: KOMPASS I and KOMPASS II

recalculation results for the multistage isotropic test: TK-031 (BGR)

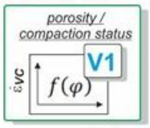


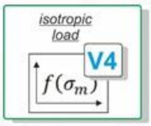
Modelling

Basic functionality/ Qualitative agreement:
All models used here are capable of reproducing
→ reduction of compaction with decrease of porosity
→ increase of compaction with increase of main stress

Realism/ Quantitative Agreement:
Quantitative fit is still improvable in several models
→ Functional relationship
→ Material parameter set

Completeness of the validation:
→ only 2 influence factors: main stress, porosity
→ only in a limited range
σ_m = [0→ [10÷20] →25] MPa
φ = [1→ [17÷7] → 30] %





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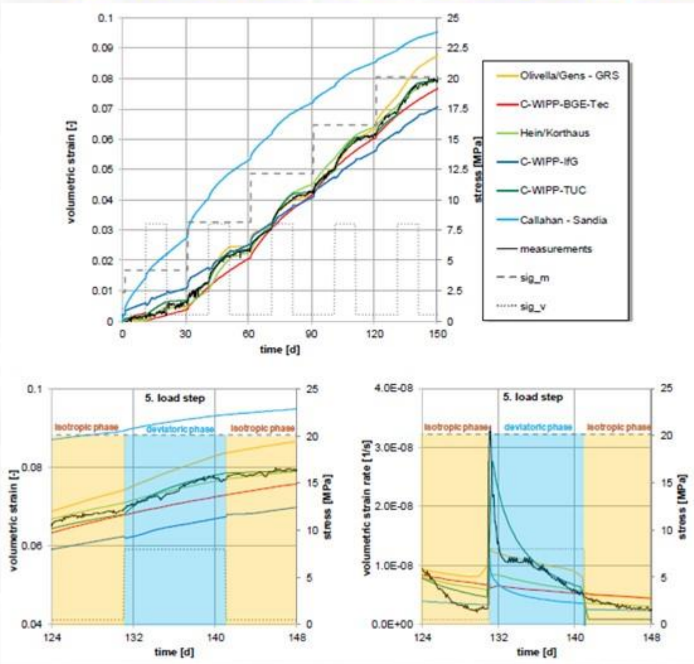
Results and next steps: KOMPASS I and KOMPASS II

recalculation results for the multistage isotropic and deviatoric test: TUC_V2



Modelling

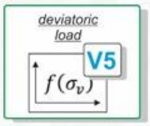
Basic functionality/ Qualitative agreement:
Most models used here are capable of reproducing increase of compaction by activation of deviatoric stress

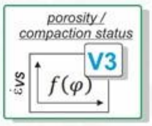
Realism/ Quantitative Agreement:
Quantitative fit is still improvable in several models
→ Functional relationship
→ Material parameter set

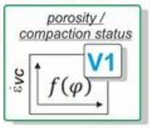
Completeness of the validation:
→ only 3 influence factors: porosity, main, deviatoric stress
→ only in a limited range
σ_m = [0→ [4÷20] →25] MPa
φ = [1→ [17÷9] → 30] %
σ_v = [0 → [8] → 20] MPa

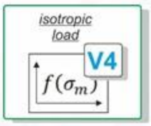
Lab

- **Innovative B/C with isolated σ_v**
- **Measurable influence**

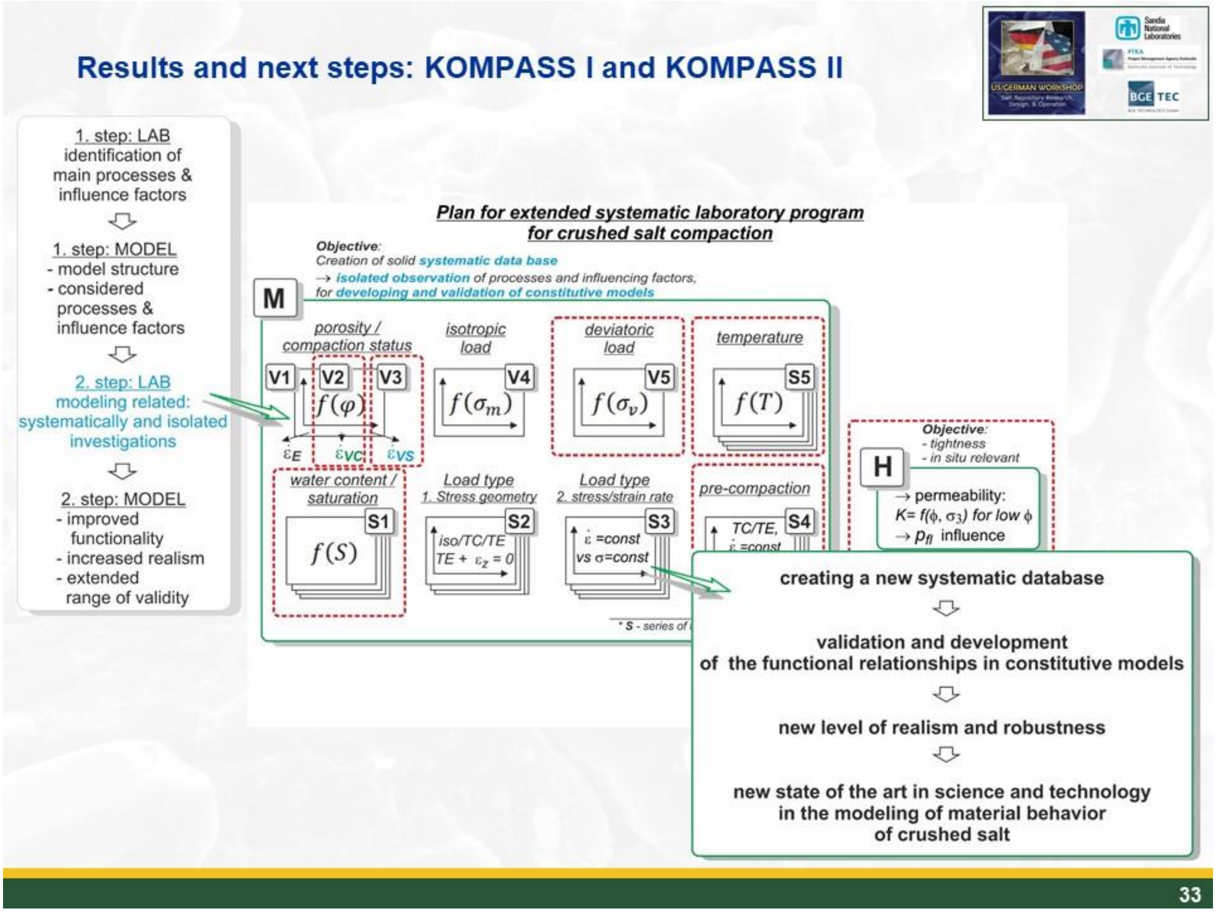








32


Results and next steps: KOMPASS I and KOMPASS II
1. step: LAB
identification of main processes & influence factors
1. step: MODEL
- model structure
- considered processes & influence factors
2. step: LAB
modeling related: systematically and isolated investigations
2. step: MODEL
- improved functionality
- increased realism
- extended range of validity
Plan for extended systematic laboratory program for crushed salt compaction
Objective:
Creation of solid systematic data base
→ isolated observation of processes and influencing factors,
for developing and validation of constitutive models
M
porosity / compaction status
V1 V2 V3
$f(\varphi)$
$\dot\varepsilon_E$ $\dot\varepsilon_{VC}$ $\dot\varepsilon_{VS}$
isotropic load
V4
$f(\sigma_m)$
deviatoric load
V5
$f(\sigma_v)$
temperature
S5
$f(T)$
water content / saturation
S1
$f(S)$
Load type
1. Stress geometry
S2
iso/TC/TE
TE + ε_z = 0
Load type
2. stress/strain rate
S3
$\dot\varepsilon$ =const
vs σ=const
pre-compaction
S4
TC/TE,
Objective:
- tightness
- in situ relevant
H
→ permeability:
K= f(ϕ, σ3) for low ϕ
→ p_{fl} influence
creating a new systematic database
validation and development
of the functional relationships in constitutive models
new level of realism and robustness
new state of the art in science and technology
in the modeling of material behavior
of crushed salt
US/GERMAN WORKSHOP
33


Plan for extended systematic laboratory program
for crushed salt compaction
M
porosity / compaction status
V1 V2 V3
$f(\varphi)$
isotropic load
V4
$f(\sigma_m)$
deviatoric load
V5
$f(\sigma_v)$
temperature
S5
$f(T)$
water content / saturation
S1
$f(S)$
Load type
1. Stress geometry
S2
iso/TC/TE
TE + ε_z = 0
Load type
2. stress/strain rate
S3
$\dot\varepsilon$ =const
vs σ=const
pre-compaction
S4
TC/TE,
$\dot\varepsilon$ =const
vs σ=const
* S - series of tests, V - individual test
Thank you
for your attention
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH
GRS
PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie
Supported by:
Federal Ministry
for Economic Affairs
and Energy
on the basis of a decision
by the German Bundestag
IfG Institut für Gebirgsmechanik GmbH Leipzig
TU Clausthal
BGR
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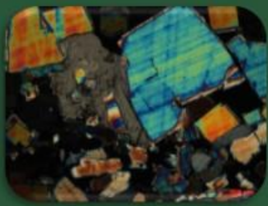


11th US/German Workshop on Salt Repository Research, Design, and Operation

The KOMPASS project – Future work of relevance for LTS

L. Friedenberg, O. Czaikowski, J. Wolf

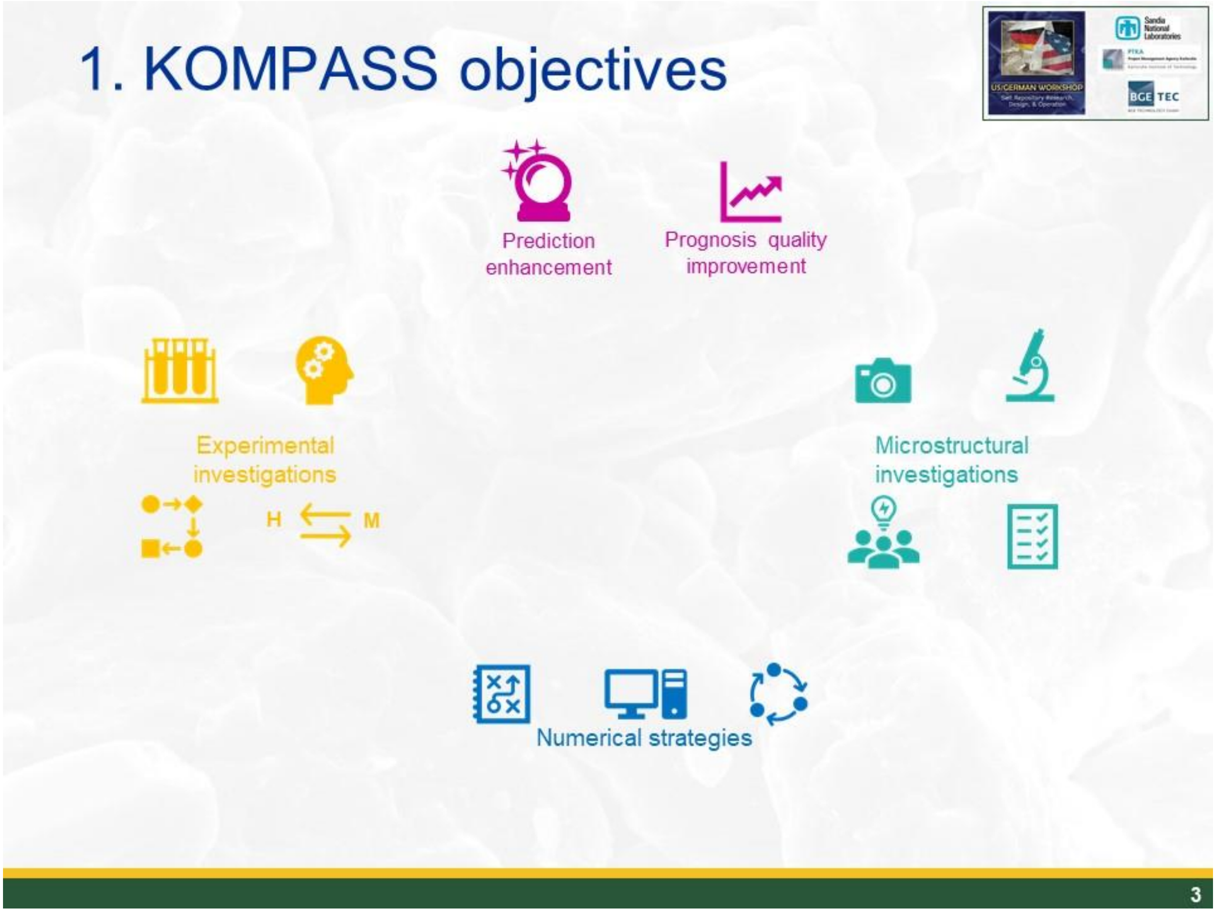
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)

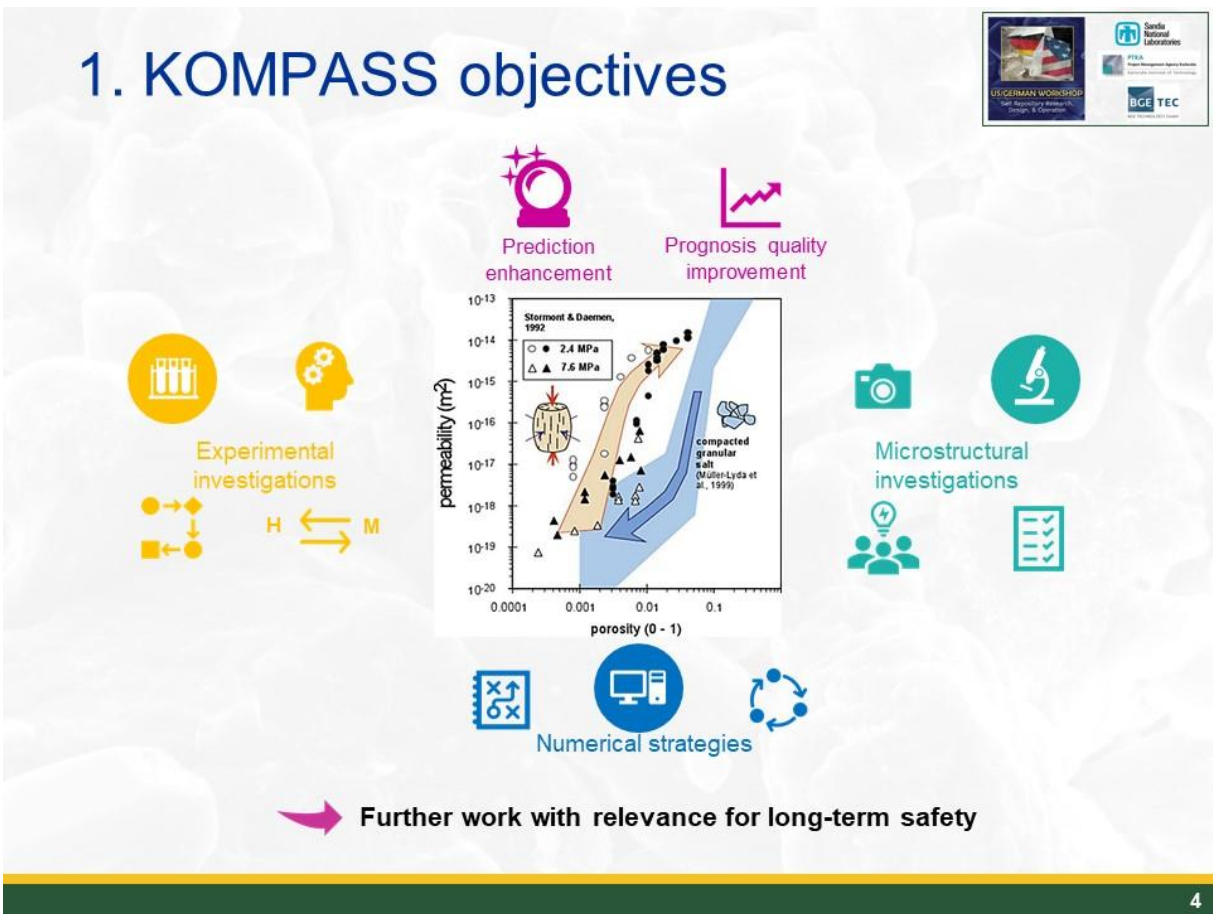
Part 2 of the online workshop
June 17, 2021

Outline

1. KOMPASS objectives
2. Requirements for long-term safety
3. KOMPASS future

2


1. KOMPASS objectives
Prediction enhancement
Prognosis quality improvement
Experimental investigations
H
M
Microstructural investigations
Numerical strategies
3


1. KOMPASS objectives
Prediction enhancement
Prognosis quality improvement
Experimental investigations
H
M
Microstructural investigations
Stormont & Daemen, 1992
2.4 MPa
7.6 MPa
compacted granular salt (Müller-Lyda et al., 1999)
permeability (m²)
porosity (0 - 1)
Numerical strategies
Further work with relevance for long-term safety
4

2. Requirements for LTS
(DECOVALEX 2023 TASK F)

- Staged model development to build up to a full PA
  1. Flow + radionuclide mobilization and transport
  2. + drift convergence (**salt creep and backfill consolidation**)
  3. + heat flow and temperature-dependence of drift convergence
  4. + model uncertainty in **backfill consolidation model**
  5. (+ gas generation)

- ➢ Experimental basis: porosity vs. permeability relationship
- ➢ Physical equation: permeability derivative with time
- ➢ Implementation and application for LTS modelling

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3. KOMPASS future

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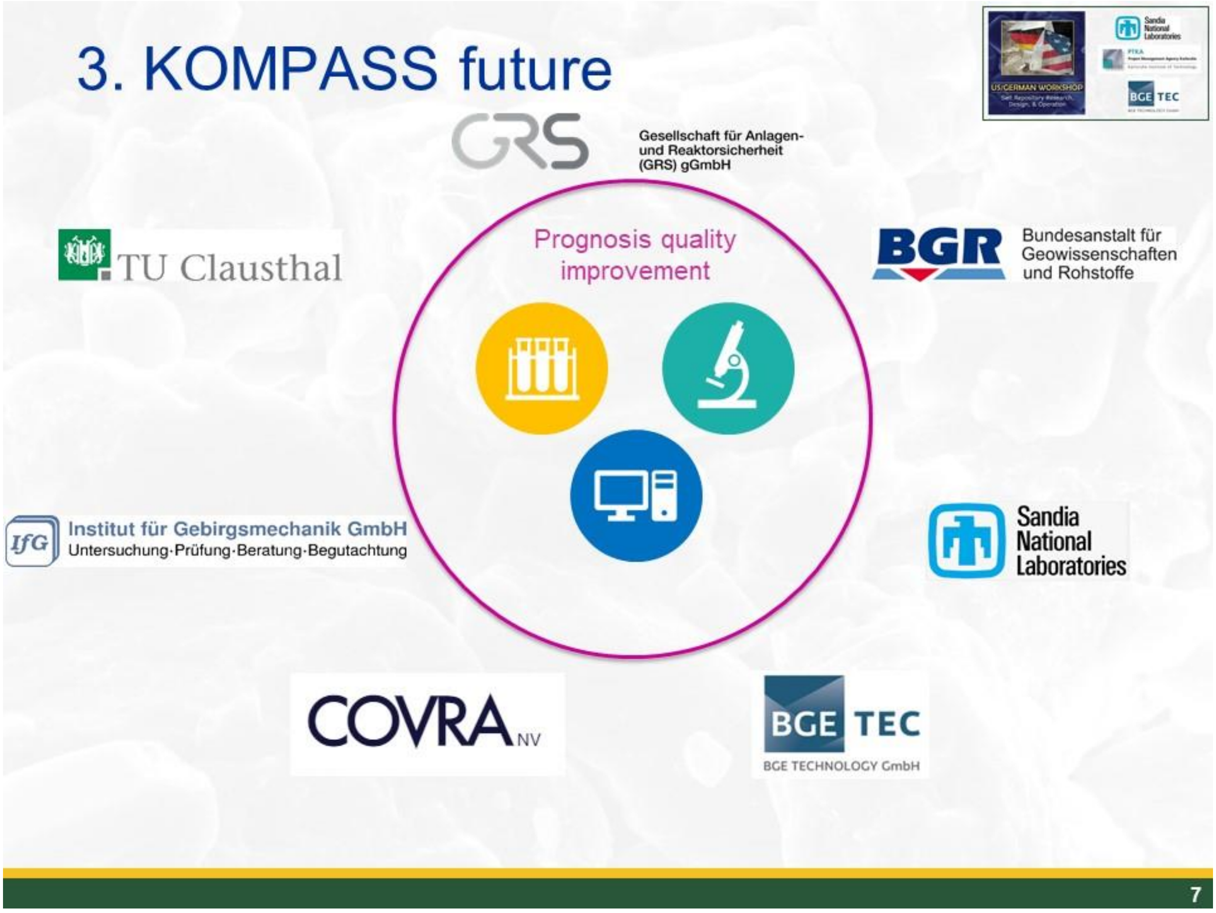
3. KOMPASS future
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
TU Clausthal
Prognosis quality improvement
BGR Bundesanstalt für Geowissenschaften und Rohstoffe
Institut für Gebirgsmechanik GmbH
Untersuchung·Prüfung·Beratung·Begutachtung
Sandia National Laboratories
COVRA NV
BGE TEC
BGE TECHNOLOGY GmbH
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Thank you
BGE TEC
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Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag
Attended by:
PTKA Projektträger Karlsruhe
Karlsruher Institut für Technologie
U.S. DEPARTMENT OF ENERGY
Emily Stein for the excellent support
… for you attention!
8


Investigations on in-situ material behavior of matrix-stabilized crushed rock salt backfill under consideration of different filling technologies
– Review of the GESAV II Project –
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH
Stefan Pötzsch (Presenter)
TU Bergakademie Freiberg (until April 30, 2021)
Prof. Dr. Helmut Mischo (Project Leader)
TU Bergakademie Freiberg
Part 2 of the online workshop
June 17, 2021
11th US/German Workshop on Salt Repository Research, Design, and Operation


Investigations on in-situ material behavior of matrix-stabilized crushed rock salt backfill under consideration of different filling technologies
– Review of the GESAV II Project
Agenda
▪ GESAV-Material – Approach / Application
▪ Underground Test Site and Measurement Technology
▪ Suitable Filling Technologies and their Adaption
▪ Results of the Underground Tests
▪ Summary and Outlook
2

Approach and Application

Crushed Rock Salt (dry or wet)

+ Easily available / characteristic
+ Simple backfilling methods

- No initial load bearing capacity
- High initial porosity

Building Materials (e.g. salt-concrete)

+ No settlements
+ Low initial porosity

- Complex processing methods
- Long-term cement stability

GESAV-Material

+ Characteristic for salt formations
+ Early load bearing capacity
+ Favorable porosity development
+ Low brine content (< 4 M.-%)
+ High filling progress

Repository concept - salt ⇒ *Benefits* ⇐

➢ Stabilisation of underground openings = minimisation of the EDZ-development

➢ Qualified and fast back filling of access drifts = support of waste retrieval

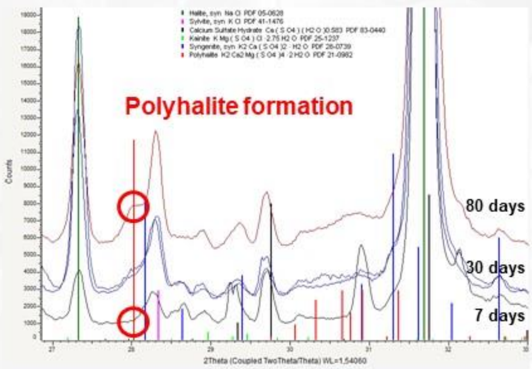
Review of the GESAV II Project 3

Chemical Composition of GESAV-Material

Rock salt – NaCl: 85 %

Salt binder: 15 %

- $CaSO_4 \cdot 0{,}5\ H_2O$
- Kieserite – $MgSO_4 \cdot H_2O$
- K_2SO_4
- $MgCl_2$-H_2O brine



Formation of **Polyhalite $K_2Ca_2Mg(SO_4)_4 \cdot 2\ H_2O$**
(via Syngenite and Kainite)

➢ Polyhalite is long-term stable (thermo-dynamically stable) in the hexanary oceanic salt system

Review of the GESAV II Project 4

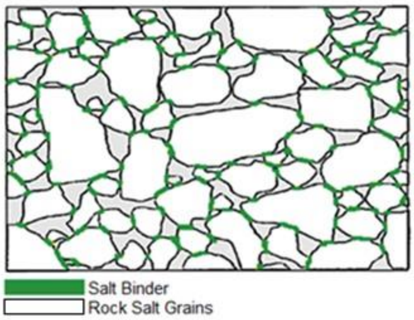
Structure of the GESAV-Material

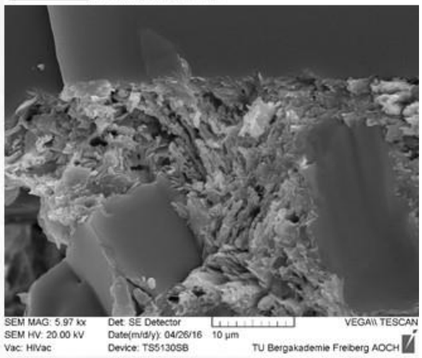
- Optimized crushed rock salt fractions (85 %)
- Max. grain size of 14 mm
- Moisture content 3,75 %

➢ Moistened bulk material

- Salt binder forms polyhalite-bridges on the contact surfaces of the rock salt grains

➢ Matrix-stabilization, no gap filling

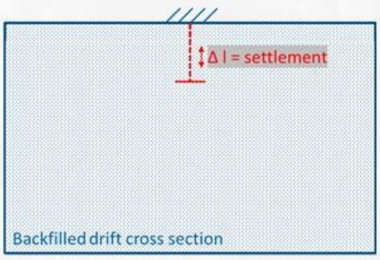


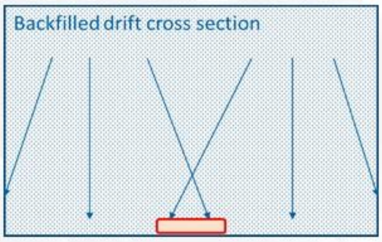


Experimental Approach

Relevant Material Parameters

Time dependent settlement	Load bearing capacity	Integral permeability





In situ Measurement Systems

Settlement sensor

Earth pressure sensor

Flow-through installation

Not visible:

- Moisture & temperature sensors
- 3D-Laserscans
- Convergence measurements

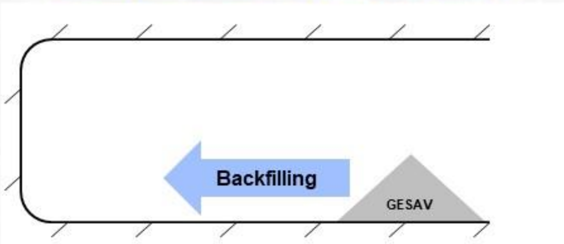
Review of the GESAV II Project 7

Filling Technologies in Salt Mining

Pneumatic Stowing
Hydraulic fill
Paste fill
Dump fill
Slinger fill
Push fill
Stack fill

➢ **4 Mock-Up tests:**
salt mine Sondershausen

GESAV-Material before backfilling



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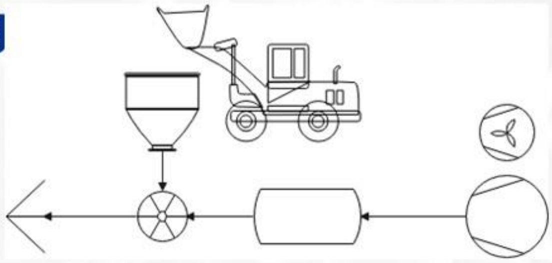
(1) Pneumatic Stowing

- Adapted shotcrete machine
- Compressor with pressure vessel
- Additional Feeding hopper
- Mobile Loader
- Fan (Dust)



https://www.wernermader.de/cms/de/betonsanierung/trockenspritzen

9

https://www.swisstruck.ch/surf_detail.php?occasion=SPRA789_1078333

(2) Slinger Fill

- Adapted slinger machine
- Load-Haul-Dump machine

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(3a) Push Fill

- Dam-construction machine (based on LHD & scaler)
- Load-Haul-Dump machine

https://www.lmbv.de/index.php/verwahrungsmanagement.html

11

(3b) Push Fill & Vibratory Compaction

- Small loader
- Attachment vibratory plate

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Material proof

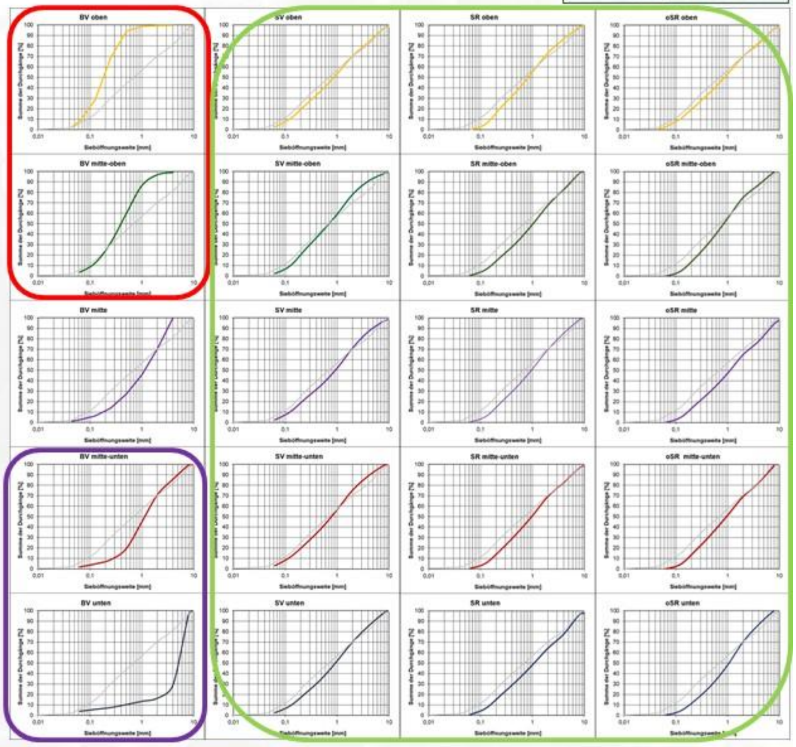
Grain Size Distribution

(1) Pneumatic Stowing:

- Fine grain surplus in the upper parts of the backfill body
- Coarse grain surplus in the lower parts of the backfill body

All other technologies:

- Grain size distribution close to target



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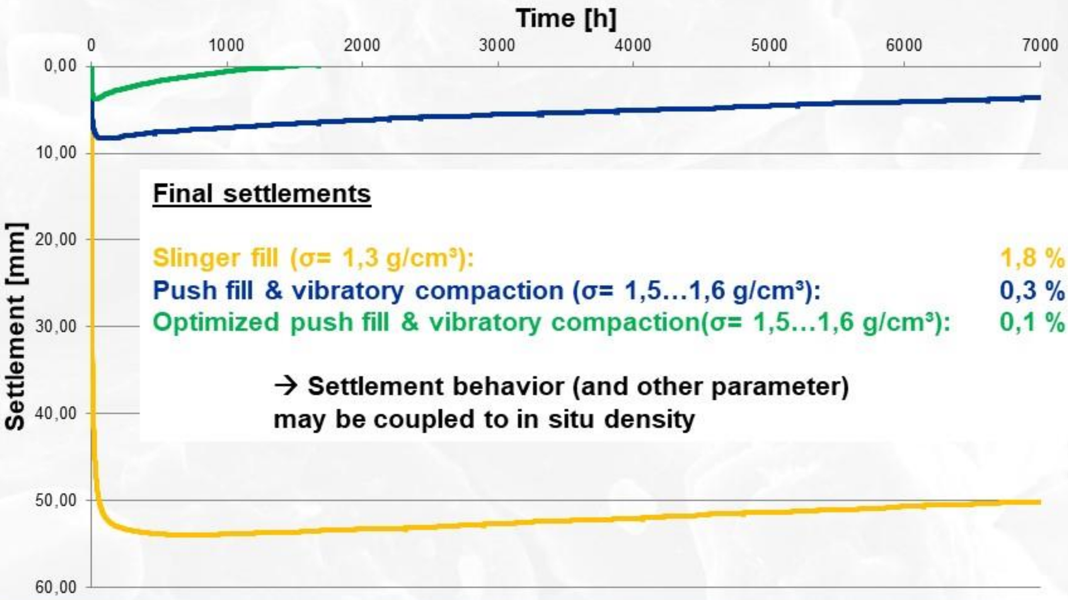
Time dependent settlement



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Sampling

- Hammer drill
- Chainsaw

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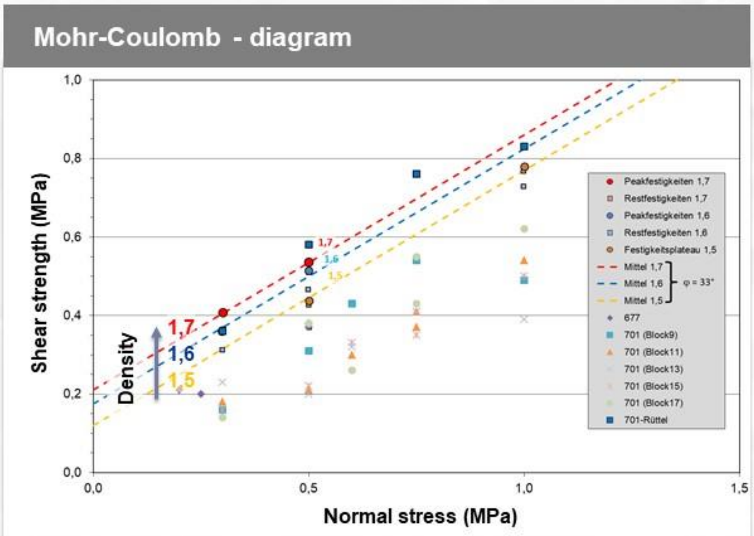
Shear strength

- Confirmation of the results of prior testing of laboratory samples
- Shear strength depends on the material density

Push fill & vibratoy compaction:

c = 0,21 MPa

φ = 34°



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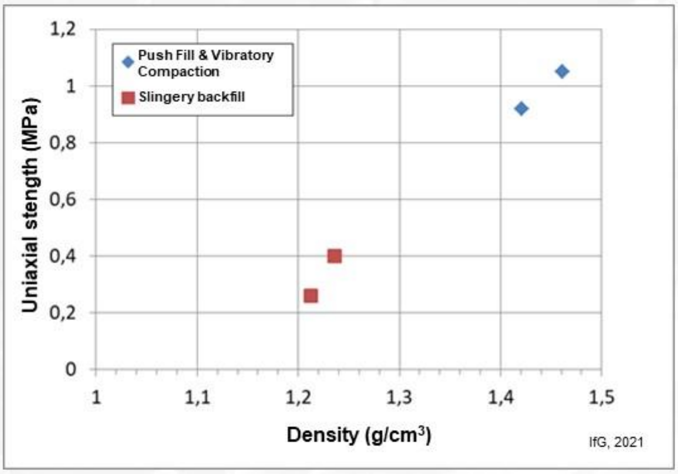
Uniaxial compressive strength

- Also clear dependence on the material density
- Max. approx. 1,1 MPa



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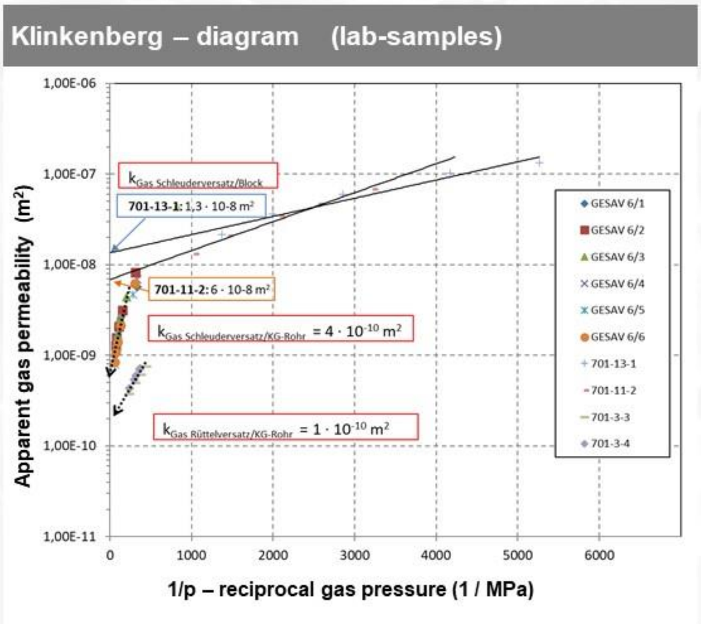
Gas-Permeability

- Slinger fill:
  k_{Gas}: $4 \cdot 10^{-10}$ m²
- Push fill & vibratory compaction
  k_{Gas}: $1 \cdot 10^{-10}$ m²



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Lessons learned

- **Requirements on the filling technology**:
  - Guarantee of uniform material properties during filling process
  - **Achieving of a high material density!**

  → *Push fill & vibratory compaction techniques are identified as the most suitable filling technology for bulk-like backfill materials in HAW-Repositories in Salt formations*

- **Characterisation of material properties** (lab & in situ):
  - A comprehensive understanding of binding processes exist
  - Parameters of the load bearing capacity (e.g. strength, settlement) for GESAV-Material are determined
  - Permeability values of backfill samples exist,

    but the integral permeability of the system (backfill – roof void – EDZ) has to be further investigated

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Outlook

- **Application** in future backfill operations:
  - Gain of technical experience for choice of the best filling technology
  - **Improvement of the emplacement technology:** Combination of pushing & compaction in one machine

- **Follow-Up R&D-Project „SAVER":**
  - Comparison of backfill bodies made of **conventional crushed rock salt** and **GESAV-Material** regarding the scope of application in future HAW-Repositories
  - Influence of the backfill material on waste retrieval

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THANKS TO THE GESAV II PROJECT TEAM!

TU BERGAKADEMIE · FREIBERG ·

GSES Glückauf Sondershausen Entwicklungs- und Sicherungsgesellschaft mbH

IfG

Project Team:

Stefan Pötzsch; Ute Fliege; Ronny Jentzsch; Matthias Gruner; George Barakos; Helmut Mischo; Regina Moßig; Melanie Pannach; Iris Paschke; Daniela Freyer; Till Popp; Michael Wiedemann; Christopher Rölke; Thomas Kießling; Christian Baum

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THANK YOU FOR YOUR ATTENTION.

GLÜCKAUF!

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Appendix C – Program and Presentations of Part 3 (8th September 2021)

Berlin time		8th September 2021 – Part 3	
16:00	16:10	Welcome by the organizers	K. Kuhlman/SNL P. Herold/BGE TEC
EBS, Materials and Backfilling Chair: P. Herold			
16:10	16:40	Development of methods for evaluating the properties of backfilling and sealing materials taking into account corrosion	R. Gholami, M. Heidmann-Ruhz, F. Rempel (all BGE)
16:40	17:10	ELSA - Bitumen and asphalt sealing elements for shaft seals - results of borehole tests and conclusions for the sealing concept	J. Aurich/TU Freiberg
17:10	17:40	Investigation of T-H-M-C processes on sealing systems in rock salt	T. Meyer/GRS
17:40	17:50	10 min Break	
17:50	18:20	Clay seam laboratory testing	S. Sobolik/SNL
18:20	18:50	STROEFUN III - Fluidic functional verification for closuring structures and fluid-supported sealing of the contact area	J. Bauermeister/TU Clausthal
18:50	19:00	Summary and Outlook	K. Kuhlman/SNL P. Herold/BGE TEC

Development of methods for evaluating the properties of backfilling and sealing materials taking into account corrosion

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

Sandia National Laboratories

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

BGE TEC
BGE TECHNOLOGY GmbH

R. Gholami, F. Rempel, M. Heidmann-Ruhz
BGE, EMO-SL.3

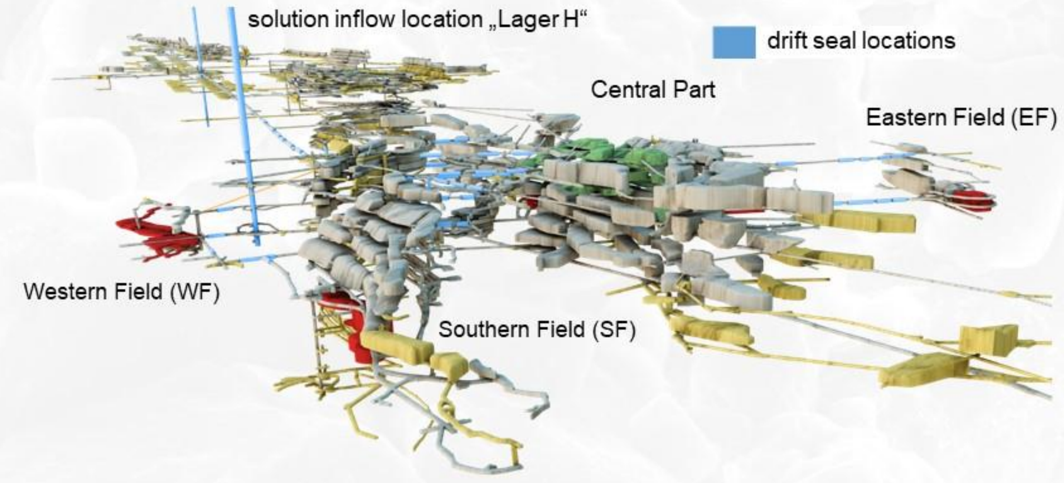
Part 3 of the online workshop
September 8, 2021

Content

1. Introduction
2. Corrosion
3. Challenges in assessing corrosion
4. Selected materials for drift seals

2

Morsleben Repository (ERAM)
Closure Concept and Sealing Measures



- **Extensive backfilling of excavations ~5 million m³ salt concrete**
- 2 shaft seals
- 24 (rock salt) + 1 (anhydrite) drift seals in Bartensleben and Marie
- Ca. 100 borehole seals

3

Material groups for drift seals
considered in the closure concept ERAM

Salt concrete | **MgO-material** | **Bitumen**

Mass concrete | **Mass concrete** | **Shotcrete**

- Sufficient long-term stability in salt environment (solution composition at the respective sealing site)
- Compatibility with the host rock (Saline)
- Low permeability
- Sufficient strength and stiffness
- At least constant volume (no shrinkage), otherwise if necessary combination with injection material
- Handling should not be to complex
- Combination of material groups possible

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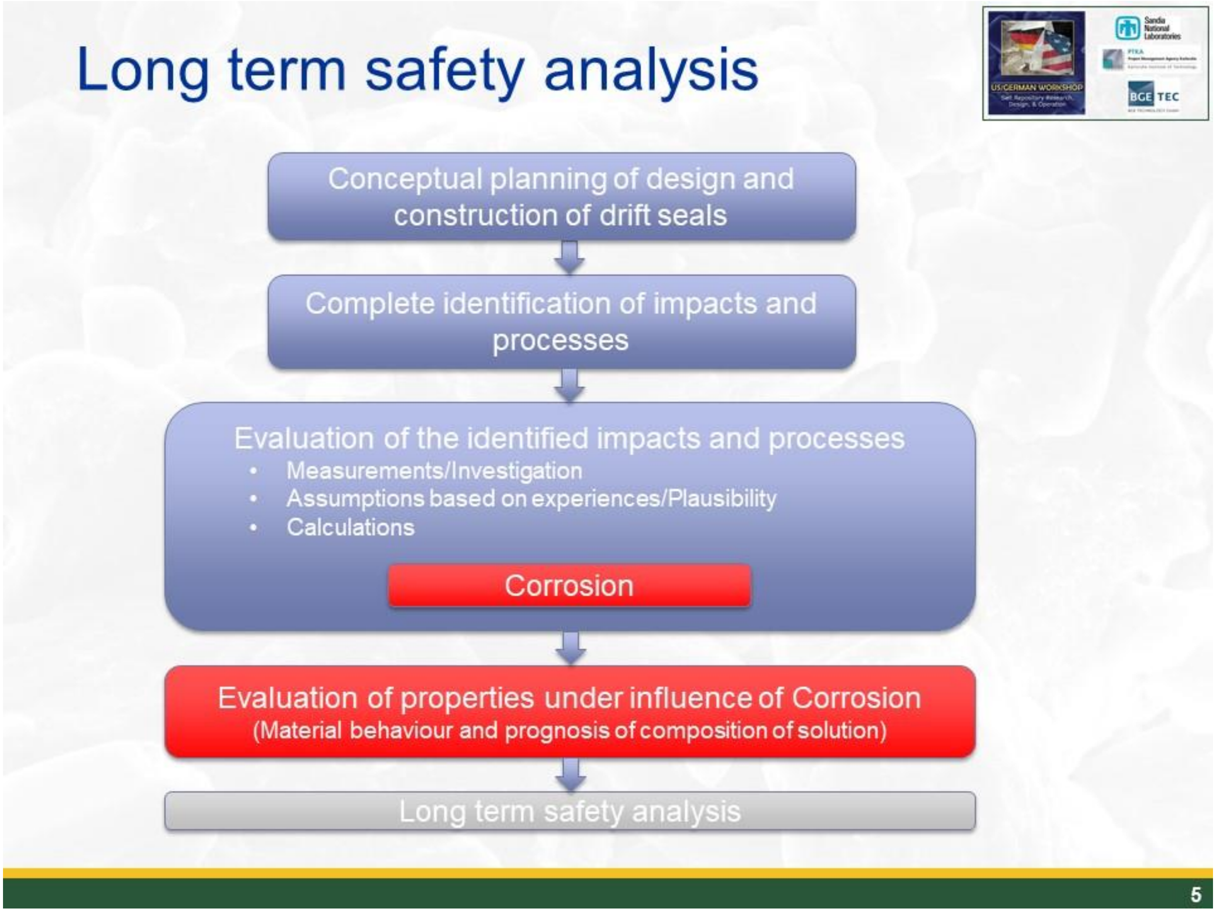
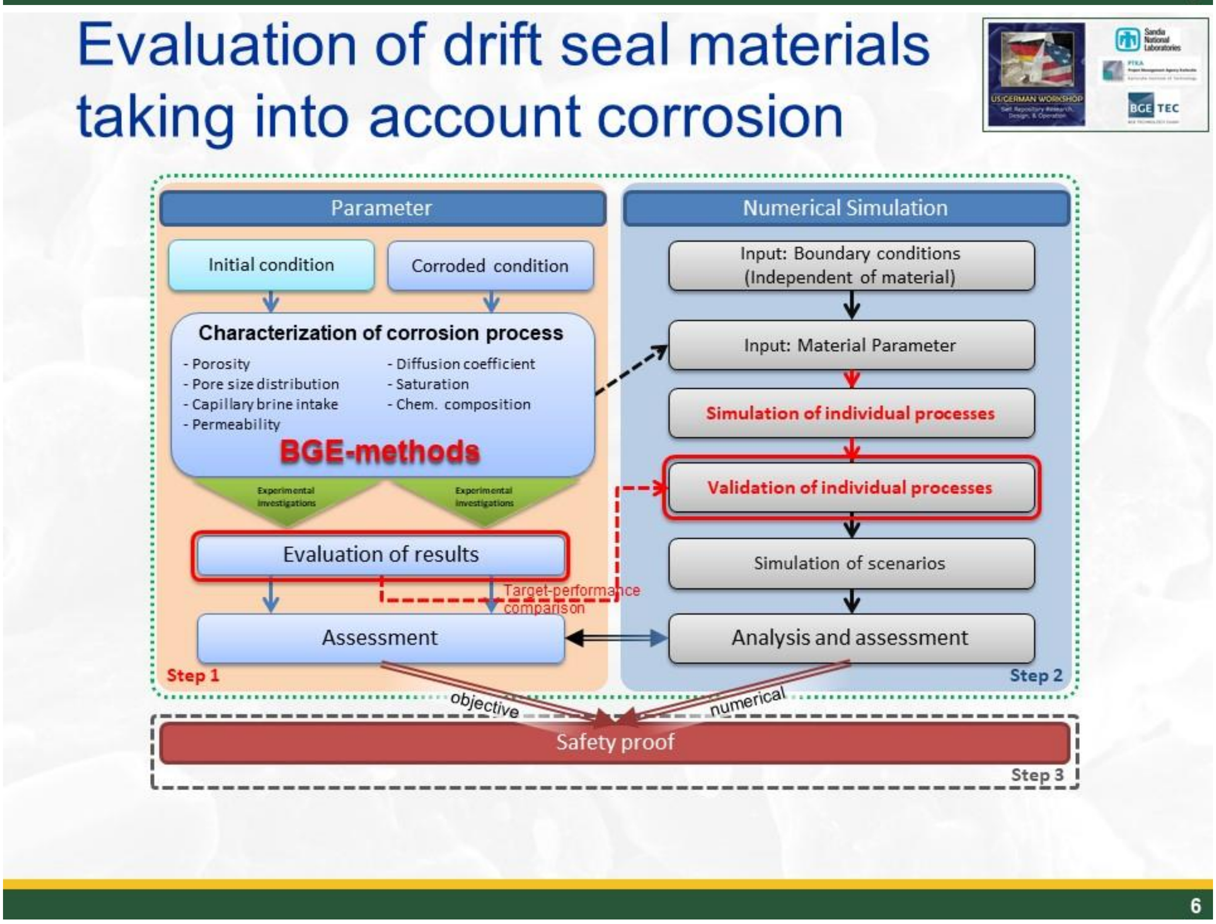

Long term safety analysis
US/GERMAN WORKSHOP
Sandia National Laboratories
PTKA
BGE TEC
Conceptual planning of design and construction of drift seals
Complete identification of impacts and processes
Evaluation of the identified impacts and processes
• Measurements/Investigation
• Assumptions based on experiences/Plausibility
• Calculations
Corrosion
Evaluation of properties under influence of Corrosion
(Material behaviour and prognosis of composition of solution)
Long term safety analysis
5


Evaluation of drift seal materials taking into account corrosion
US/GERMAN WORKSHOP
Sandia National Laboratories
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BGE TEC
Parameter
Initial condition
Corroded condition
Characterization of corrosion process
- Porosity
- Pore size distribution
- Capillary brine intake
- Permeability
- Diffusion coefficient
- Saturation
- Chem. composition
BGE-methods
Experimental investigations
Experimental investigations
Evaluation of results
Target-performance comparison
Assessment
Step 1
Numerical Simulation
Input: Boundary conditions (Independent of material)
Input: Material Parameter
Simulation of individual processes
Validation of individual processes
Simulation of scenarios
Analysis and assessment
Step 2
objective
numerical
Safety proof
Step 3
6

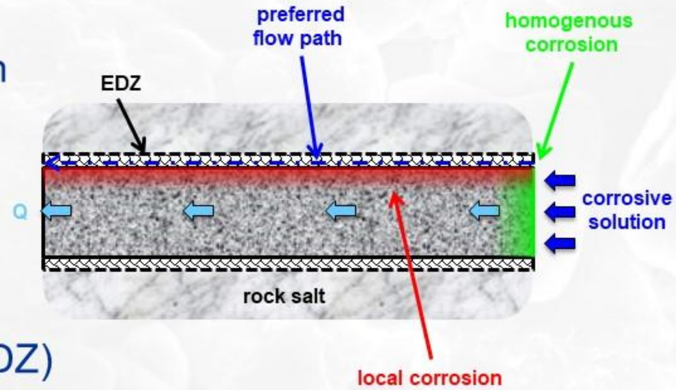
Why can corrosion be important?

1. Homogenous corrosion
- No preferred flow path
- Plane corrosion

⇒ Slow, no issue

2. Local corrosion
- Preferred flow path (EDZ)
- Mass transport is deciding, not flow rate
- Higher permeability + lower porosity
- Much higher flow velocity
- Process can be exponential

⇒ Reality: Mixture of both concepts



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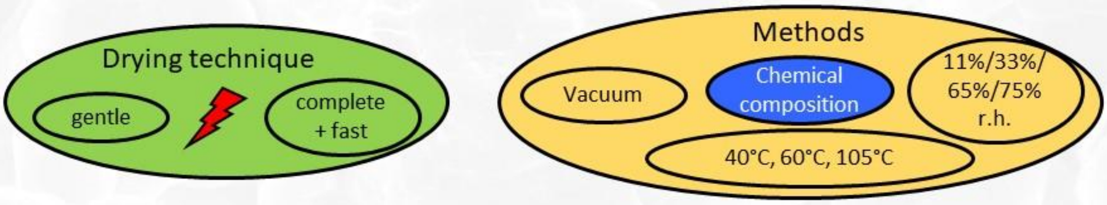
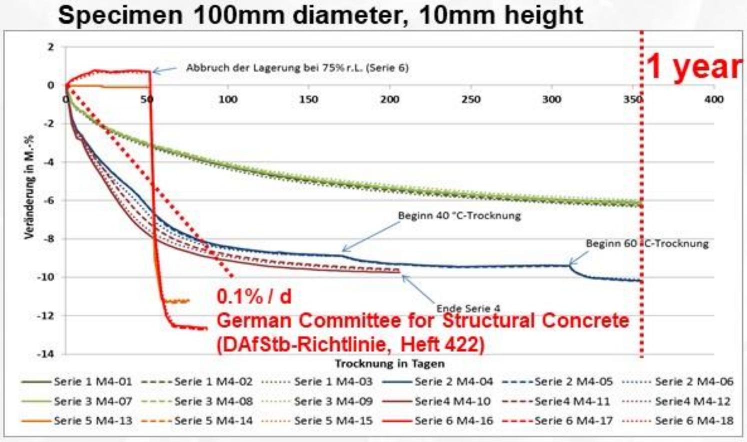
Sample preparation: Drying



⇒ Development of methods

⇒ Additional measurements

Specimen 100mm diameter, 10mm height



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Sample preparation: Summary

- Drying (in progress)
  - Salt precipitations unavoidable (solution can‘t be displaced)
- Saturation (in progress)
  - Interactions between solution and material unavoidable

⇒ Measurements without (unwanted) material changes not possible

⇒ Affects almost all measurements of corrosion parameters

⇒ Plausibility check

⇒ Validation/cross check

⇒ Measurements are really substantial and complex

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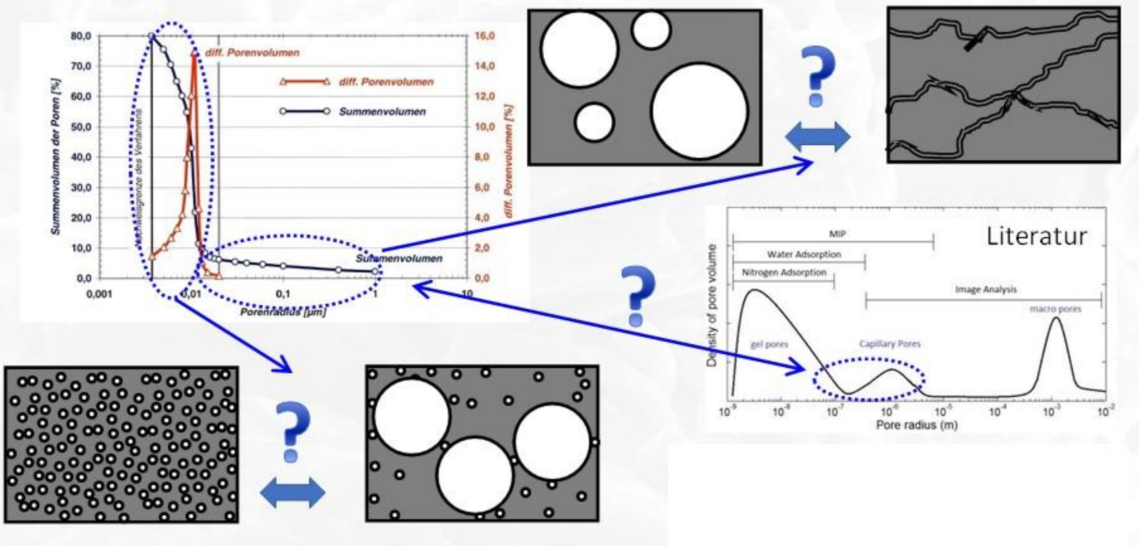
Structure analysis - Background



- Goal: Visualization of structure from nm to mm
- Not possible with one method

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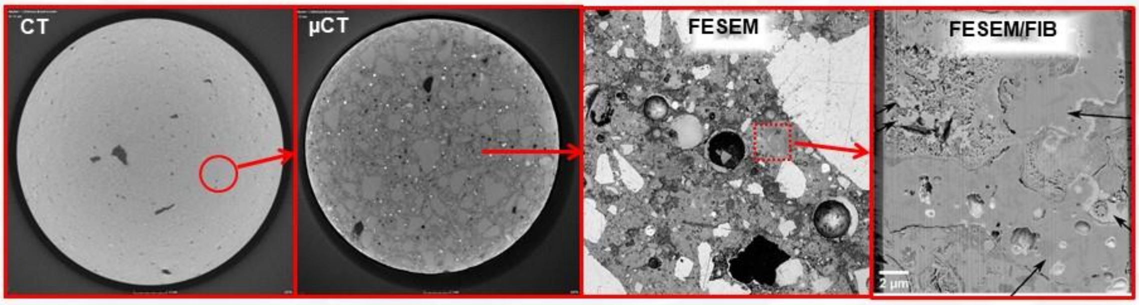
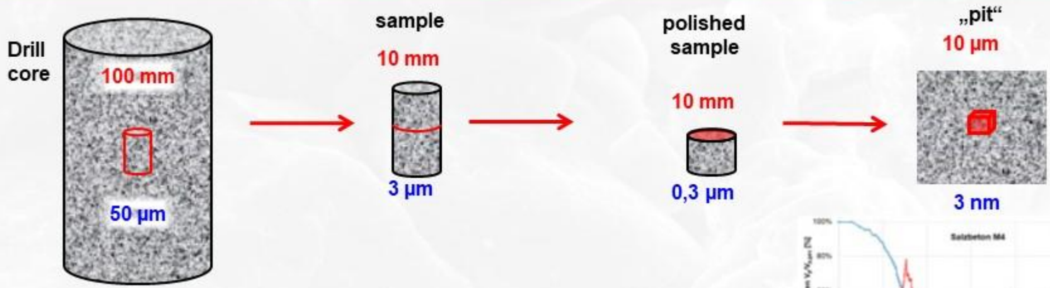
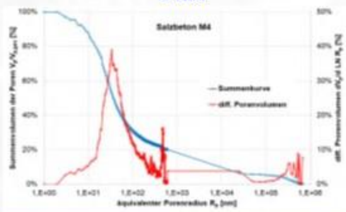
Structure analysis - Procedure



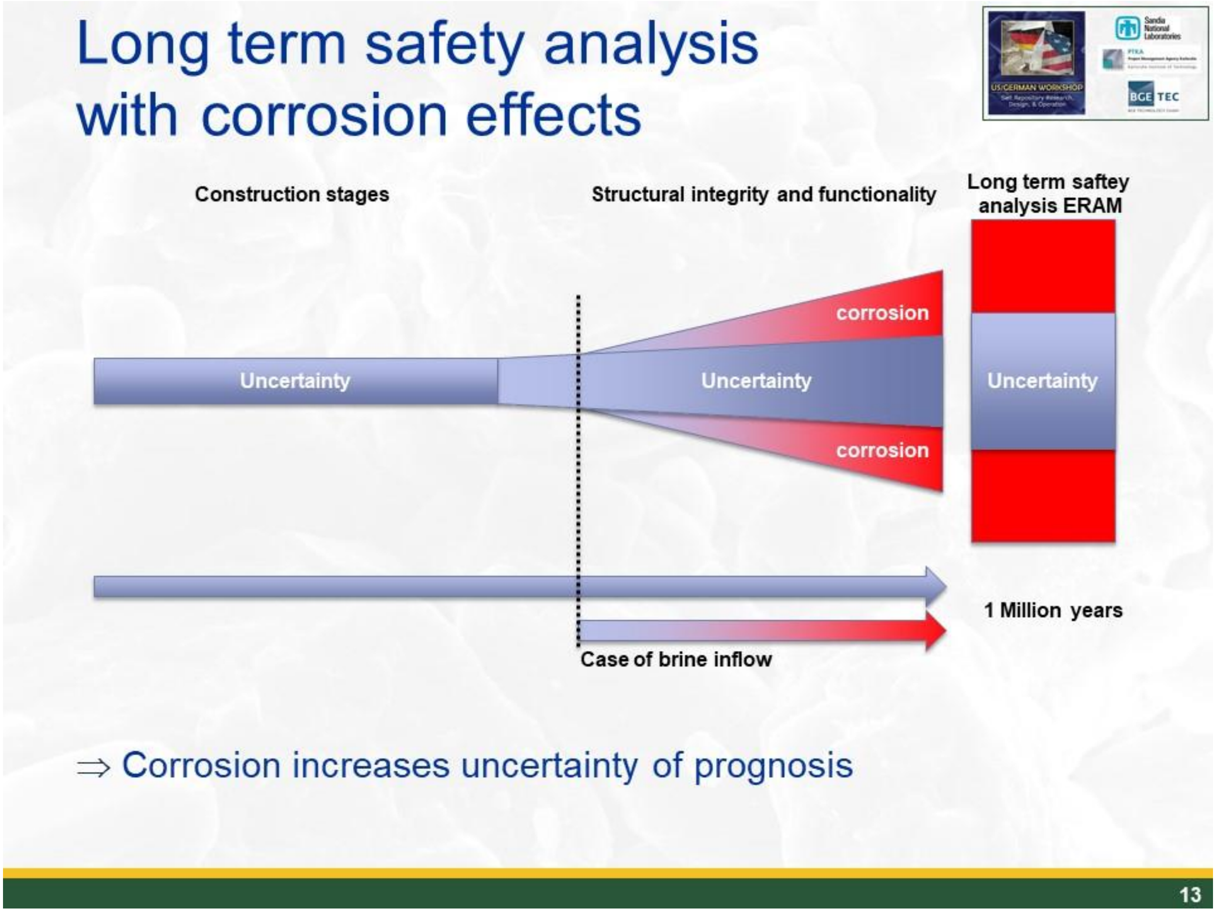


- Combination + connecting of 4 methods
- Pore distribution + EDX



Summary - corrosion

- Prognosis of corrosion is highly challenging:
  - Unwanted material changes
  - Additional investigations
    - Develop methods
    - Validation (results and software)
    - Understanding of corrosion
  - Long term experiments (sealing material)
- Further challenges
  - Permeability measurement (low flow + material changes)
  - Parameter changes due to corrosion
  - Diffusion
  - Simulation (including validation)
- Conclusion: Avoid corrosion, if you can ✓


Long term safety analysis
with corrosion effects
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Construction stages
Structural integrity and functionality
Long term saftey analysis ERAM
corrosion
Uncertainty
Uncertainty
Uncertainty
corrosion
1 Million years
Case of brine inflow
⇒ Corrosion increases uncertainty of prognosis
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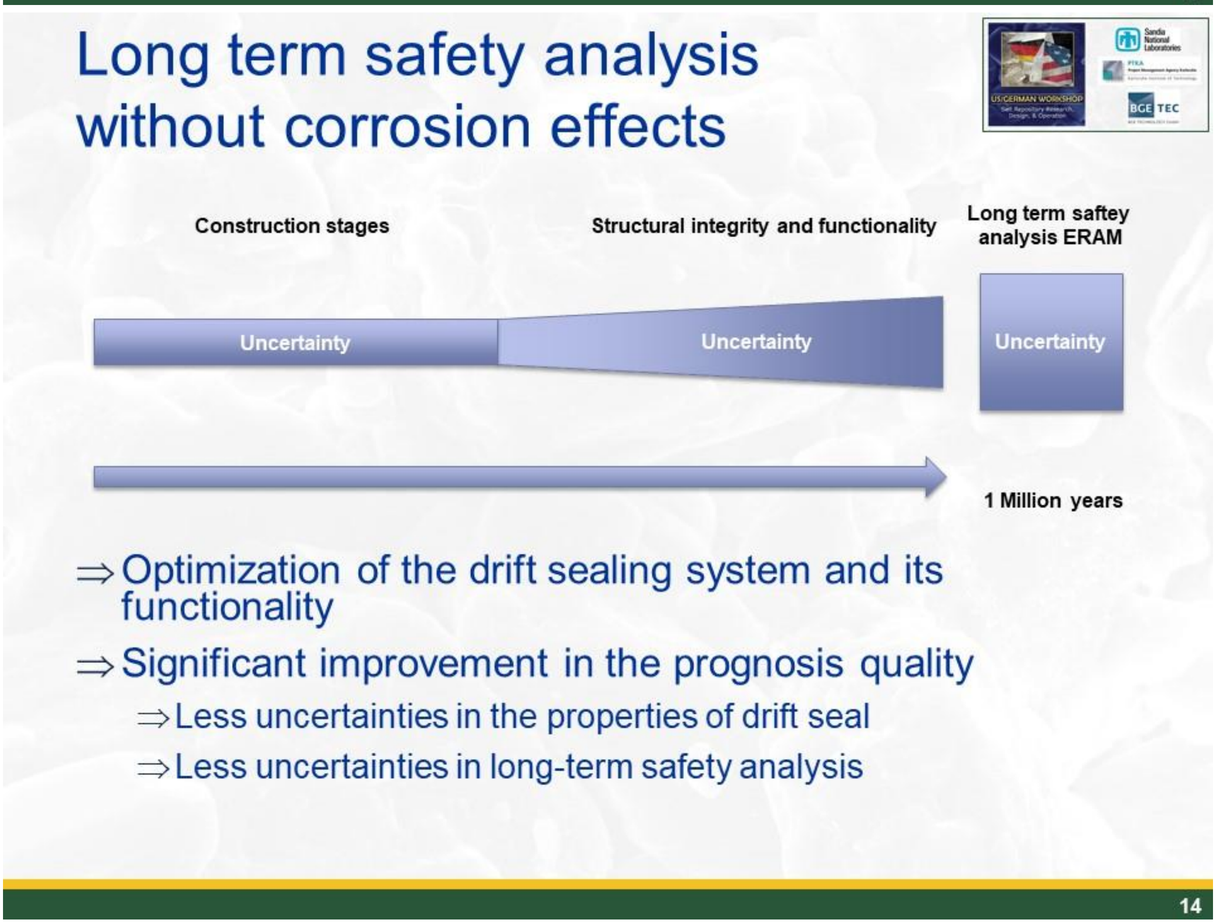
Long term safety analysis
without corrosion effects
US/GERMAN WORKSHOP
Sandia National Laboratories
PTKA
BGE TEC
Construction stages
Structural integrity and functionality
Long term saftey analysis ERAM
Uncertainty
Uncertainty
Uncertainty
1 Million years
⇒ Optimization of the drift sealing system and its functionality
⇒ Significant improvement in the prognosis quality
⇒ Less uncertainties in the properties of drift seal
⇒ Less uncertainties in long-term safety analysis
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Selected materials for drift seals

Current knowledge:

- Solution composition at sealing sites:
  $\Rightarrow$ $MgCl_2$-concentration content at all sites
- Stability of MgO-Phases
  $\Rightarrow$ Stable even at low concentration of Mg^{2+} ($\geq 0.5 \pm 0.6$ molal)

$\Rightarrow$ No corrosion of MgO-material expected

- MgO-material: solely drift sealing material in ERAM!
- Salt concrete: no more drift sealing material in ERAM!
- Bitumen as an optional additional material for some drift seals locations is taken into consideration (e.g. in anhydrite and “Lager H”)

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Thank you for listening

TUHH Technische Universität Hamburg

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Technische Universität Braunschweig

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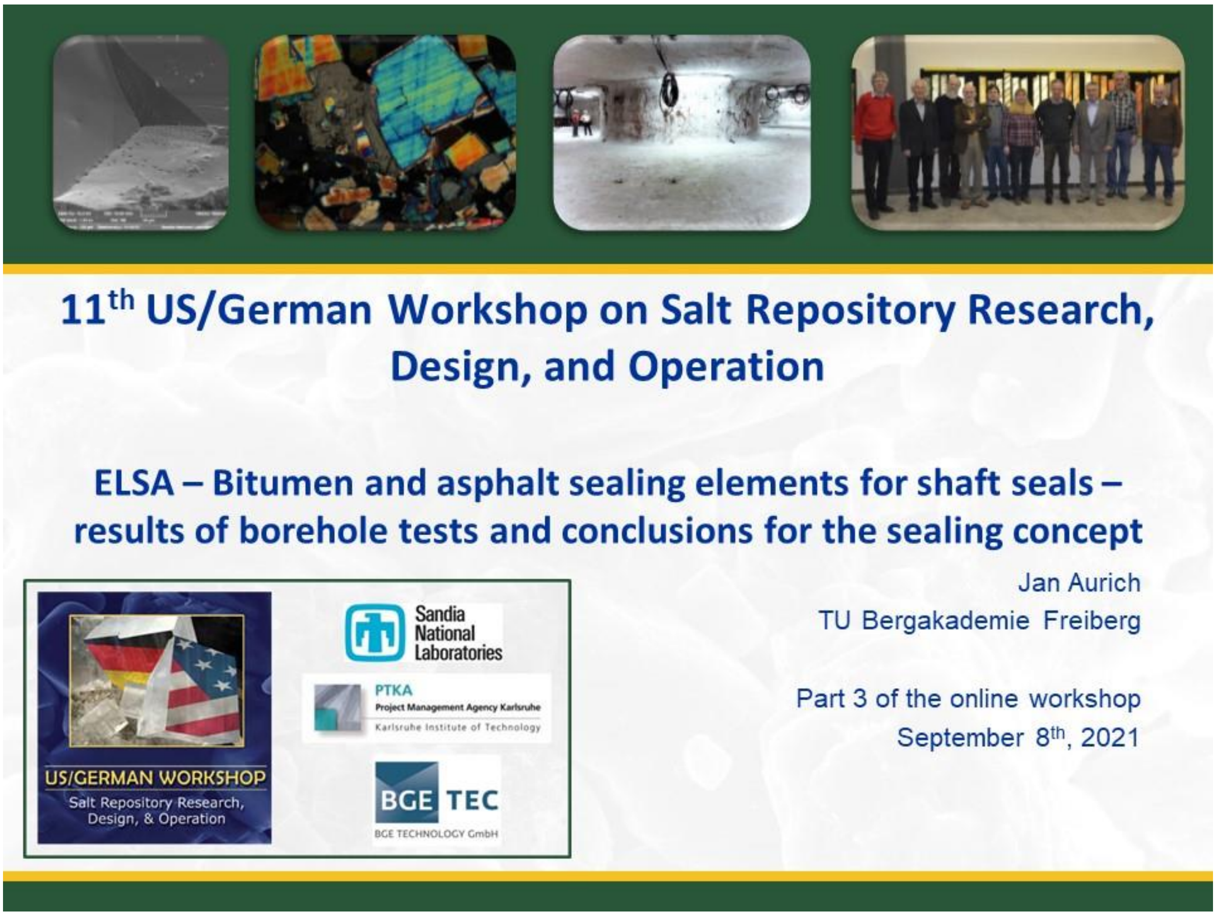
11th US/German Workshop on Salt Repository Research, Design, and Operation
ELSA – Bitumen and asphalt sealing elements for shaft seals – results of borehole tests and conclusions for the sealing concept
Jan Aurich
TU Bergakademie Freiberg
Part 3 of the online workshop
September 8th, 2021
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
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Project Management Agency Karlsruhe
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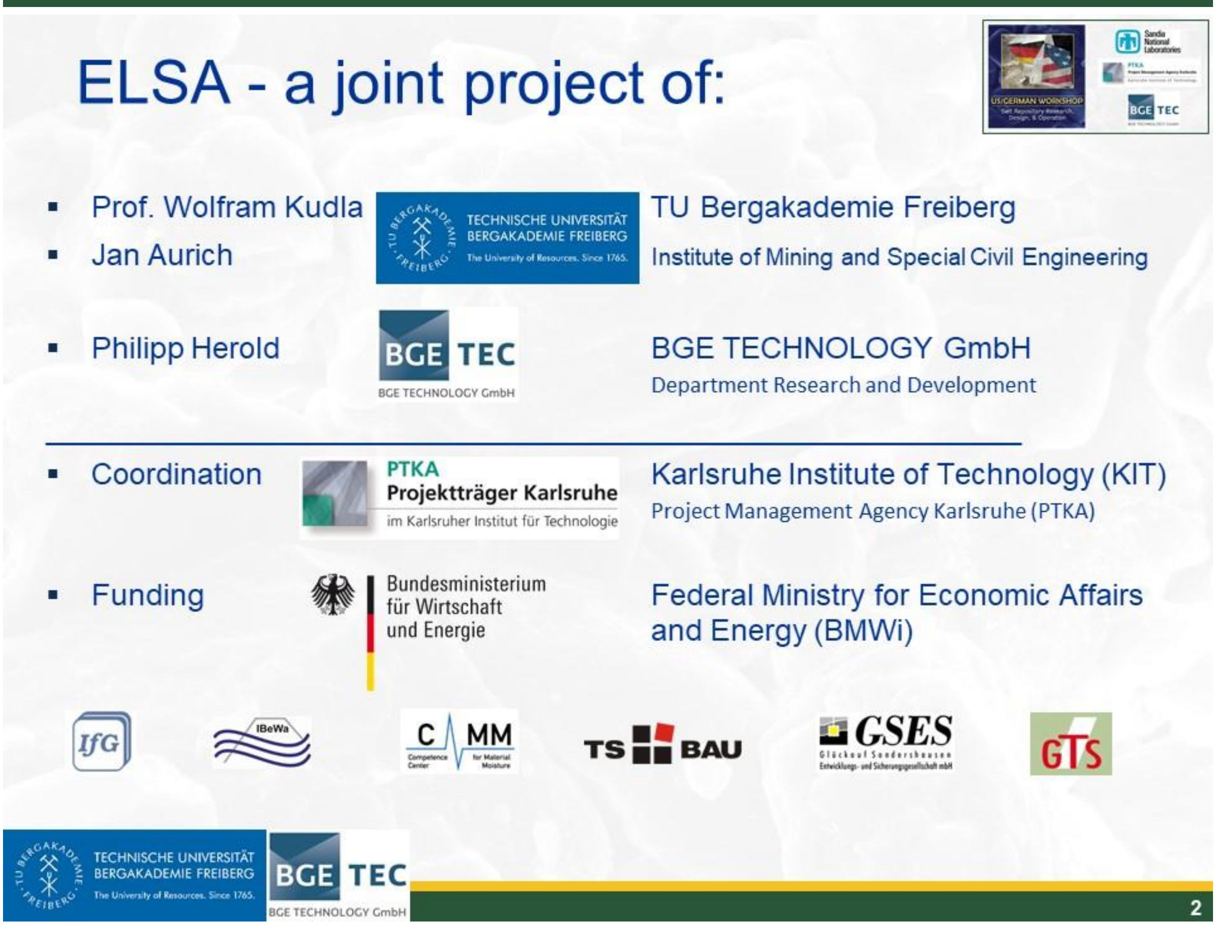
ELSA - a joint project of:
Prof. Wolfram Kudla
Jan Aurich
TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
The University of Resources. Since 1765.
TU Bergakademie Freiberg
Institute of Mining and Special Civil Engineering
Philipp Herold
BGE TEC
BGE TECHNOLOGY GmbH
BGE TECHNOLOGY GmbH
Department Research 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)
IfG
IBeWa
C MM
TS BAU
GSES
GTS
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Contents

1. Introduction into the ELSA II project
2. Experimental objectives
3. Experimental setup und overview of trials
4. Experimental results
5. Summary and conclusions

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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
- modelling the behavior of sealing elements in the context of construction and future hydraulic evolution
- simulating possible earthquake induced settlements in backfilled shafts

ELSA Phase 2 FC 02E11193A/B 2013 - 2020

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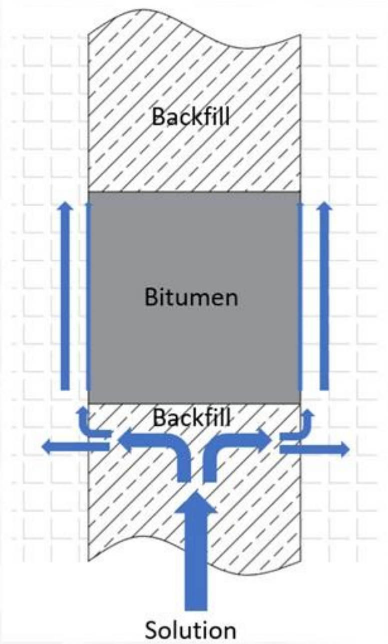
Experimental objectives

Some key points on Bitumen:

- Very proven sealing material in underground mining and landfill construction
- No diffusion of water or aqueous solutions (sealing capacity)
- Rheologic properties lead to a autonomous closure of flow paths (liquid behavior of bitumen)

⇨ Possible transport mechanism / routes through EDZ and contact gap between sealing element and host rock.



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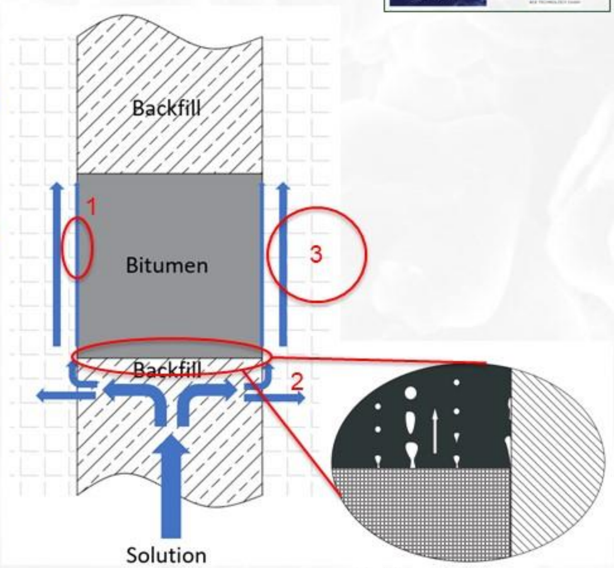
Experimental objectives

Investigation objectives:

- Examination of possible contact gap formation 1
- Examination of possible mobile voids (due to differences in fluid densities) 2
- Observation of thermal evolution of the sealing system and host rock properties (hot installation) 3 ⇨ specified temperature criterion 100 °C, because of evaporation of water



Problem with excess gas pressure.

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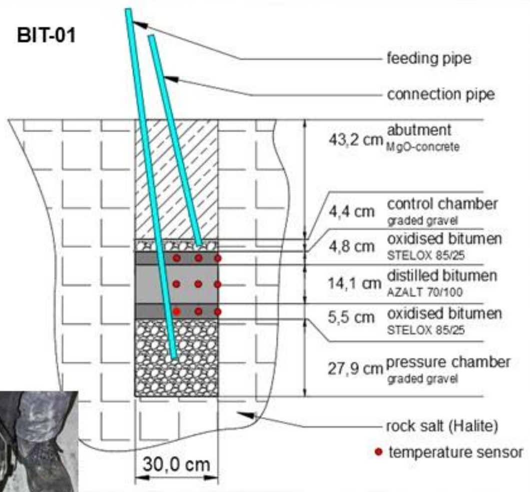
Experimental setup

Basic concept bitumen (principle hard shell – soft core)

- Hard shell: oxidized bitumen STELOX 85/25 – position stability of sealing element (Prevention of gravimetric drain)
- Soft core: distilled bitumen AZALT 70/100 – facilitated inflow in pathways (optimized sealing properties)
- Pressurization with traced air and NaCl-Solution



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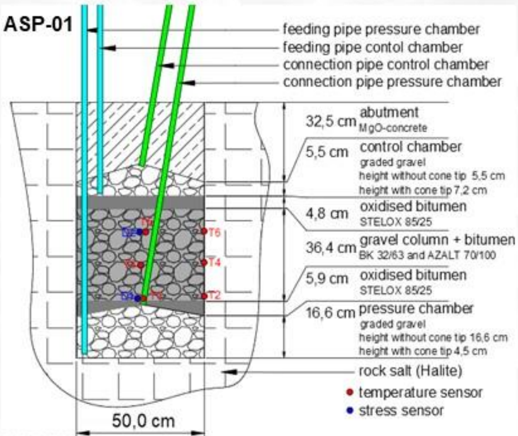
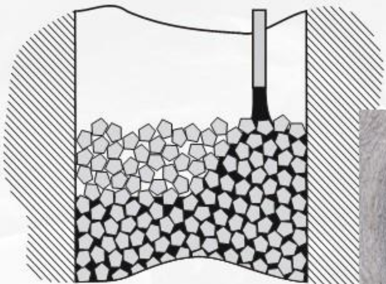
Experimental setup

Basic concept gravel column filled with bitumen

- Installation stepwise (1st gravel installation, 2nd grouting hot bitumen)
- increase of positional stability
- Obstruction of uprising gas / liquid voids





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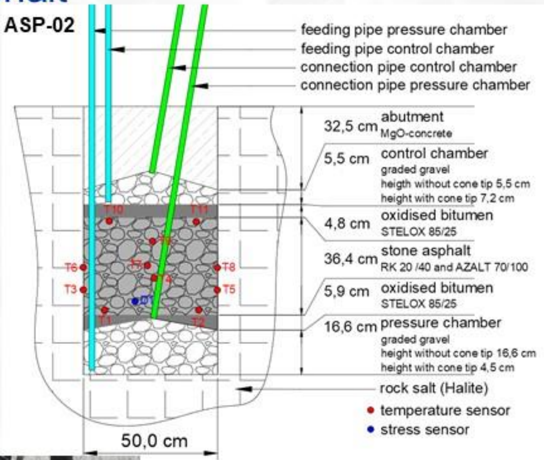
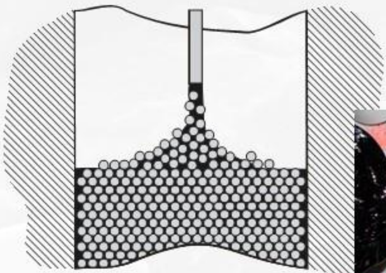
Experimental setup

Basic concept dense stone asphalt

- Installation in one step (premixing of the bitumen and mineral aggregate)
- Prevention of dust accumulation (resulting from attrition during gravel installation)





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Overview of in-situ trials

Name	Material	Test site	Investigations
BIT-01	core: AZALT 70/100 shell: STELOX 85/25	Test site rock salt (Sondershausen mine)	• temperature • gas permeability • dismantling
BIT-02	core: AZALT 70/100 shell: STELOX 85/25		• gas permeability • fluid permeability • dismantling
ASP-01	core: gravel column filled with AZALT 70/100 shell: STELOX 85/25		• temperature • pressure • gas permeability
ASP-02	core: dense stone asphalt with AZALT 70/100 and rounded basalt gravel “Saxorund 20/40” shell: STELOX 85/25		• temperature • pressure • gas permeability
BIT-03	core: AZALT 70/100 shell: STELOX 85/25	Test site clay (open pit Wiesa)	• temperature • gas permeability • dismantling
ASP-03	core: gravel column filled with AZALT 70/100 shell: STELOX 85/25		• temperature • gas permeability • dismantling
ASP-04	core: dense stone asphalt with AZALT 70/100 and rounded basalt gravel “Saxorund 20/40” shell: STELOX 85/25		• temperature • gas permeability • dismantling

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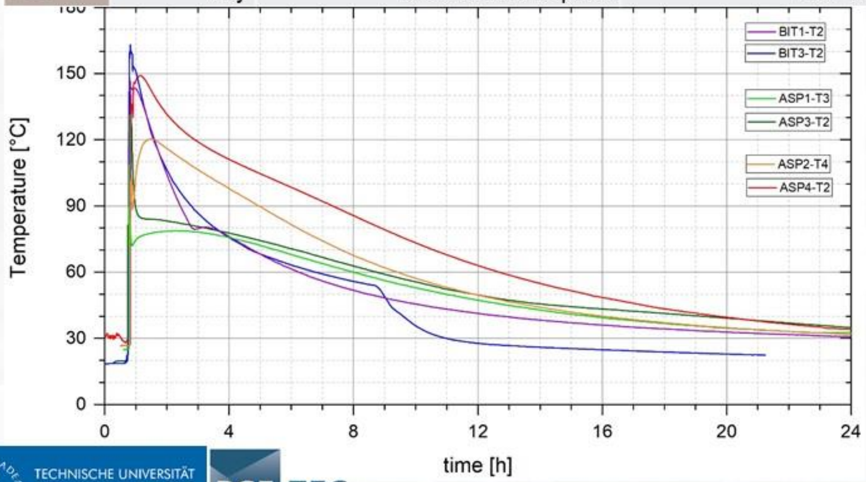
Results of thermal investigations

	Host rock	Design principle	Maximum temp. in the middle	Initial temp. Rock / test side
BIT-1	rock salt	pure bitumen	146 °C	27 °C
BIT-3	clay	pure bitumen	163 °C	18 °C
ASP-1	rock salt	bitumen filled gravel column	109 °C	25 °C
ASP-2	rock salt	dense stone asphalt	131 °C	27 °C
ASP-3	clay	bitumen filled gravel column	142 °C	20 °C
ASP-4	clay	dense stone asphalt	149 °C	23 °C



- high temperatures decrease viscosity of bitumen ➪ enhanced permeation into gaps and voids between gravel grains

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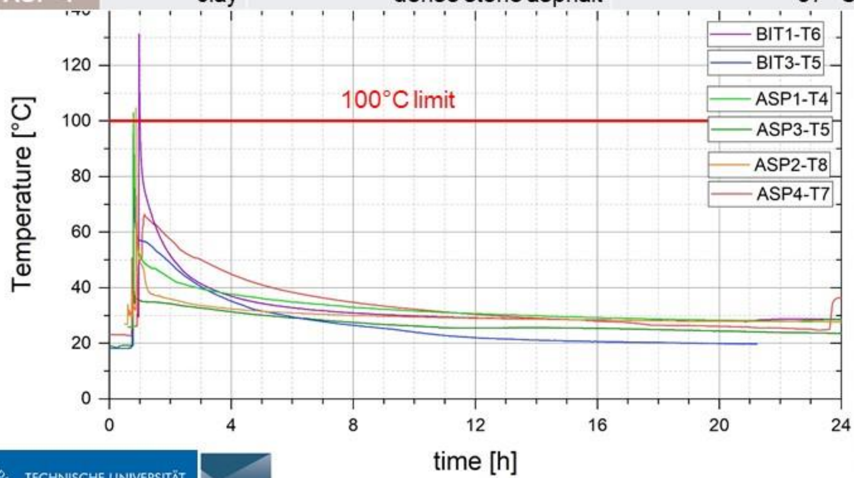
Results of thermal investigations

	Host rock	Design principle	Maximum temp. on contour	Initial temp. Rock / test side
BIT-1	rock salt	pure bitumen	131 °C	27 °C
BIT-3	clay	pure bitumen	101 °C	18 °C
ASP-1	rock salt	bitumen filled gravel column	103 °C	25 °C
ASP-2	rock salt	dense stone asphalt	105 °C	27 °C
ASP-3	clay	bitumen filled gravel column	95 °C	20 °C
ASP-4	clay	dense stone asphalt	67 °C	23 °C



- Max. temperature for a very short time interval
- Experience from first trials led to adjustments on the later trials

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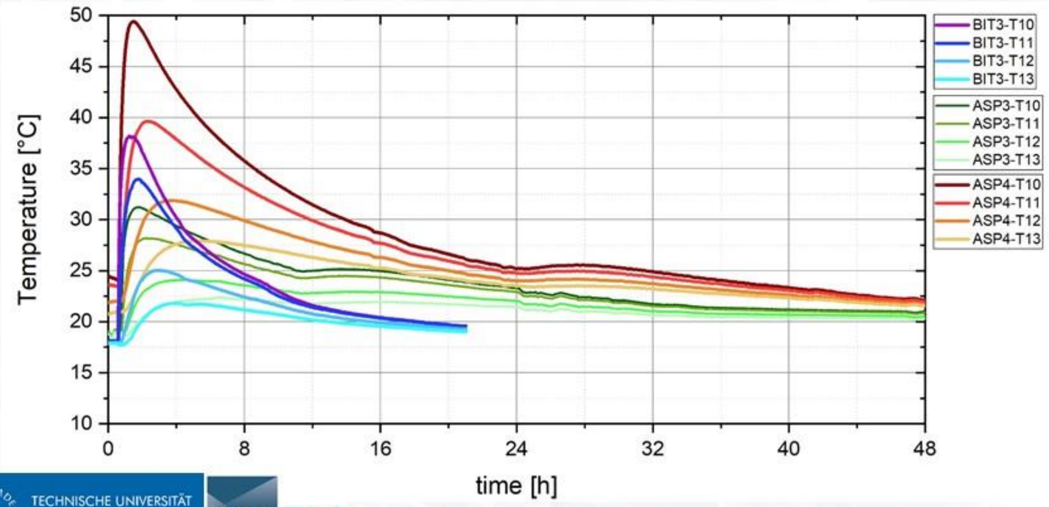
Results of thermal investigations

Thermal evolution in clay (2cm, 5 cm, 10cm, 15 cm from contour)

- BIT-03: pure bitumen with borehole diameter of 30 cm
- ASP-03: bitumen filled gravel column with diameter of 50 cm
- ASP-04: dense stone asphalt with diameter of 50 cm



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Results of thermal investigations

Comparison of heat balance:

- Considerably differences of total thermal energy amount ΔQ between pure bitumen, bitumen filled gravel column and dense stone asphalt
- Approx. same relative thermal energy input (ΔQ / lateral surface) into host rock resp. contour by comparison of pure bitumen and bitumen filled gravel column
- Higher relative thermal energy input (ΔQ / lateral surface) in dense stone asphalt trials due to additionally heated gravel

	Mass bitumen	Mass gravel	Initial temp. bitumen / asphalt	Initial temp. Rock / test side	Thermal energy ΔQ	ΔQ / lateral surface
	[kg]	[kg]	[°C]	[°C]	[kJ]	[kJ/m²]
BIT-1	10.2	-	143	27	2,130	16,148
BIT-3	15.5	-	163	18	4,046	20,942
ASP-1	24.1	96.0	170	25	6,290	13,953
ASP-2	26.3	138.8	140	27	15,732	27,820
ASP-3	28.6	94.9	171	20	7,773	16,440
ASP-4	24.9	112.5	168	23	16,357	36,666

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Results of pressurization

- Pressurization with compressed air (doted with FREON) and saline solution (NaCl saturated)
- No detection of FREON gas on test sides within control chambers ⇨ system initial gastight
- Closed contact gap
- Hydraulic behavior of EDZ shows no damage due to hot installation

Name	Host rock	Pressure medium	pressure	Permeability	Remarks
BIT-01	rock salt	doped compressed air	0.12 MPa	$3 \cdot 10^{-21}$ m²	
		doped compressed air	1.05 MPa	$2 \cdot 10^{-20}$ m²	
BIT-02	rock salt	doped compressed air	1.05 MPa	$6 \cdot 10^{-20}$ m²	
		saline solution	1.20 MPa	$1 \cdot 10^{-20}$ m²	
BIT-03	clay	-	-	-	not performed
ASP-01	rock salt	doped compressed air	0.20 MPa	$4 \cdot 10^{-20}$ m²	
ASP-02	rock salt	doped compressed air	0.23 MPa	$3 \cdot 10^{-19}$ m²	
ASP-03	clay	doped compressed air	0.15 MPa	$1{,}5 \cdot 10^{-14}$ m²	
ASP-04	clay	doped compressed air	0.15 MPa	-	pressure buildup not possible
Natural gas permeability at test side – rock salt				$1 \cdot 10^{-21}$ m²	
Natural gas permeability at test side – clay				ca. $1 \cdot 10^{-17}$ m²	

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Dismantling of trials

Results and observations:

- Detection of gas filled voids within pure bitumen trials (green arrow fist-sized void, red arrows smaller impressions)
- No voids detected within asphalt trials
- Sufficient adhesion of bitumen on host rock surface (primer used in rock salt)
- Penetration of bitumen into gaps in salt rock and clay (fluid character and viscosity of distilled bitumen)
  ⇨ Obstruction of transport through EDZ and contact gap between sealing element and host rock

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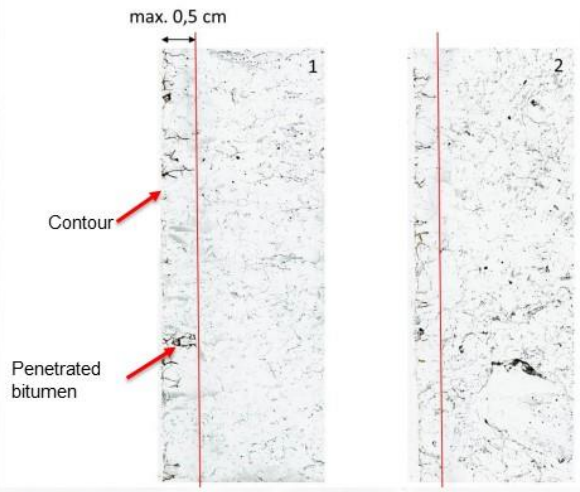
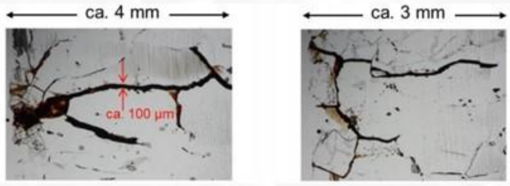
Micro section analysis by BGE TEC

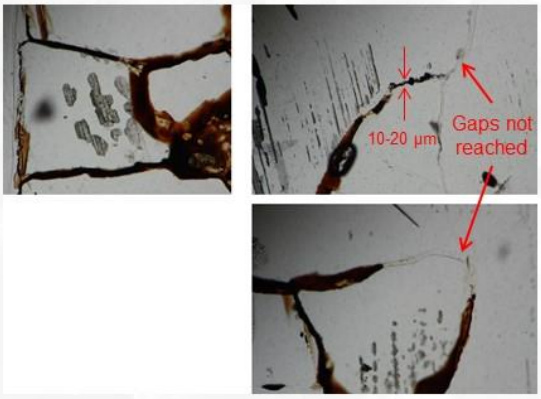


Micro sections from BIT 01 and BIT-02 in radial direction from borehole contour (left site)

⇨ approx. 5 mm deep penetration of the bitumen into rock salt with a gap width down to approx. 10 µm



Magnified sections: visualization of penetration into rock salt



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Summary

- Sufficient hydraulic properties of bitumen based sealing elements esp. in result of the penetration into small gaps and adhesive character
- With elements made of pure bitumen a risk of uprising gas voids is given, dense stone asphalt and bitumen filled gravel columns obstruct mobile voids
- Stone asphalt and bitumen filled gravel columns have both a static function (abutment) and sealing function (rheologic properties of hot bitumen)
- Thermal energy input into host rock adjustable as a result of the scale of a later shaft (setting of installed mass resp. installed layer thickness)
- No dust accumulations in stone asphalt due to the premixing, but more work-intensive, heatable containers for shafts still have to be developed

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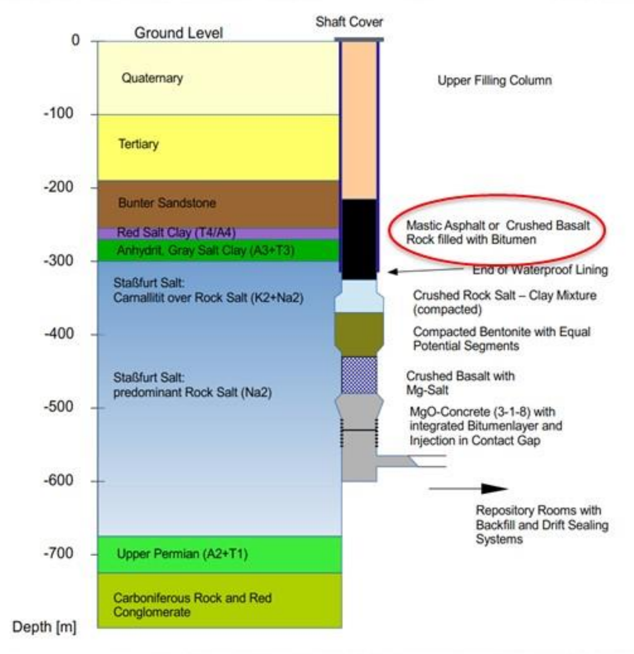
Conclusions for sealing concepts



Generic sealing concept with diversified and redundant sealing system for the host rock salt: one element made of bitumen filled gravel.

- Bitumen filled gravel column has been tested on a large scale: Project BiSETO, Hermsdorf, Germany, 2013 and at ERA Morsleben, “IB Gesenk”, 2017
- Dense stone asphalt still needs to be verified in large scale

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Many thanks and Glückauf!

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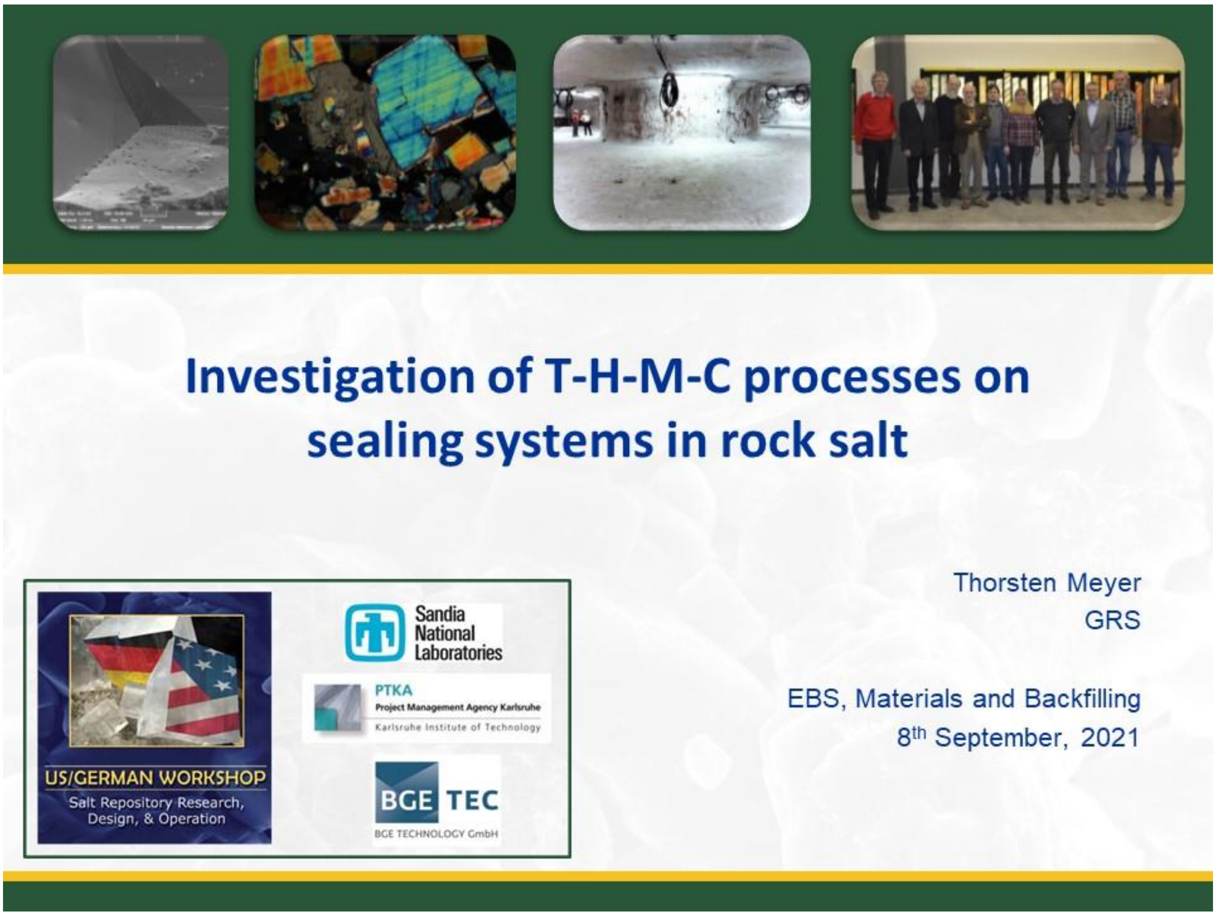
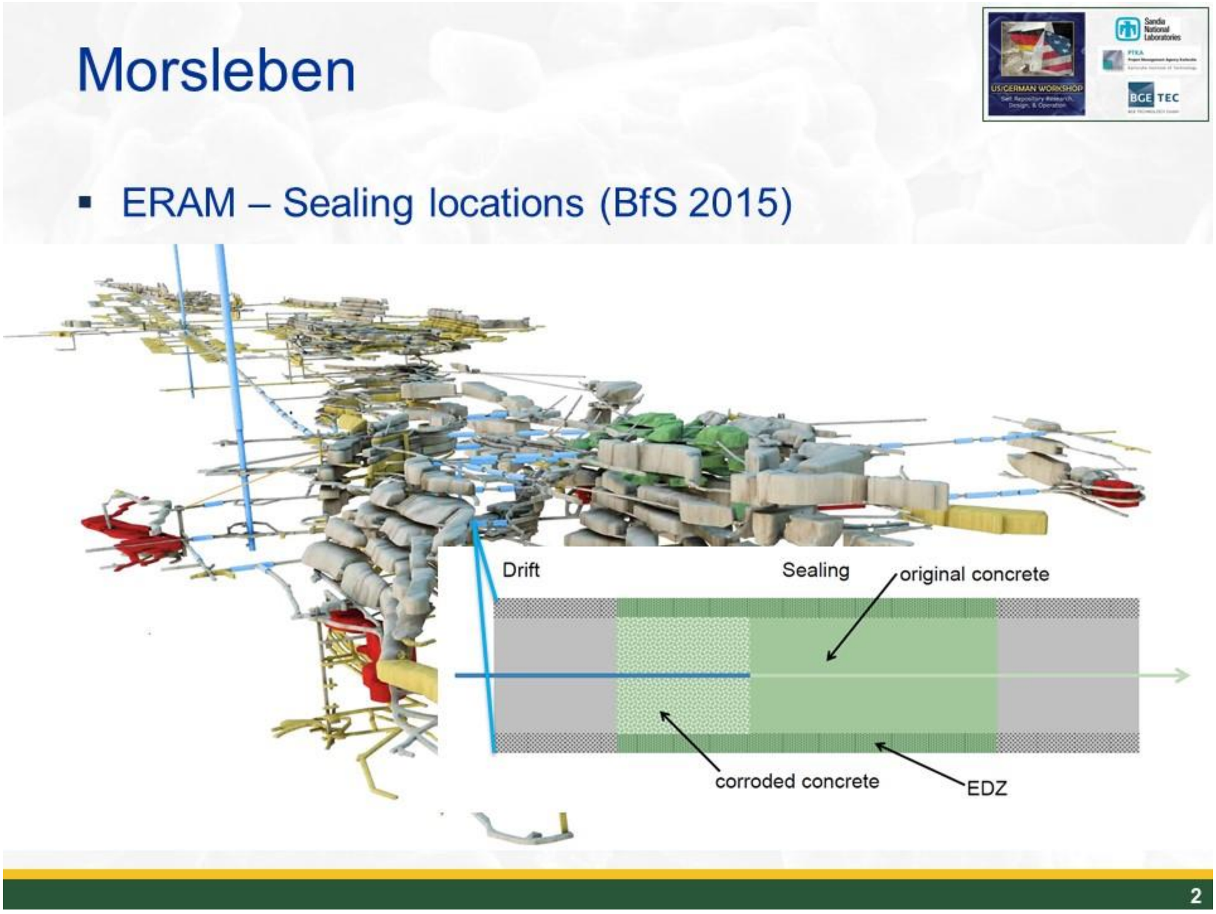
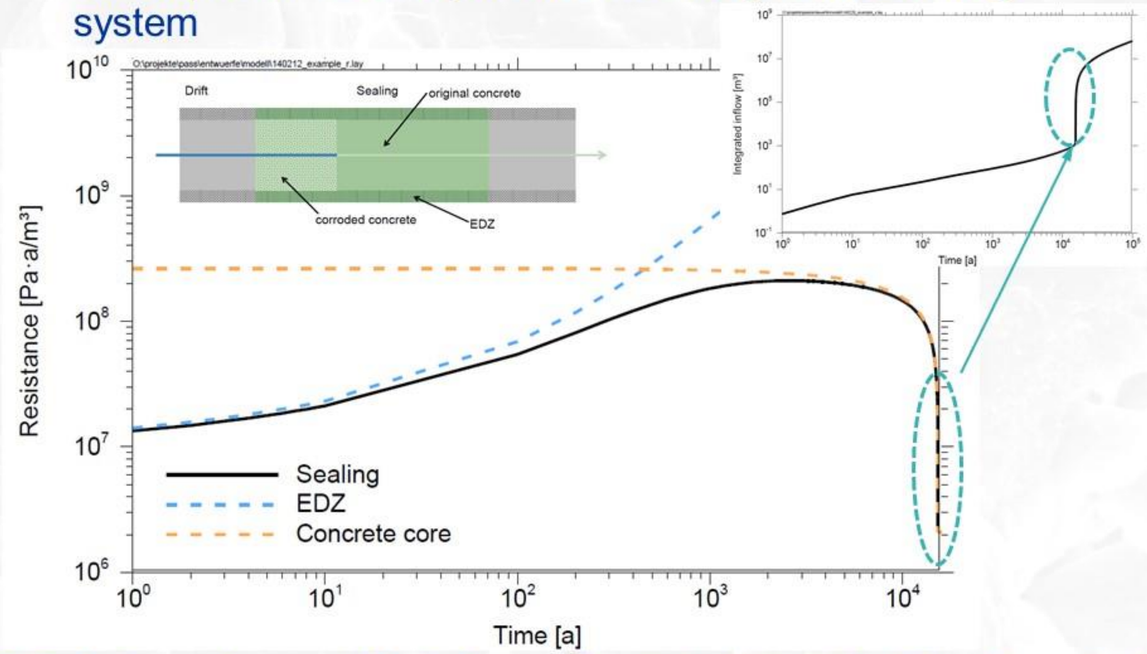

Investigation of T-H-M-C processes on sealing systems in rock salt
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH
Thorsten Meyer
GRS
EBS, Materials and Backfilling
8th September, 2021


Morsleben
ERAM – Sealing locations (BfS 2015)
Drift
Sealing
original concrete
corroded concrete
EDZ
2

Performance Assessment

- development of the hydraulic resistivity of the sealing system



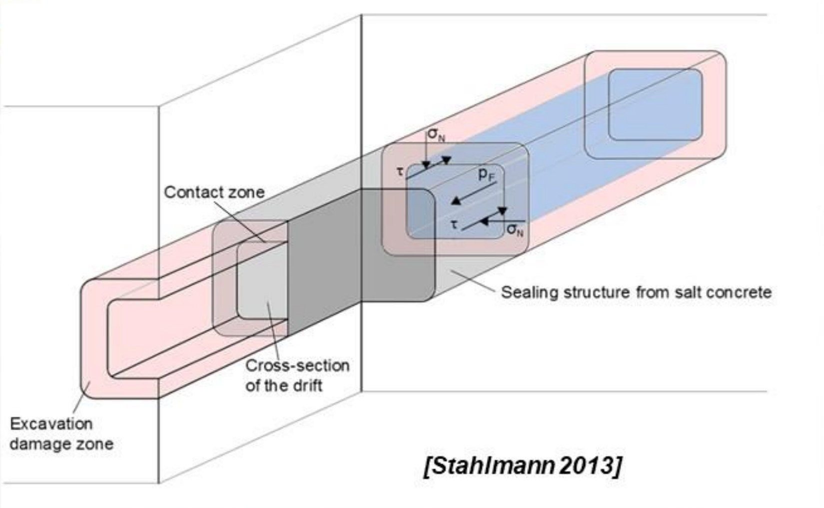
GRS-415 - Performance Assessment of Sealing Systems - Conceptual and integrated modelling of plugs and seals

3

Motivation / Objectives

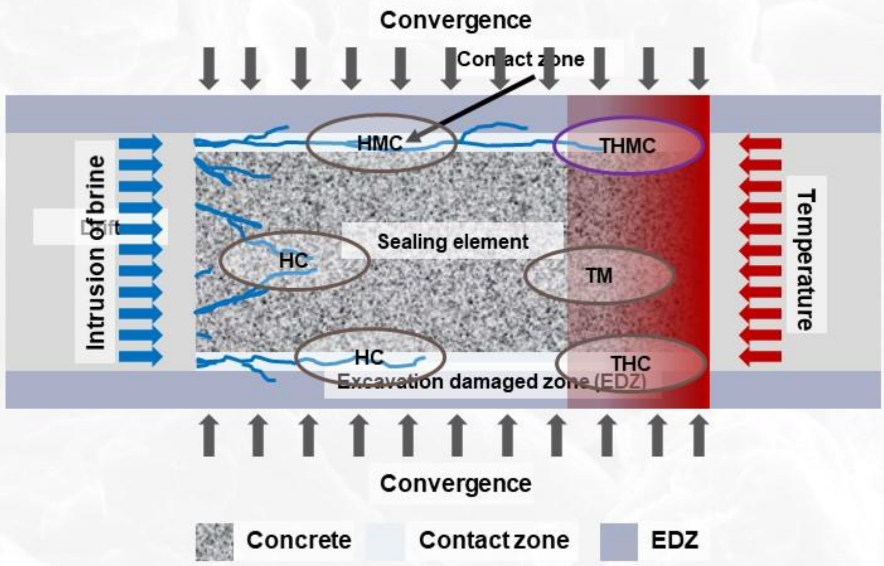
Assessment of the sealing system

- excavation damage zone
- sealing material
- contact seam



4

T-H-M-C processes – sealing system

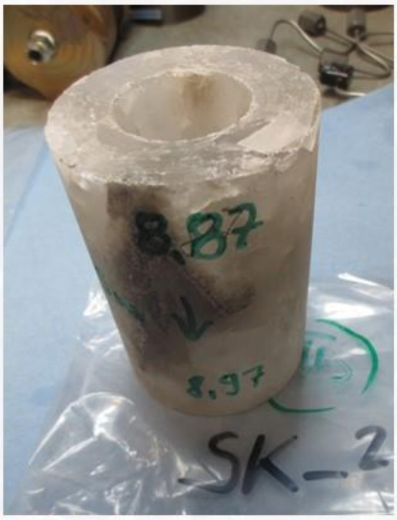


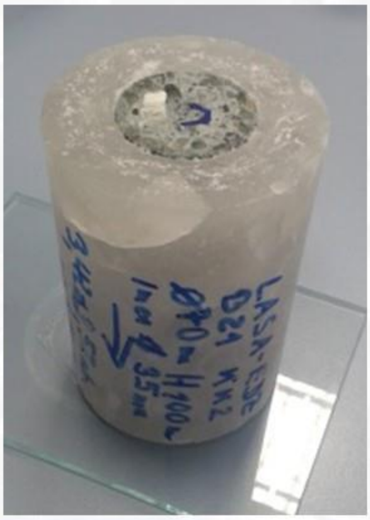
5

Experimental Model System

Assessment of the sealing system

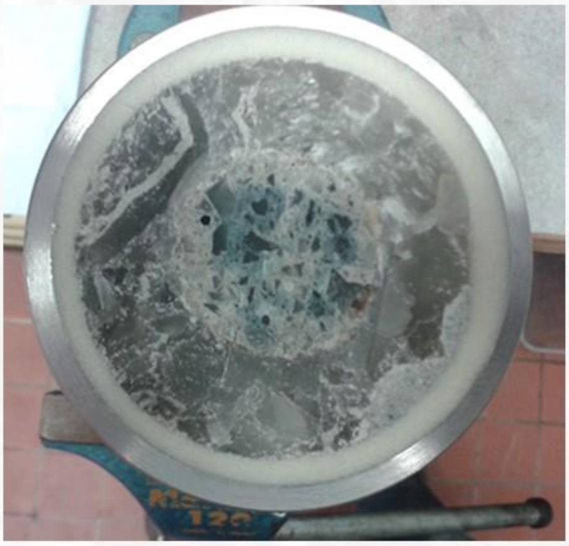
- sealing material   salt cylinder (EDZ)   sealing system





6

Experimental Model System



- metal jacket
- Araldit (resin)
- salt cylinder
  - Asse
  - ERAM
- concrete
  - M2 (salt concrete)
  - M4 (salt concrete)
  - A1 (Sorel concrete)
  - Asse concrete (in-situ)

7

Materials

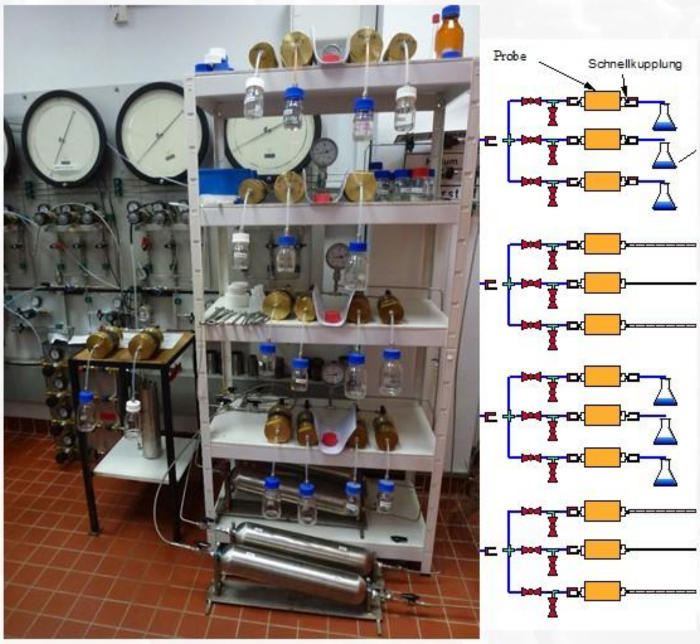
Sorel concrete A1 (318-Rezeptur)	Sorel concrete D4 (518-Rezeptur)
11,3 wt% MgO (reactivity 200 – 250 sec)	15,95 Ma-% MgO (reactivity 200 ± 50 sec)
63,7 wt% crushed salt (4 mm)	68,1 Ma-% gravel /sand (0–8 mm)
25,0 wt% $MgCl_2$ solution (4-5 molal)	15,95 Ma-% $MgCl_2$ solution (5 molal)

In-situ samles
M2 – from ERAM sealing
SBA – Salt concrete „Type Asse“ (contact zone)

Salt concrete M2	Salt concrete M4
16,4 wt% CEM III/B	14,4 wt% CEM III/B
53,8 wt% crushed salt	32,8 wt% crushed salt
13,4 wt% water	7,7 wt% water 7,2 wt% NaCl solution Typ I
16,4 wt% hard coal fly ash (HKV / PA VII/21)	21,3 wt% sand 16,9 wt% limestone

8

HC - Investigations



- permeability measurement - no confining pres.
- advection cells
- fluids: NaCl, IP21 (Q-TEC 4.0)
- $P_{Solution}$ up to 2 MPa
- T = 25° C
- monolithic samples (sealing material)
- combined samples (sealing system)

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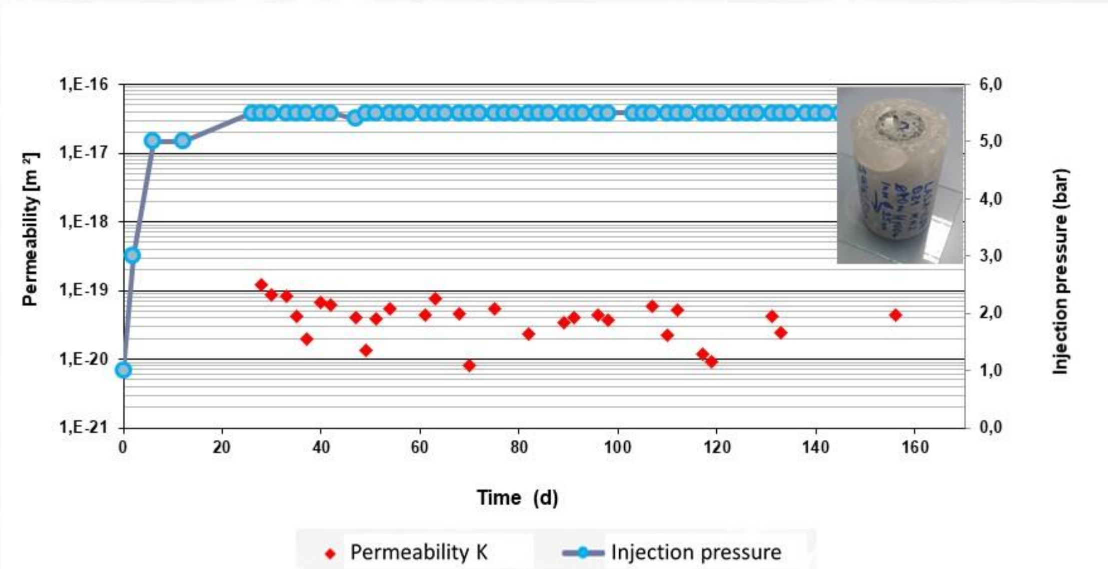
HC - Investigations

- Salt concrete (M2_KP_6) / NaCl solution



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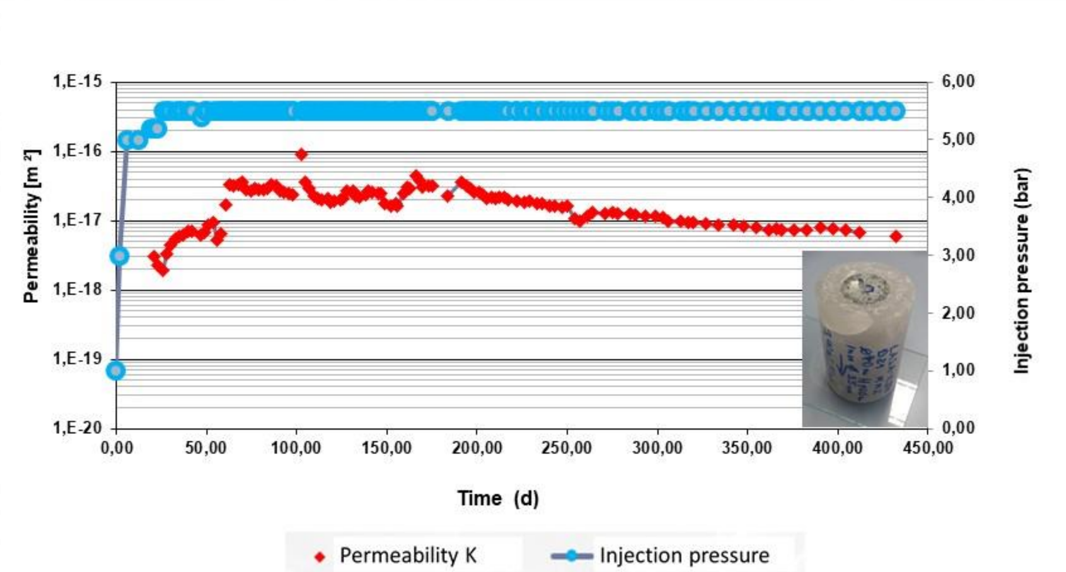
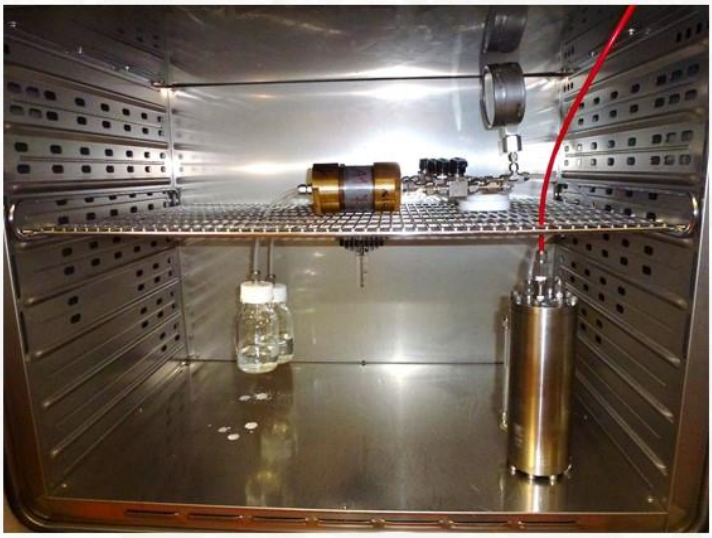
HC - Investigations

- Salt concrete (M2_KP_7) / IP21 solution



11

THC - Investigations

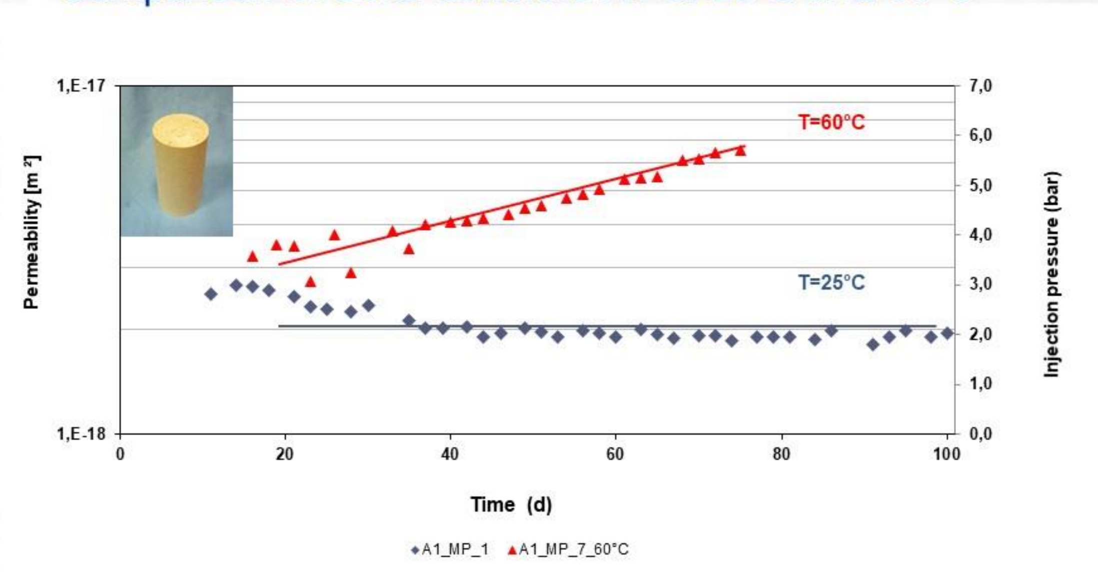


- advection cells
- permeability measurement
- no confining pressure
- $P_{Solution}$ up to 2 MPa
- T = 60° C
- monolithic sample (sealing material)
- combined samples (sealing system)

12

THC - Investigations

- Comparison of Sorel concrete A1 at 25°C and 60°C



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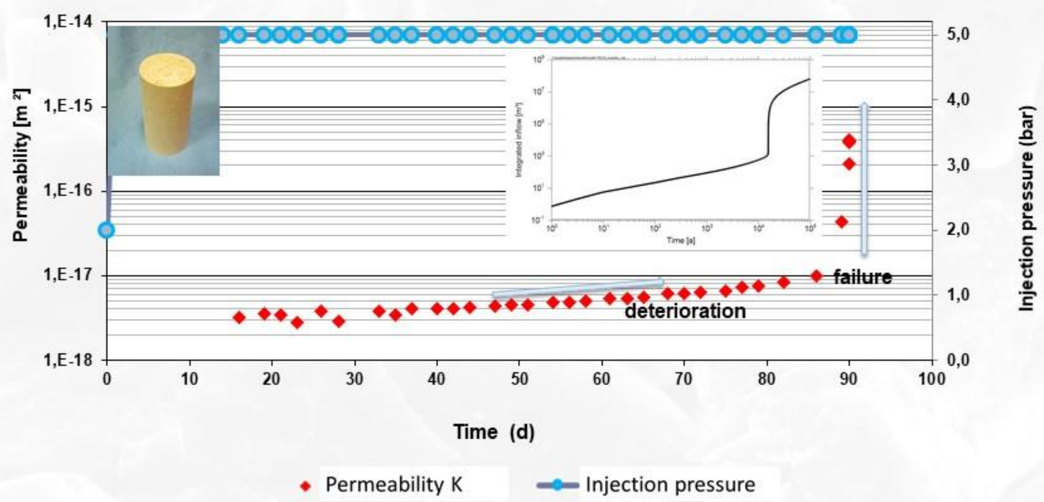
THC - Investigations

- Sorel concrete A1 at 60° / NaCl solution



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THC - Investigations

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THC - Investigations

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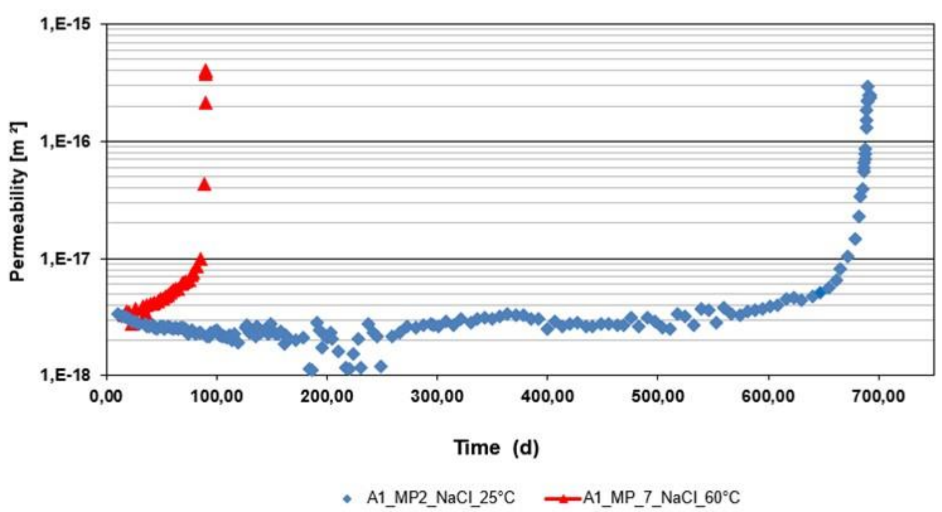
THC - Investigations

- Comparison of A1 at 25°C (long-term) and 60°C



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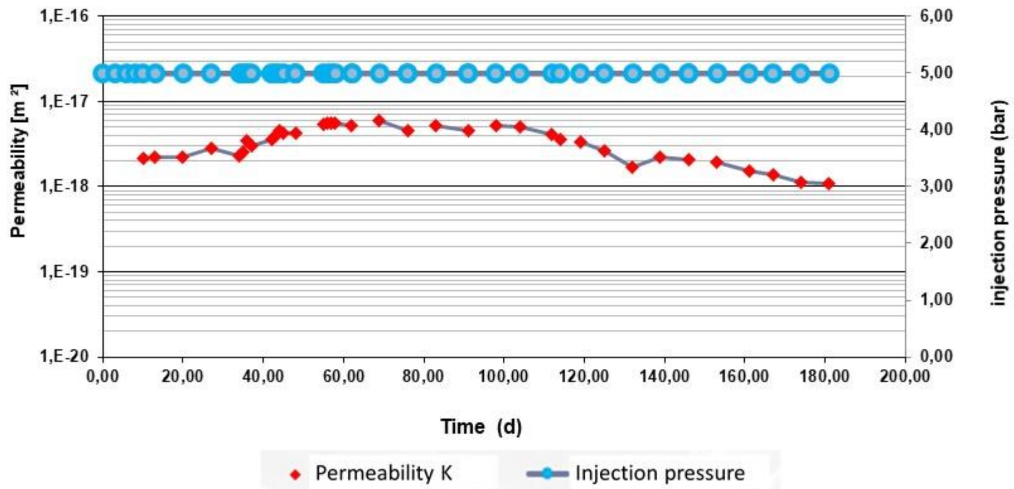
THC - Investigations

- Salt concrete (M2_KP_11) at 60°C



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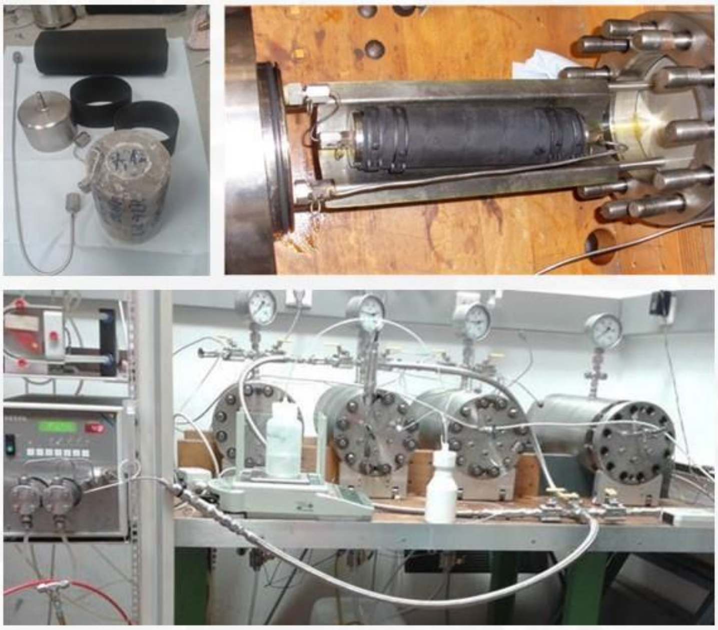
HMC - Investigations



- permeability measurements
- autoclaves
- confining pressure
- P_{conf} up to 10 MPa
- T = 25° C
- monolithic sample (sealing material)
- combined samples (sealing system)

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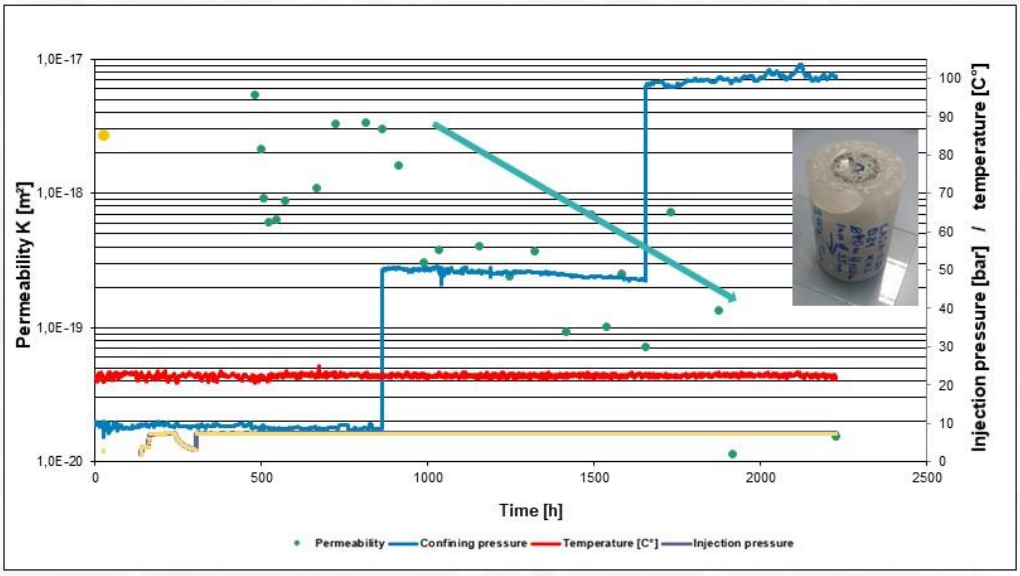
HMC - Investigations

- Salt concrete M2 (M2_KP_4) / IP21



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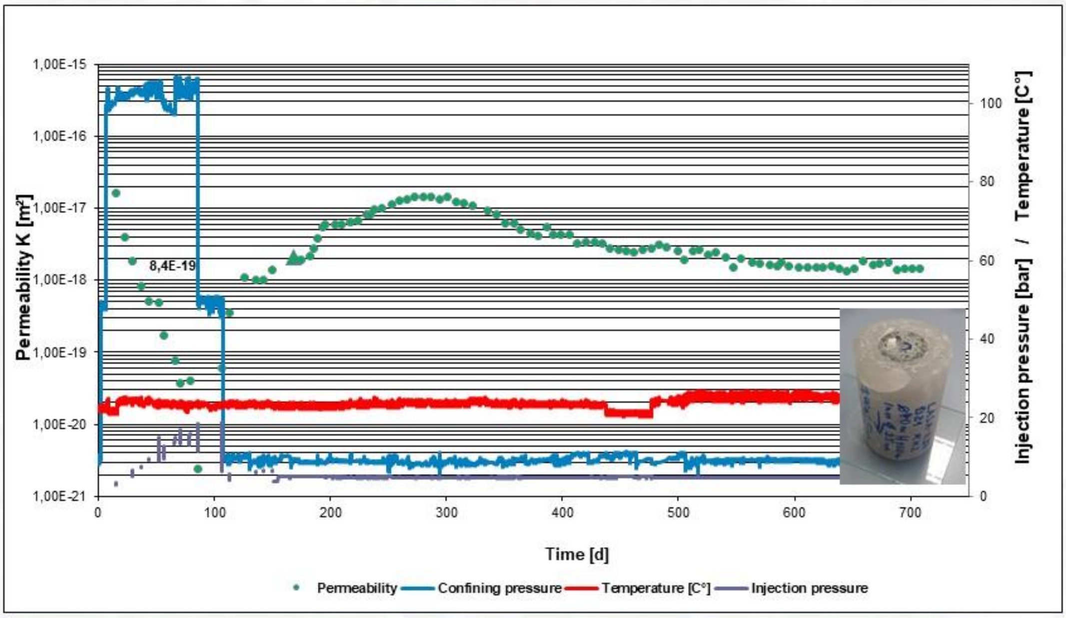
HMC - Investigations

- Sorel concrete A1 (A1_KP8) / IP21



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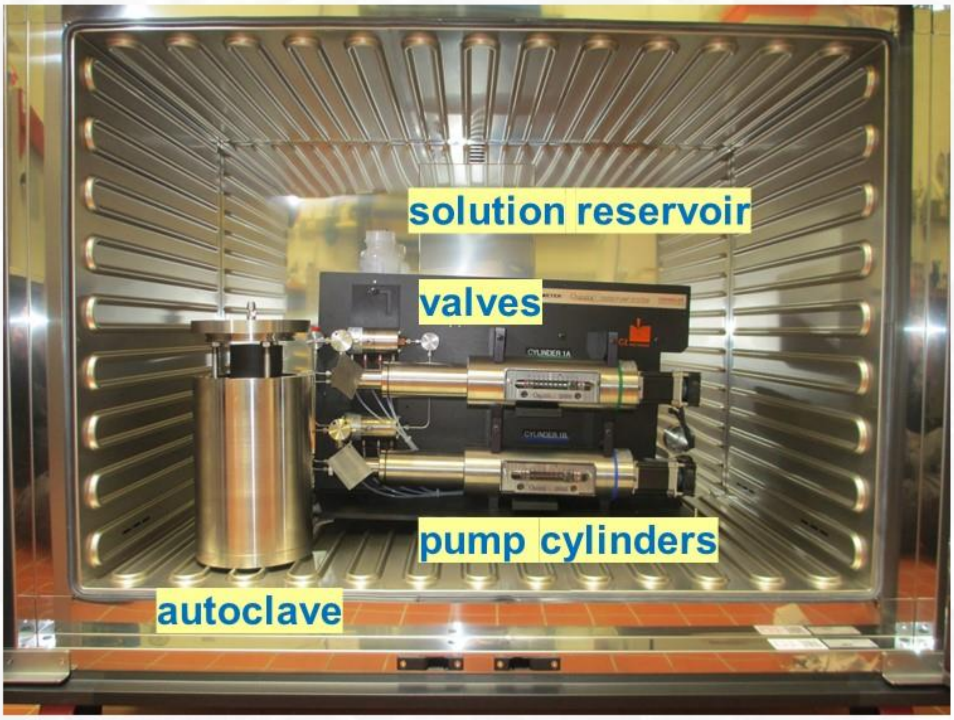
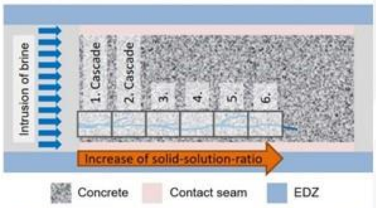
THMC - Investigations



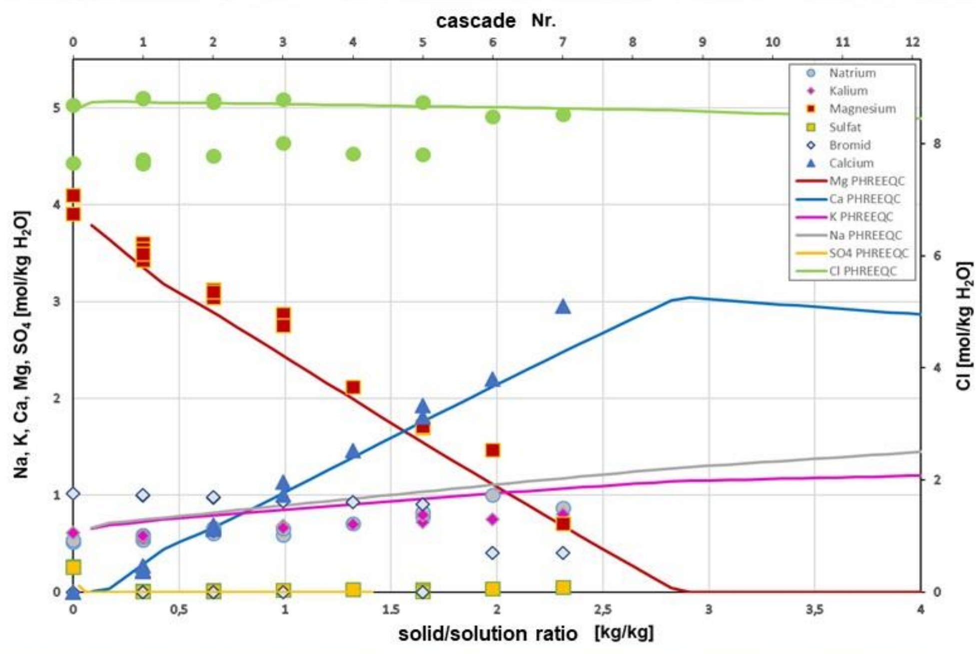
C - Investigations

- **Batch experiments**
  - solution
    - NaCl (sat.)
    - IP21-, Q-brine, Q-TEC 4.0
  - reaction time: 1 - 360 d
  - analysis eluate: ICP-OES, ICP-MS
  - analysis solid: XRD, ICP-OES, ICP-MS
- **Cascade experiments**
  - reaction time: 4 - 90 d (estimated by pre-experiments)
  - analysis solid: XRD, ICP-OES, ICP-MS
- **Diffusion experiments**
  - through-diffusion



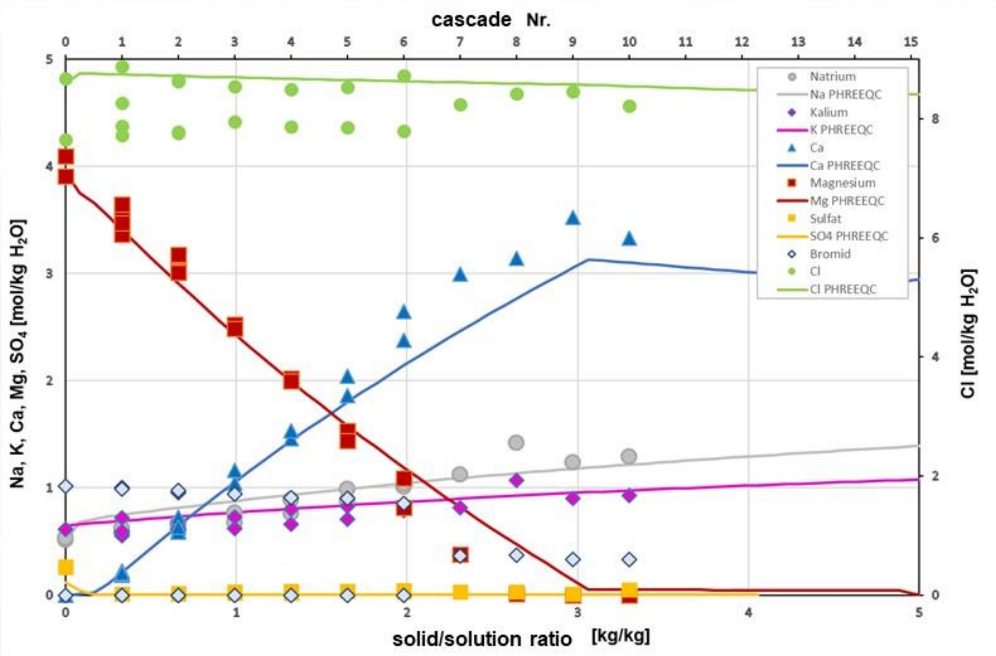
C – Cascade Experiments

- Salt concrete M2 / Q-TEC 4.0 (reference solution)



C – Cascade Experiments

- Salt concrete M4 / Q-TEC 4.0 (reference solution)



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Summary

- Results of T-H-M-C investigations
  - C-experiments
    - geochemical millieu
      - solution evolution
      - corrosion products
    - definition of reference solutions
    - source term for assessment of elements/substances eluted by intruding solutions and further release into the biosphere: Cr, Pb
  - HC/THC-experiments
    - hydraulic development of the sealing material / model system
    - evolution of the flow-through solution
    - porosity of the system -> CT-measurements
    - corrosion products -> REM
    - kinetc aspects

    - Comparison of THC and long-term experiments

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Summary

- HMC/-experiments
  - simulation of confining pressure
  - hydraulic development of the material/sealing system
  - evolution of the flow-through solution
  - porosity of the system -> CT-measurements
  - corrosion products -> REM
  - long-term experiments
- THMC-experiments
  - experimental simulation of sealing model systems
  - experimental set-up developed and procured
  - in-flow/out-flow monitoring

-> Basis for coupled process modeling

-> First answers for PA

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Acknowledgements

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

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

28


Clay Seam Laboratory Testing
11th US/German Workshop on Salt Repository Research, Design, and Operation
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH
Steven Sobolik, Benjamin Reedlunn, Chet Vignes
Sandia National Laboratories, USA
Evan Keffeler, Stuart Buchholz
RESPEC, USA
Part 3 of the online workshop
September 8, 2021
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. SAND2021-10894C.


Joint Project WEIMOS:
Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt
April 2016 – (March 2019) extended: September 2021,
(writing of synthesis report until March 2022)
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
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
WEIMOS
Dr. Andreas Hampel
Institut für Gebirgsmechanik GmbH Leipzig
Leibniz Universität Hannover
TU Clausthal
Sandia National Laboratories
2

Joint Project WEIMOS:

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 ("healing")

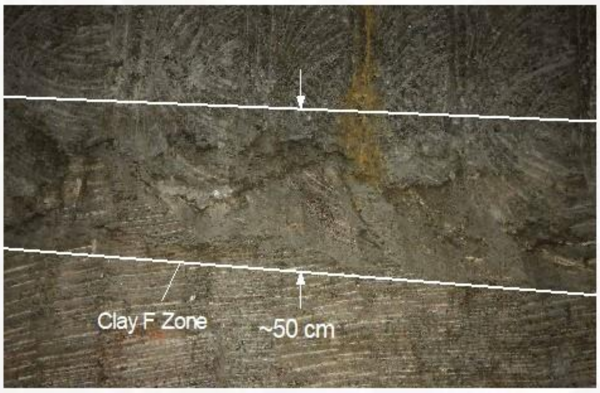
WP 3: Deformation behavior resulting from tensile stresses

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

WP 5: Virtual demonstrator

WEIMOS Dr. Andreas Hampel | Institut für Gebirgsmechanik GmbH Leipzig | Leibniz Universität Hannover | Technische Universität Braunschweig | TU Clausthal | Sandia National Laboratories 3

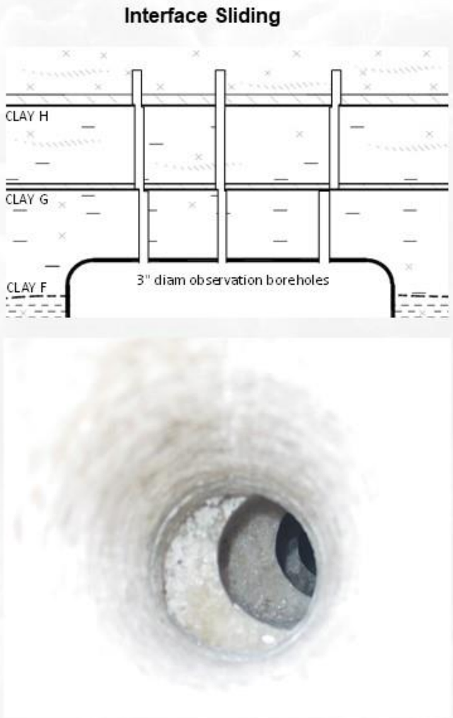
Pictures of Clay Seams at WIPP



- Clay seam G is thin (~8-25 mm), somewhat linear, contains clay and little else
- Clay seam F is thick (up to 50 cm), wavy, contains clay + other materials, possibly has intersecting salt crystals

4

Motivation



- Simulated room closure rates are highly dependent on bedding plane interfaces, such as clay seams.
- Roof falls frequently detach at clay seams
- The mechanical behavior of bedding plane interfaces is one of five Joint Project WEIMOS work packages.

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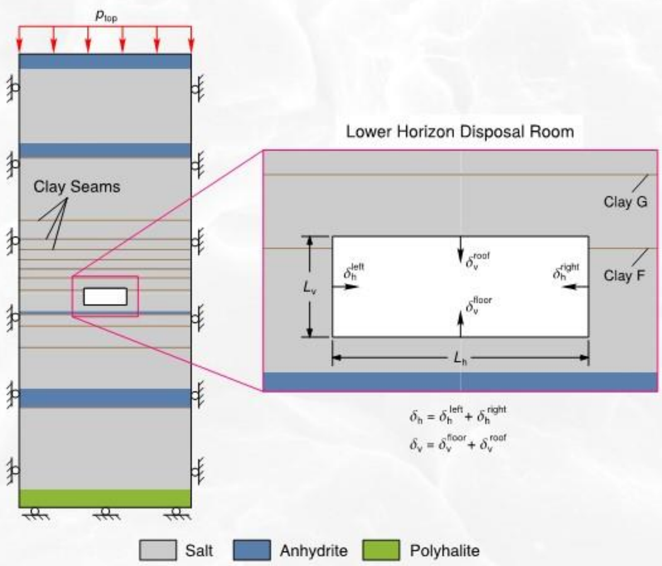
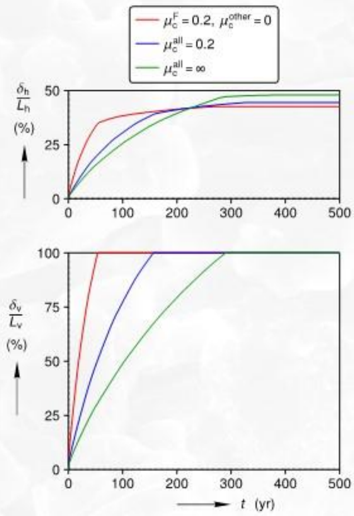
WP 4: Influence of inhomogeneities (layer boundaries, interfaces)



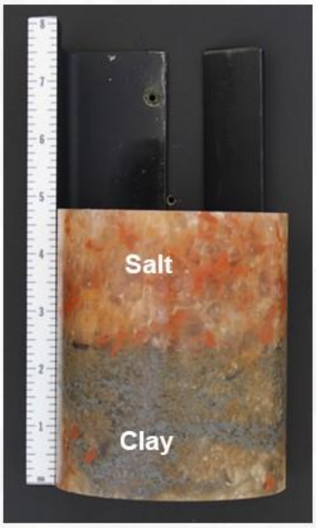


Reedlunn, B. and Bean, J. (2020). Impact of Properly Specifying the Clay F and Clay G Friction Coefficients in Disposal Room Closure Simulations at the Waste Isolation Pilot Plant. Memorandum. SAND2020-3575 CTF.

Modeling results show room closure rate is highly dependent on characterization of inhomogeneities such as clay seams.

6

1st series samples



Intact test, σ_n=1500 psi (10.3 MPa); salt crystals cross through interface

Salt/clay interface Fracture shown is typical of all tests

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

7

Influence of inhomogeneities (layer boundaries, interfaces) – First test series

<u>Shear tests of interfaces in salt</u>

First series of tests completed in 2018 at RESPEC with intact samples – NM salt, salt/clay, salt/polyhalite, salt/anhydrite.

Tests performed at four different normal stresses (3.4, 6.8, 10.3, 16.6 MPa), shear velocity of 0.25 mm/min.

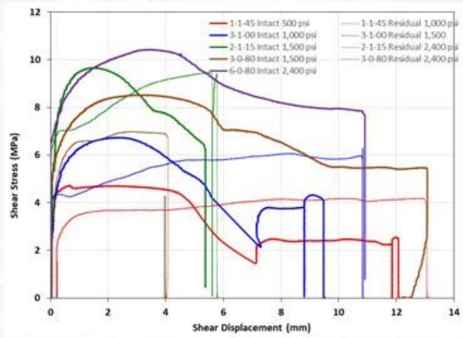
Some repeatability observed in maximum residual shear stress at same normal stress after interface fractured in intact test, fractured samples sheared in residual test.

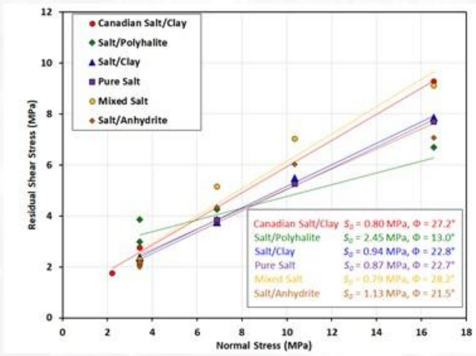
Clay/salt contacts much stronger than anticipated; interstitial salt crystals grown through contacts.

Sample stiffness much higher than anticipated.

Consistent behavior among different samples on intact tests.

Resulting stiffness, strength values assumed to be "upper bound".



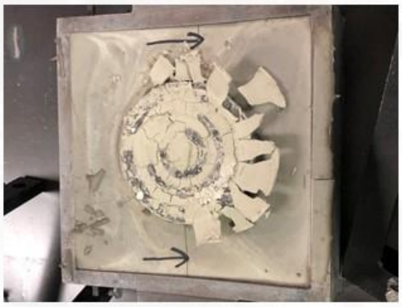


8

Influence of inhomogeneities (artificial clay seams) – Second test series

Artificial clay seam tests:

- **Goal: Establish plausible lower bound for strength and stiffness of clay seams in salt formations**
- **Shear tests with manufactured clay seam (consolidated in pressure chamber) using bentonite/brine mixture, available salt core samples.**
- **Prototype test (pictured at right) performed at 3.4 MPa normal stress, yielded at 0.6-0.7 MPa shear stress.**
- **Full test series completed March 2020: 8 tests performed by RESPEC**
  - **Pre-consolidation thicknesses of 6 mm, 12 mm (¼, ½ inches);**
  - **3 different normal pressures of 3.4, 6.8, 10.3 MPa (500, 1000, 1500 psi).**



9

Artificial clay seam shear tests – Description

- 8 samples total: 4 with seam with pre-consolidation thickness 6 mm (¼"), 4 with thickness 12 mm (½")
- Clay was made with mixture of bentonite, nearly-saturated brine
- Moisture content of clay pre-consolidation: 60% (1st batch), 54% (2nd batch)
- Samples held in consolidation chamber at 3000 psi for 2 weeks
- Post-consolidation seam height thicknesses: 12 mm down to 4.8 mm (3/16"); 6 mm down to 1.6 mm (1/16")
- Normal pressures for tests: 3.4, 6.8, 10.3 MPa (500, 1000, 1500 psi)
- Post-consolidation moisture content from chips: 13-17%
- Very little consolidation during test itself; less than 1 mm average normal displacement during test, nearly all salt deformation
- Shear ram velocity 0.004 mm/sec
- True residual tests were marginally achieved only on 4 tests

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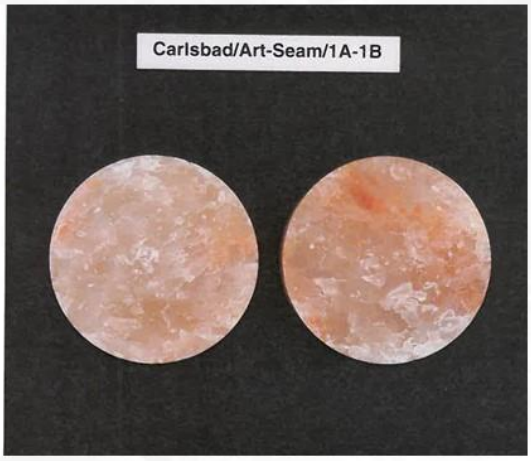
Specimen Construction – Samples from Core



Seam-side – where clay is applied | **Outside – where normal stress is applied**

Asperities were 1.3 mm deep, spaced 6 mm apart

11

Specimen Construction – Mixing Clay

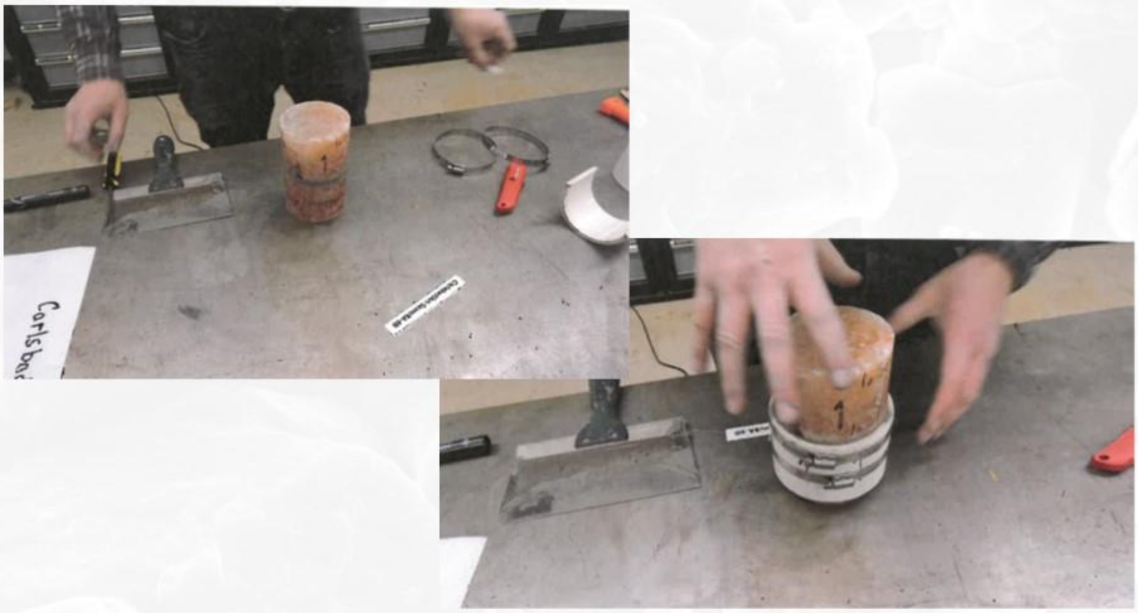
- Clay is mixture of bentonite, nearly saturated brine.
- Moisture content of clay pre-consolidation: 60% (1st batch), 54% (2nd batch).

12

Specimen Construction – Clay Application

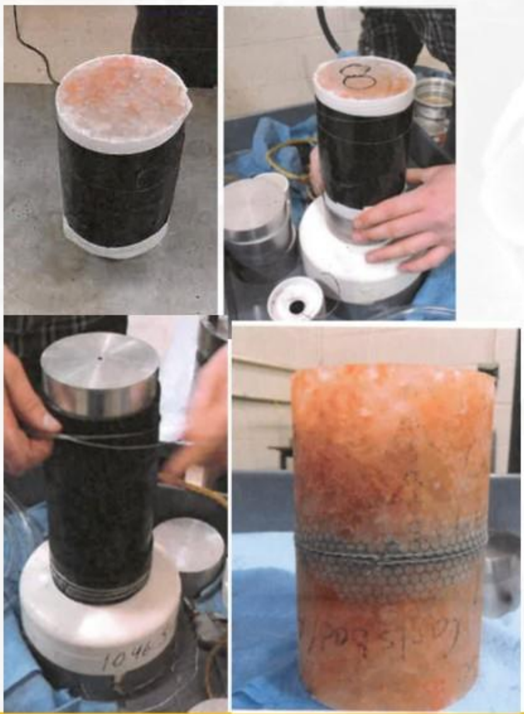
Top of PVC tube placed either 6 or 12 mm (¼" or ½") above top of salt surface; clay mixture troweled into grooves up to top of PVC.

Specimen Construction



Other cylinder is placed on top of clay, pressed downward while PVC contains clay.

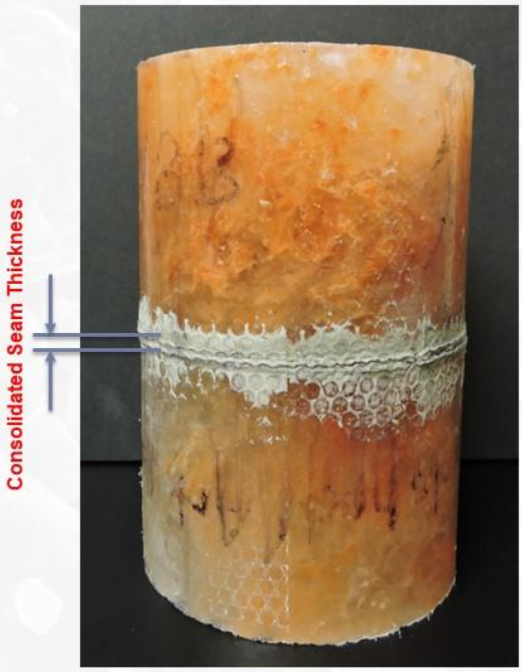
Specimen Construction – Consolidation



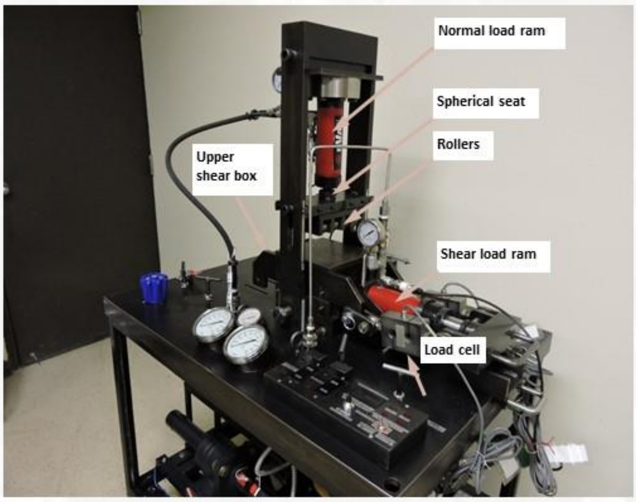
Specimen wrapped with Kimberly Clark BLOCK-IT wrap, electrical tape prior to placement in consolidation chamber.

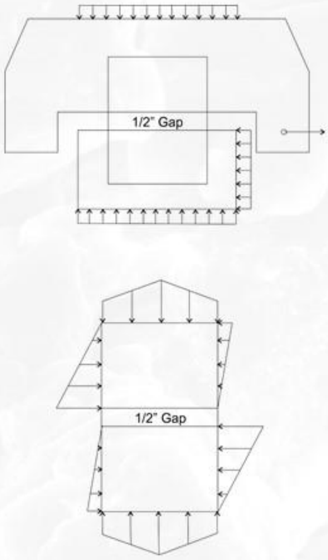
Specimen Fabrication

- 4 specimens with initial seam thickness of 6 mm
- 4 specimens with initial seam thickness of 12 mm
- Consolidated
  - 14 days at 20,7 MPa (3000 psi) hydrostatic stress and 21C
  - Excess pore fluid vented
- After consolidation
  - Approximately 1/3 of pre-consolidation thickness
  - Clay hardened
  - Fresh water moisture content 13 to 17%
  - No asperity-to-asperity contact



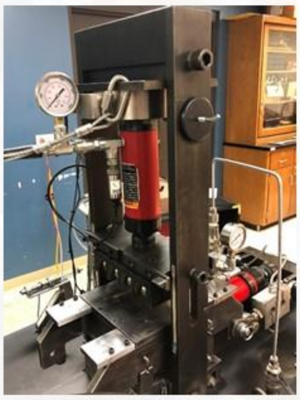
Direct Shear Test Setup



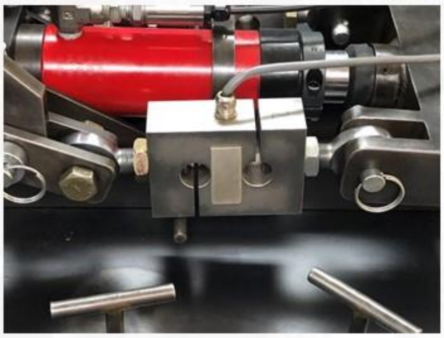


Note: All force profiles depend on contrast in stiffness between the specimen and grout.

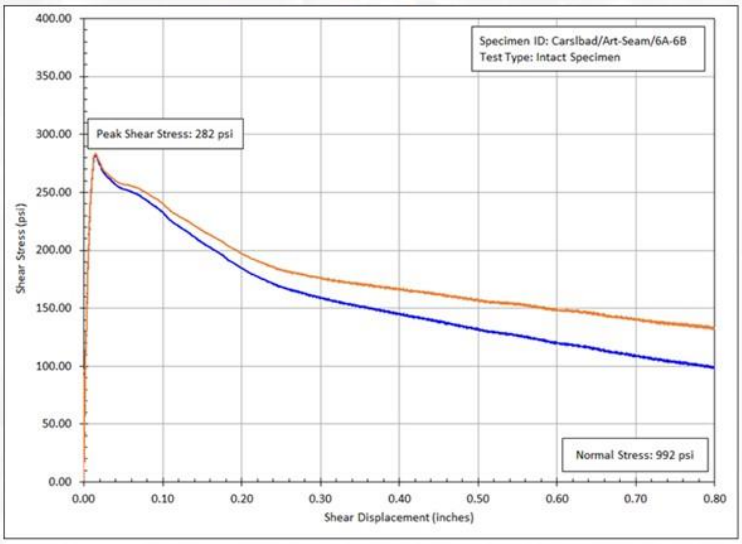
Direct Shear Test Machine



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

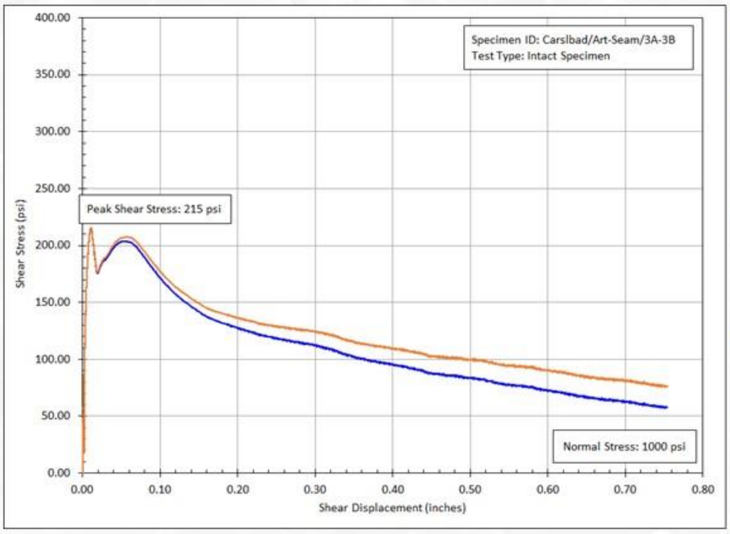


Shear Stress vs. Shear Displacement: Sample #6, 6-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



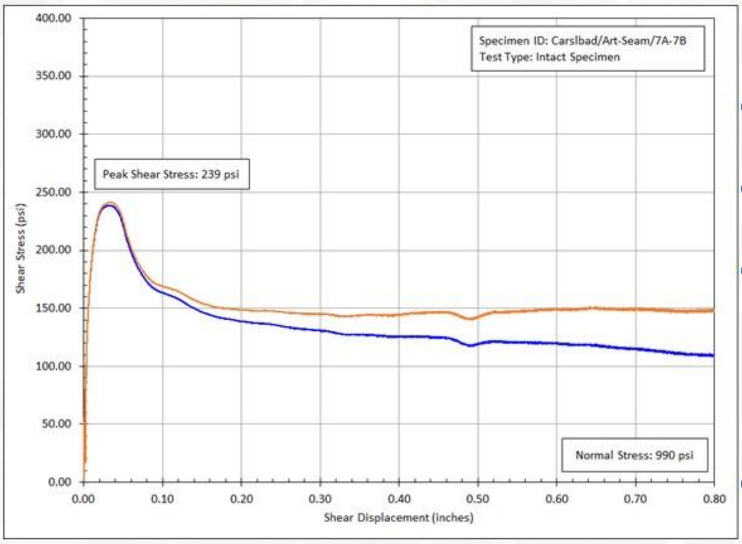
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual nominal normal stress = 992 psi (6.84 MPa)**
- **Peak shear stress = 282 psi (1.94 MPa)**
- **Never reached residual stress after initiation of shear movement**

Shear Stress vs. Shear Displacement: Sample #3, 12-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



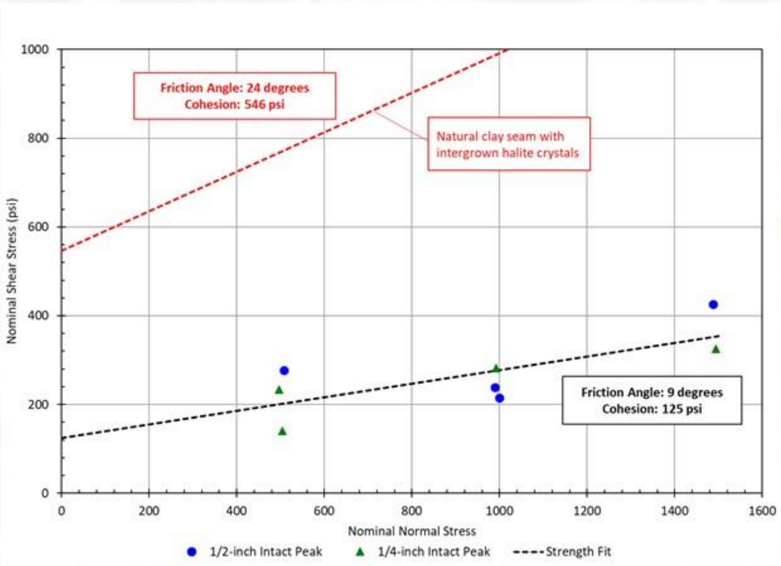
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual nominal normal stress = 1000 psi (6.89 MPa)**
- **Peak shear stress = 215 psi (1.48 MPa)**
- **Never reached residual stress after initiation of shear movement**
- **Power-related disturbance near beginning of test**

Shear Stress vs. Shear Displacement: Sample #7, 12-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



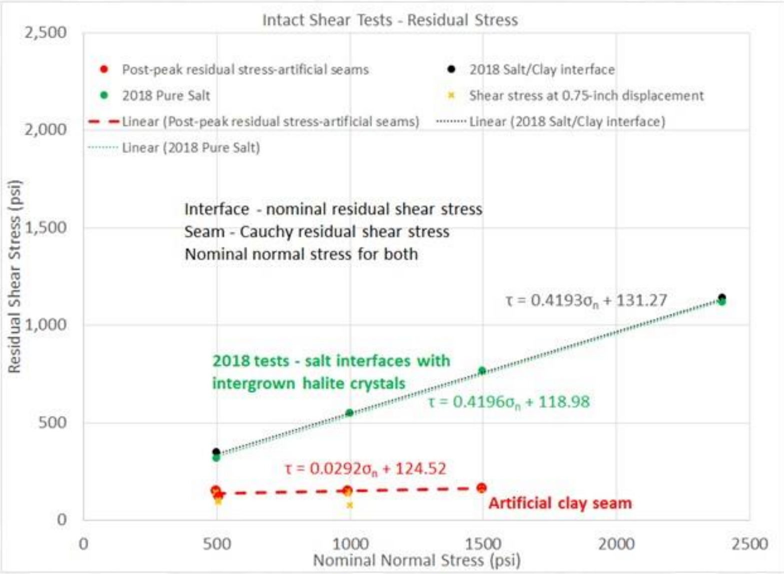
- **Repeat of Test #3 due to power-related disturbance near beginning of test**
- **Actual nominal normal stress = 990 psi (6.83 MPa)**
- **Peak shear stress = 239 psi (1.65 MPa)**
- **Reached apparent residual stress of ~150 psi (1.03 MPa) at 0.75” (19 mm) shear displacement after initiation of shear movement**
- **“Apparent” residual stress because unchanged normal load, changing contact area mean changing normal stress**

Intact Peak Stresses



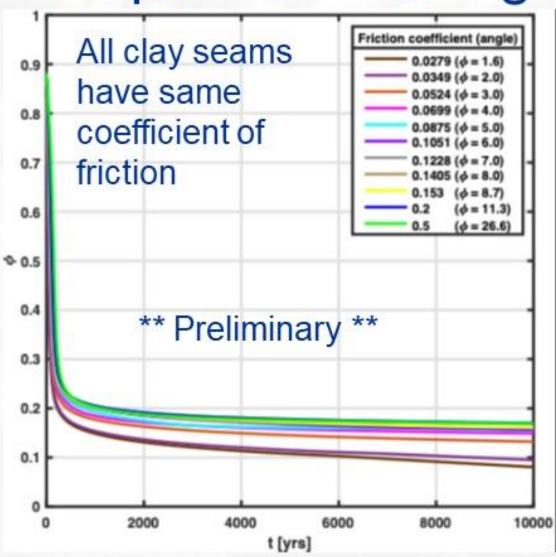
- **Average friction angle 8.7°, average cohesion 125 psi (0.86 MPa)**
- **Much lower than for previous salt interface tests: friction angle 24°, cohesion 546 psi**

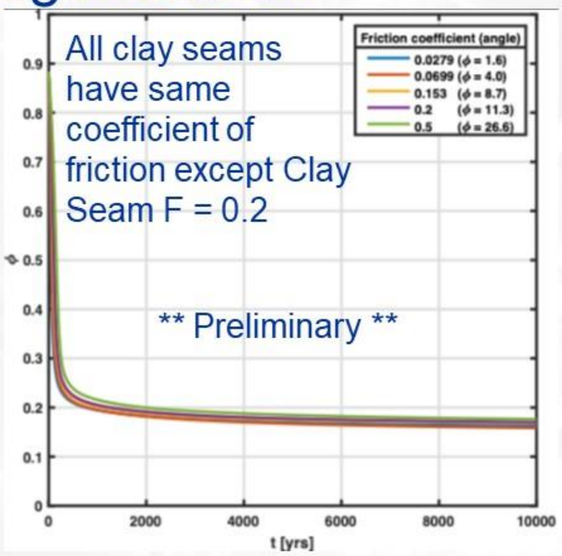
Intact shear tests – Residual Stresses



- Only 4 of 8 tests attained apparent residual stresses after initiation of shear displacement
- Friction angle 1.7°, cohesion ~125 psi (0.86 MPa)
- Lower friction angle than for previous salt interface tests: angle 13-23°, cohesion 119-355 psi (0.82-2.45 MPa)
- Values much lower than expected; softness of clay, asperity size may be factors
- Current assumption is that Clay Seam G test results will plot between interface and artificial seam results

Effect of clay seam on porosity response - zero gas generation





For case of zero gas generation, only clay seams in close proximity to drifts have influence on porosity response surface.

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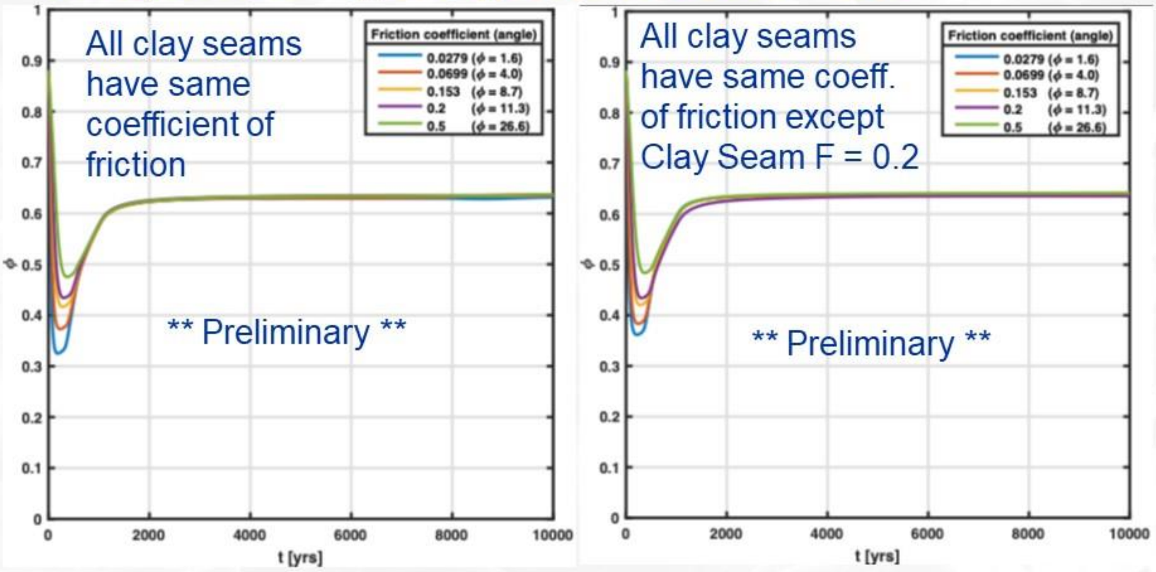
Effect of clay seam on porosity response - gas generation f=0.5



- For case of gas generation, analyses indicate larger sensitivity at short times, and insensitivity at longer times.

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Artificial clay seam shear tests – Conclusions

- Eight samples of salt with artificial clay seams of two different thicknesses were subjected to displacement-controlled direct shear tests at three different normal loads.
- Maximum, final shear strength were determined for each test.
- Although none of the tests achieved a true residual stress plateau, the final shear stresses reasonably conformed to Mohr-Coulomb behavior.
- The Mohr-Coulomb parameters were similar to those of a highly consolidated, saturated, clay, which is to say they were quite low.
- In situ WIPP clay seams F, G, others vary significantly in visual, tactile character; relation to artificial seam tests will be unknown until tests on in situ samples can be performed.

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Questions?

Thank you for your attention!

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Results of the other artificial seam shear tests

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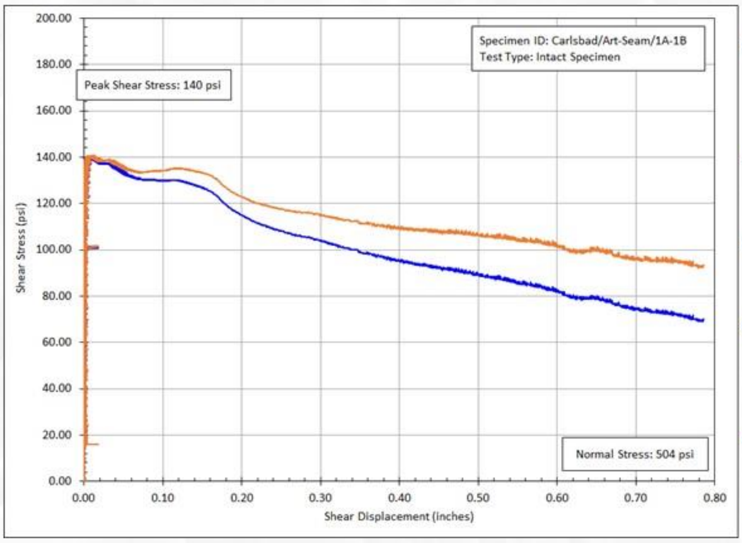
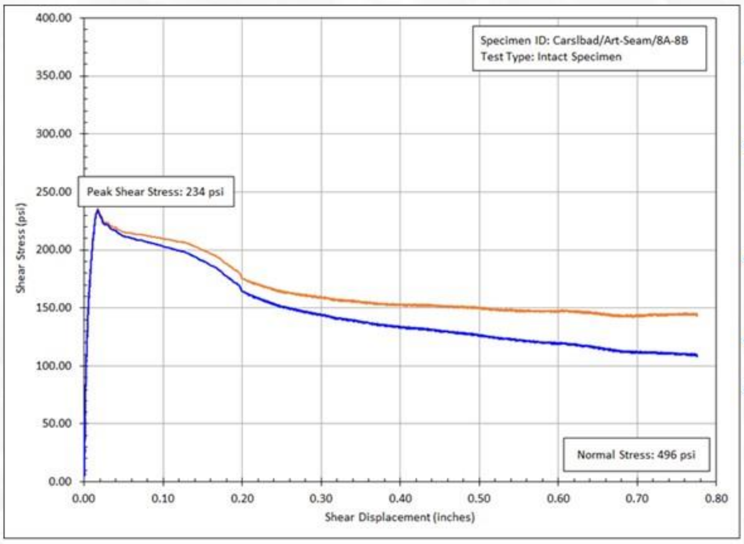
Shear Stress vs. Shear Displacement: Sample #1, ¼” seam pre-consolidation, 500 psi normal stress



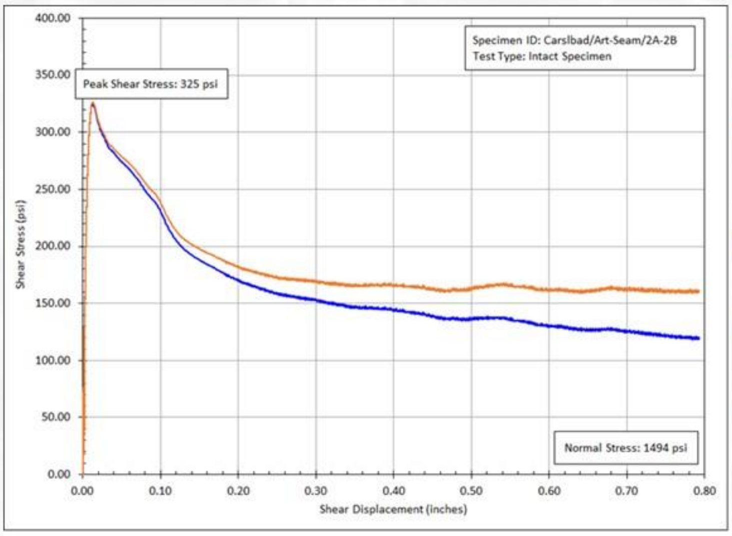
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 504 psi**
- **Peak shear stress = 140 psi**
- **Never reached residual stress after initiation of shear movement**
- **Test data was very noisy, although probably no effect on main result; Sample #8 tested at same conditions**

Shear Stress vs. Shear Displacement: Sample #8, ¼” seam pre-consolidation, 500 psi normal stress



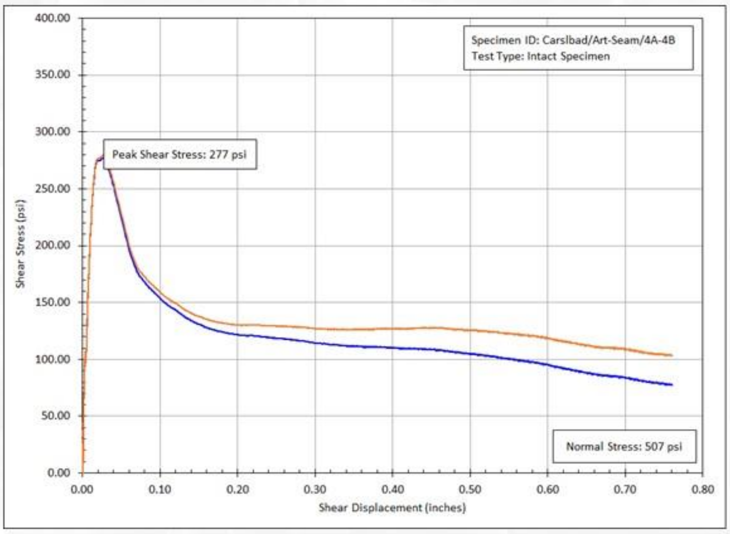
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 496 psi**
- **Peak shear stress = 234 psi**
- **Reached residual stress of ~150 psi after initiation of shear movement**

Shear Stress vs. Shear Displacement: Sample #2, ¼" seam pre-consolidation, 1500 psi normal stress



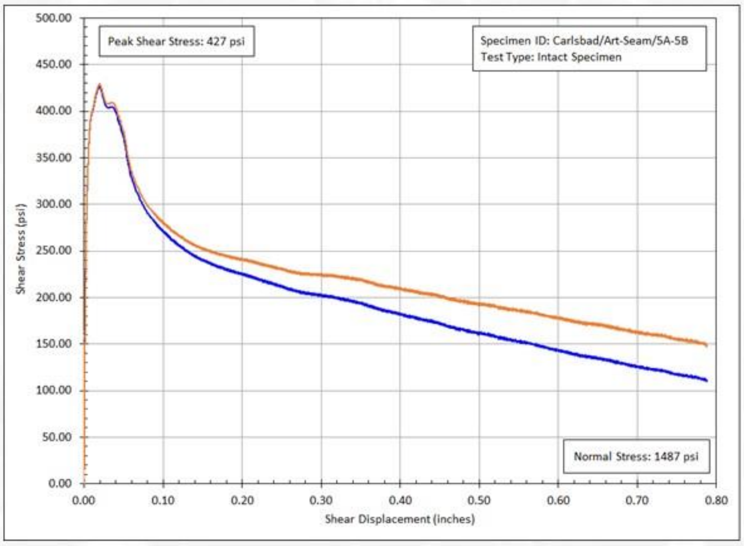
- Blue: Stress calculated with constant contact area
- Orange: Stress calculated with contact area modified by shear displacement
- Actual normal stress = 1494 psi
- Peak shear stress = 325 psi
- Reached residual stress of ~170 psi after initiation of shear movement

Shear Stress vs. Shear Displacement: Sample #4, ½" seam pre-consolidation, 500 psi normal stress



- Blue: Stress calculated with constant contact area
- Orange: Stress calculated with contact area modified by shear displacement
- Actual normal stress = 507 psi
- Peak shear stress = 277 psi
- Reached residual stress of ~130 psi after initiation of shear movement

Shear Stress vs. Shear Displacement: Sample #5, ½” seam pre-consolidation, 1500 psi normal stress



- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 1487 psi**
- **Peak shear stress = 427 psi**
- **Never reached residual stress after initiation of shear movement**

11th US/German Workshop on Salt Repository Research, Design and Operation

STROEFUN III

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

Sandia National Laboratories

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

BGE TEC
BGE TECHNOLOGY GmbH

Julius Bauermeister
TU Clausthal

Part 3 of the online workshop
September 08, 2021

Table of content

- Introduction
- Goals
- Concept
- Virtual tour
- Dam construction
- Pressure and temperature development
- Outlook

2

STROEFUN III- Introduction

- What is STROEFUN III about?
  - Fluidic functional verification for closuring structures and fluid supported sealing of the contact area
- Project from Jan. 2019 up to July 2022
  - 5 different partners and 2 service providers

TU Clausthal

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

3

STROEFUN III- Goals

- Developing a concept for proving the fluidic properties of a closure structure
- Measures for the subsequent modification of higher permeability in the contact zone
- Testing of the treatment concept on a laboratory and semi-technical scale (in situ)

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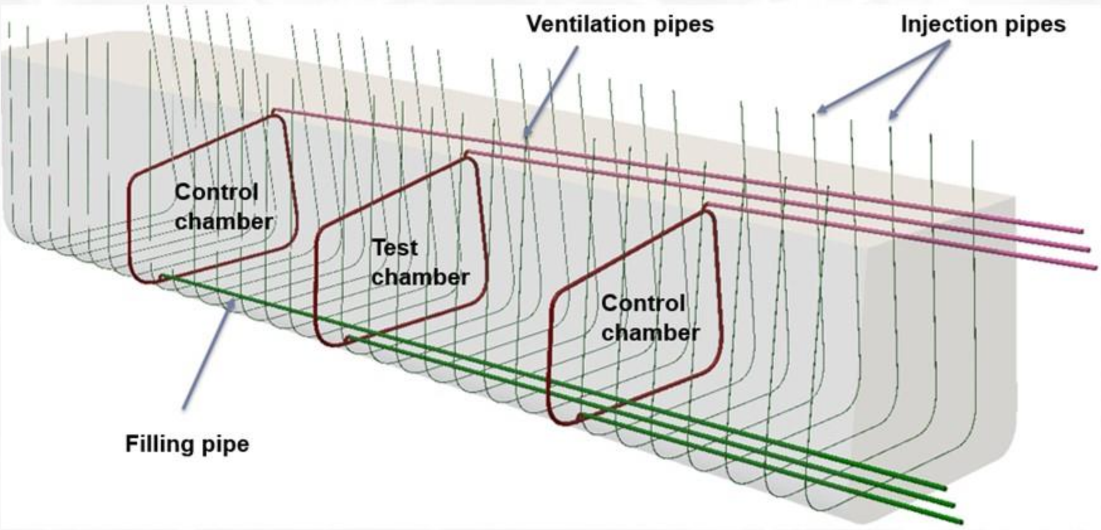
STROEFUN III- Concept



Concept: IBeWa (2019)

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STROEFUN III- Concept

- Drift after excavation

- Drift before concreting

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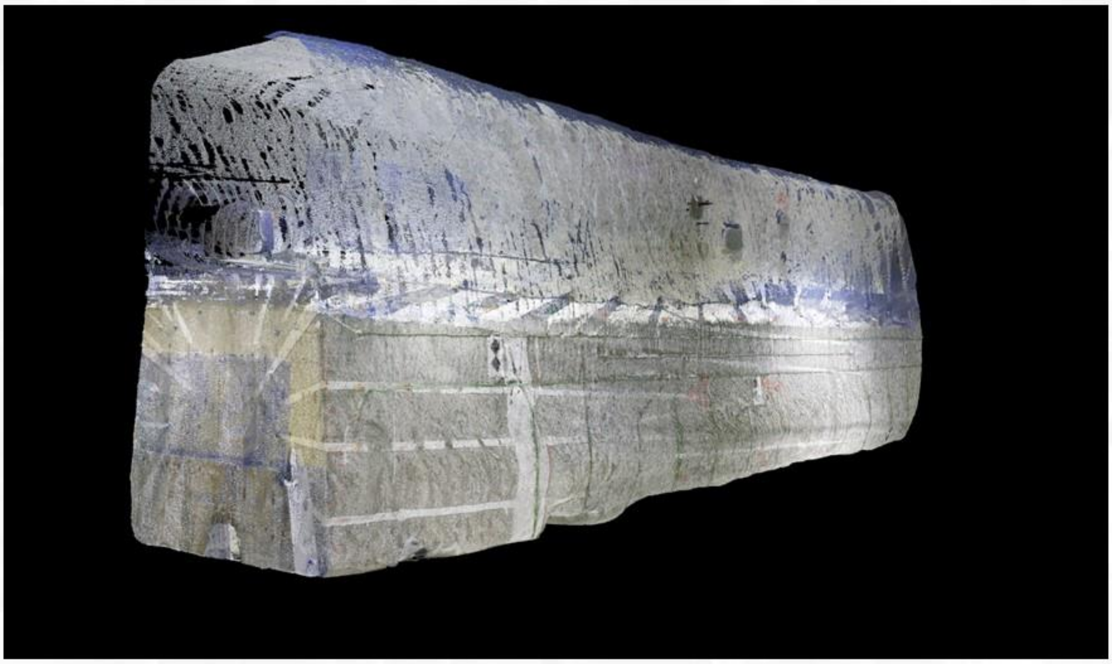
STROEFUN III- Virtual tour



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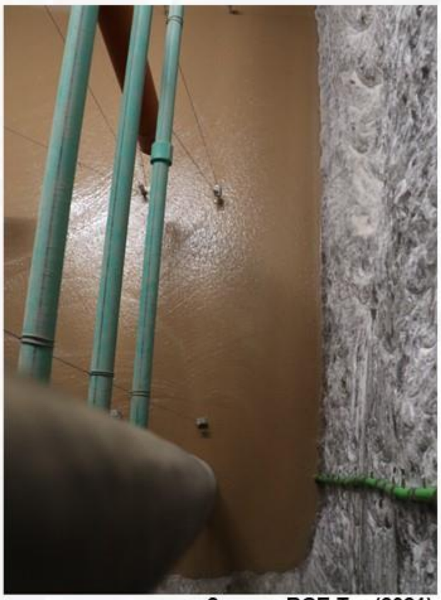
STROEFUN III- Dam construction

- The concrete is based on the A1-recipe from the BGE Tec
  - Anhydrate as an adjustment
- Challenge: Finding the suitable MgO

Source: BGE Tec (2021)



Source: BGE Tec (2021)

8

STROEFUN III- Dam construction

- Crack formation after a 2 hours break; July 27th, 2021- 16:36

Source: IBeWa (2021)

9

STROEFUN III- Dam construction

- Cracks on the surface close to the formwork

- 14 meters of crack-free-concrete

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STROEFUN III- Dam construction

- Firm connection between the concrete and the surrounding salt

- Small gap between the sewer pipe and the sorel concrete

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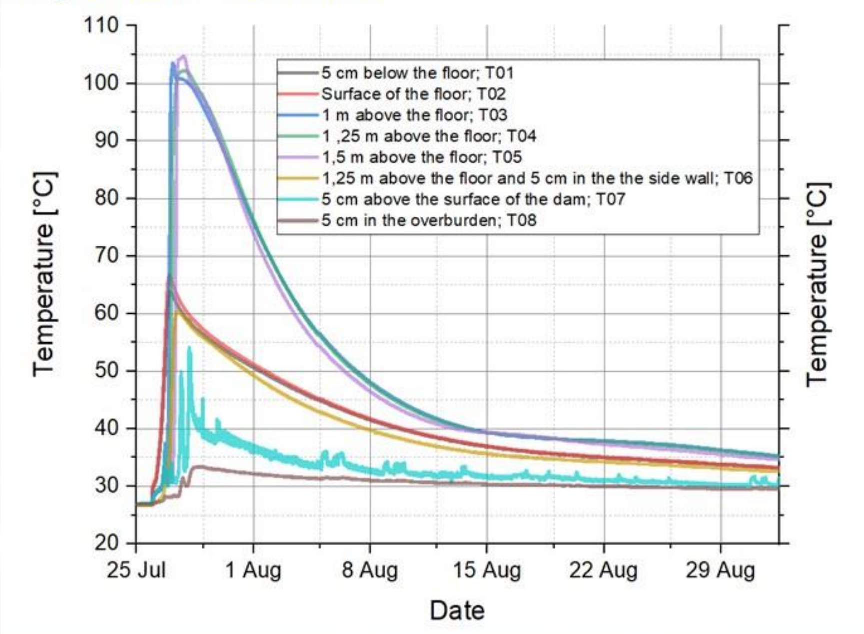
STROEFUN III- Pressure and temperature

- Temperature detection



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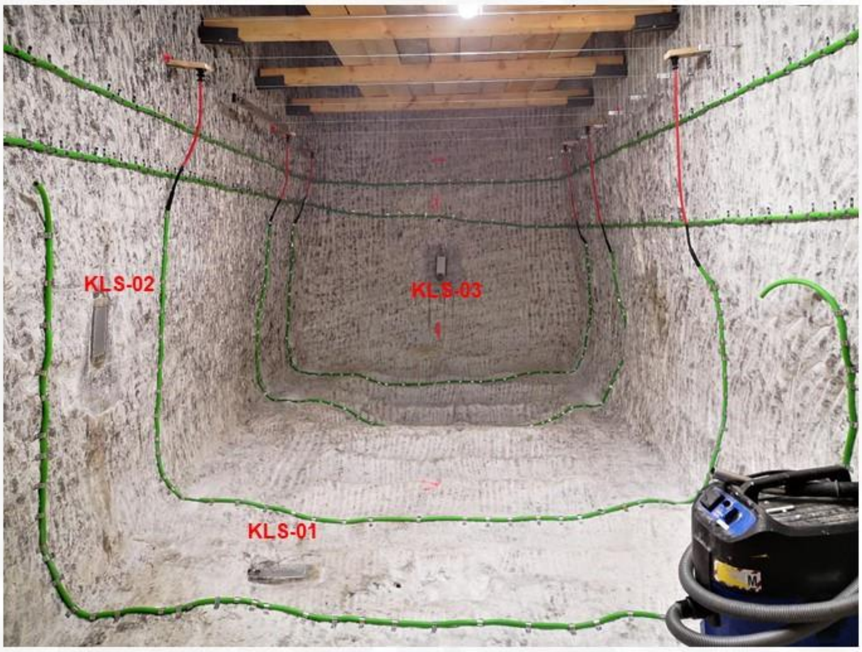
STROEFUN III- Pressure and temperature



Source: IBeWa (2021)

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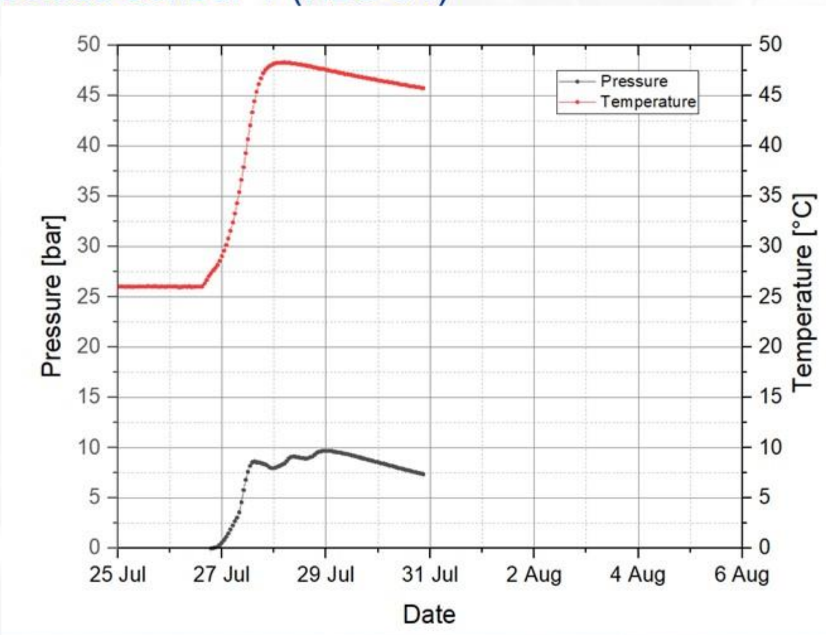
STROEFUN III- Pressure and temperature

- Wireless sensor 1 (KLS 01)



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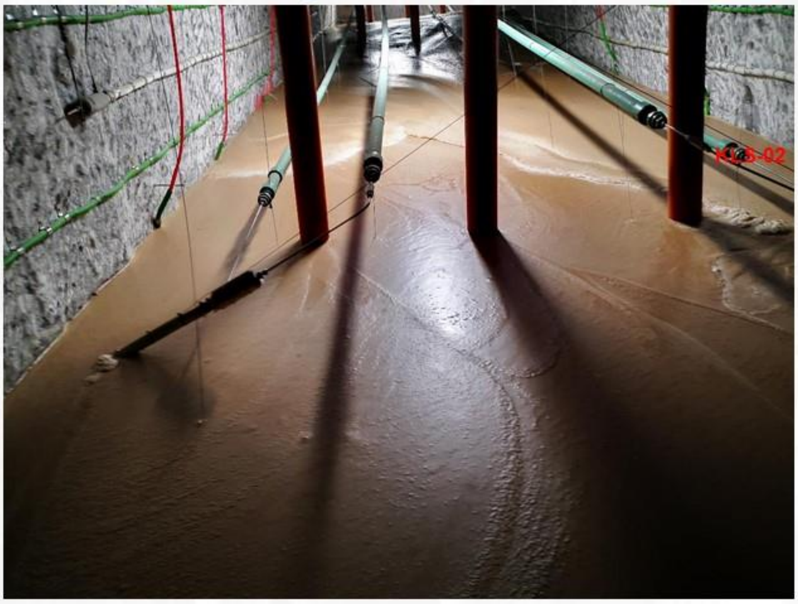
STROEFUN III- Pressure and temperature

- July 27th, 2021-17:02, the height of KLS-02 has been reached



Source: IBeWa (2021)

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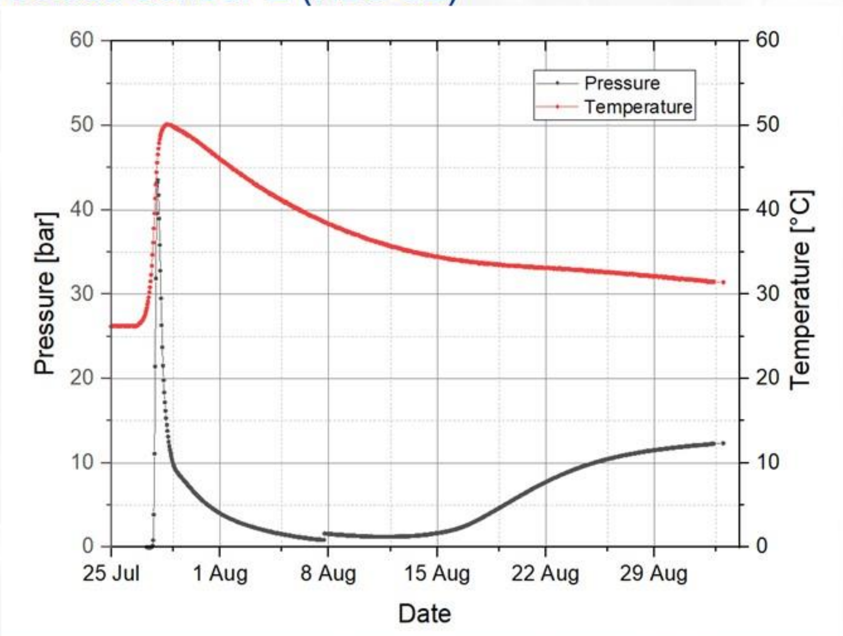
STROEFUN III- Pressure and temperature

- Wireless sensor 2 (KLS 02)



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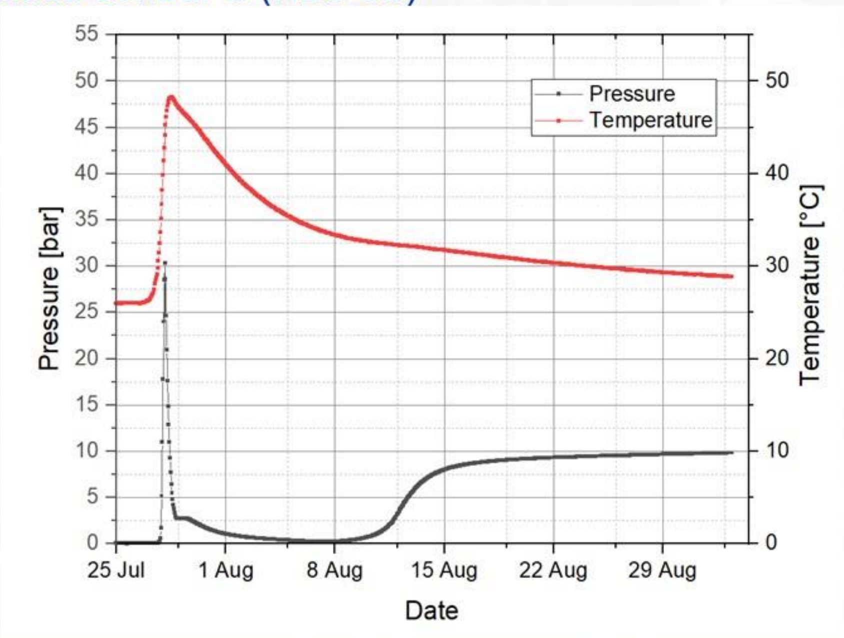
STROEFUN III- Pressure and temperature

- Wireless sensor 3 (KLS 03)



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STROEFUN III- Outlook

- Permeability measurements
- Injection with MFBBa and Epojet LV
- Drill core extraction
- Documentation

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STROEFUN III- Questions
▪ Feel free to ask questions ☺
US/GERMAN WORKSHOP
Sandia National Laboratories
PTKA
BGE TEC
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Appendix D – Program and Presentations of Part 4 (9th September 2021)

Berlin time		9th September 2021 – Day 2	
16:00	16:10	Welcome by the organizers	M. Bühler/PTKA W. Bollingerfehr/ BGE TEC
Modelling Chair: K. Kuhlman			
16:10	16:40	UVERSTOFF – The viscous behaviour of MgO-concrete and its numerical modelling	N. Müller-Hoeppe/BGE TEC
16:40	17:10	RANGERS – Development of Guidelines for Design and Integrity of Repository Seals in a Salt Host	E. Matteo/SNL, E. Simo/BGE TEC
17:10	17:40	BenVaSim - Benchmarking Results for Heterogeneous H^2M and TH^2M Models	M. Rutenberg/ TU Clausthal
17:40	17:50	10 min Break	
17:50	18:20	BATS - summary of the experiment and results	M. Mills/SNL
18:20	18:50	BATS field test and related DECOVALEX modeling	Eric Guiltinan/LANL, R. Jayne/SNL
18:50	19:00	Summary and Outlook	M. Bühler/PTKA W. Bollingerfehr/ BGE TEC

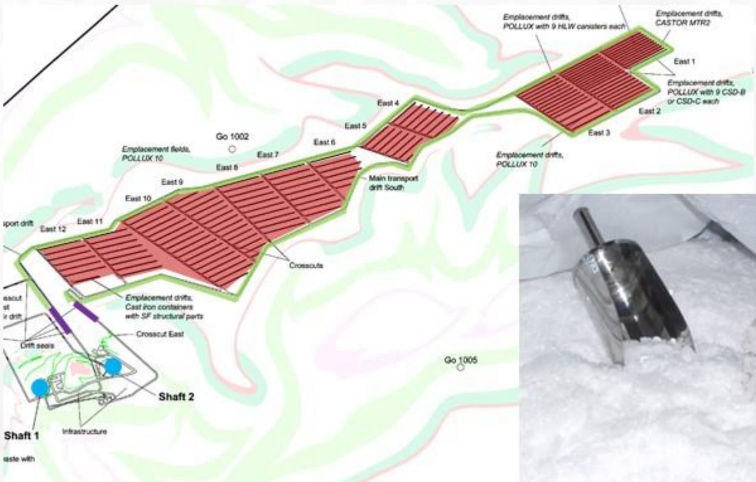
11th US/German Workshop on Salt Repository Research, Design, and Operation

UVERSTOFF – The Viscous Behavior of MgO-Concrete

Christian Lerch
Nina Müller-Hoeppe
BGE TECHNOLOGY GmbH

Part 4 of the online workshop
September 9, 2021

Isolation of Radwaste (BMU 2010) - VSG



Backfill and seals:

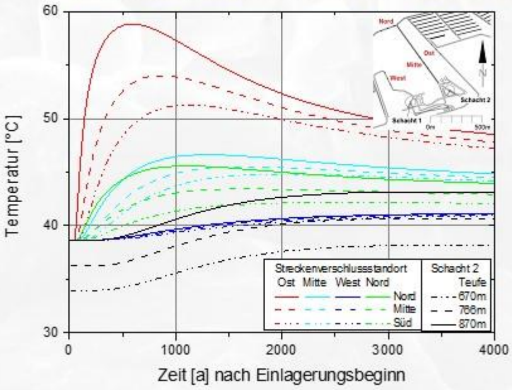
- Dry crushed salt in emplacement drifts and cross-cuts
- Humid crushed salt in access drifts
- Drift seals (made of MgO-concrete)
- Shaft seals include humid crushed salt sealing elements

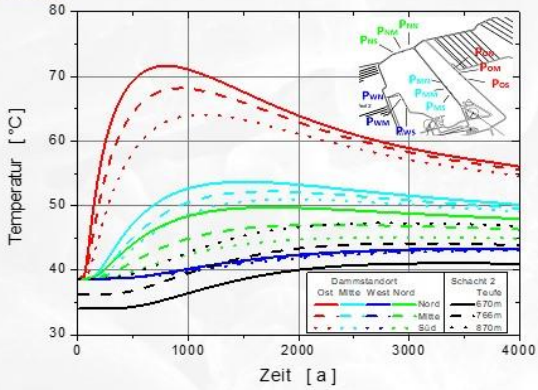
… until crushed salt is sufficiently compacted shaft and **drift seals** guarantee safe confinement!

2

Drift Seals – Thermal Impact

- Drift seals are subjected to a long-lasting thermal impact/load
- The temperature maximum will appear after repository closure
- Question: Does the thermal impact affect drift seals´ functionality due to thermomechanical induced crack formation?



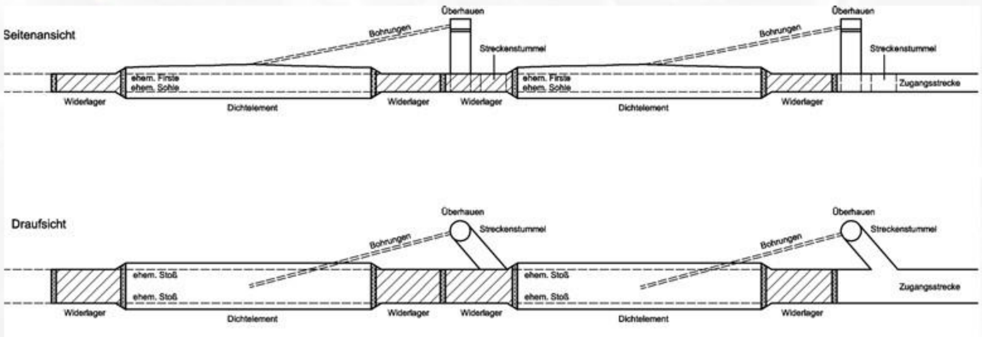


- Argumentation so far: The MgO-concrete structure was subjected to higher temperatures in its past
- However, the only significant thermal load considered is hydration heat at early age (mass concrete)
- Does this argumentation hold?

3

Structural Model – Material Model

- The geometry of a drift seal is simple
- ➢ Simple structural model



- The material behavior of concrete is complicated even in the case of conventional concrete
- So-called engineering models are used whose validness is restricted to special applications
- Question: But what about the material behavior of MgO-concrete with MgO constituting the binding agent and crushed salt the aggregate?

4

Starting Point: Conventional Concrete

Knowledge on material behavior of conventional mass concrete

- Heat release due to hydration process and coupling of concrete age to temperature history
- Evolution of elastic material properties depending on concrete age
- Evolution of mechanical strength depending on concrete age
- Evolution of shrinking/swelling depending on concrete age and hygric state
- Evolution of viscous behavior depending on concrete age and additional factors
    - Distinguishing two* types of creep behavior
    - Basic creep (long term creep/viscous flow)
    - Transient creep (short term creep/delayed elastic)

* The existence of one or two types of creep was frequently discussed in the past and the scientific discussion is ongoing. Presently, the discussion tends to two parts.

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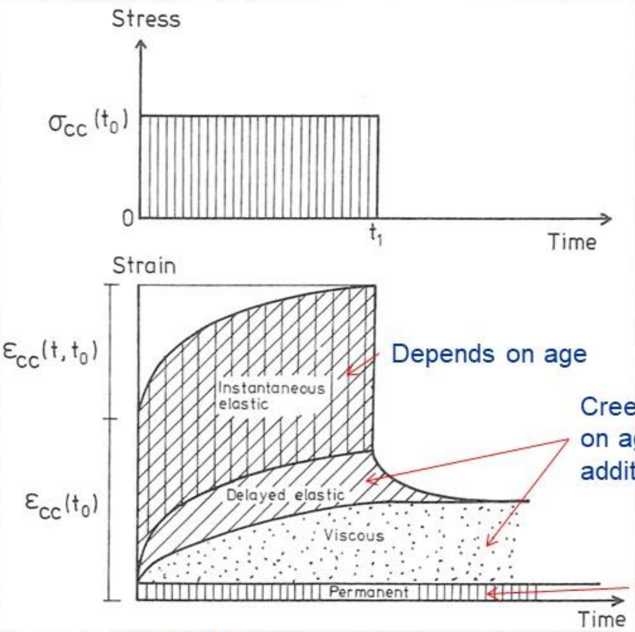
Conventional Concrete – Decomposition of Strains



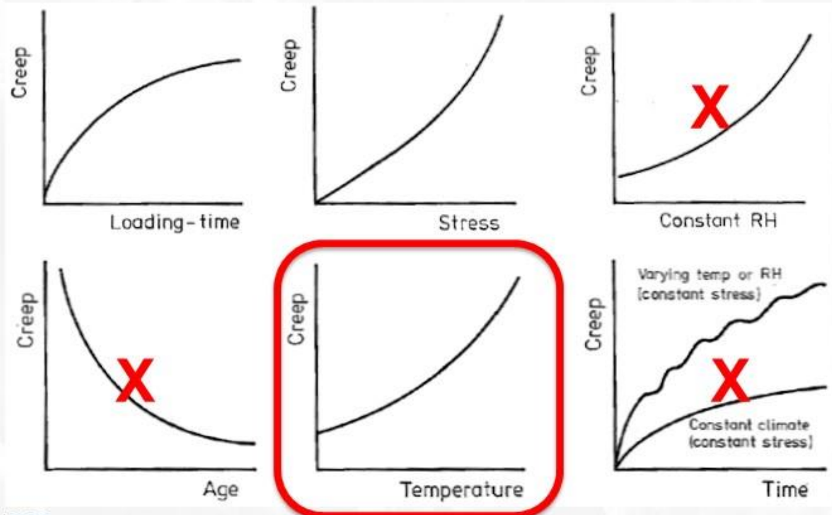
Byfors 1980

6

Conventional Concrete - Creep Influencing Factors

Under repository conditions thermal impact occurs at

- High concrete age
- Dry constant climate (expected repository conditions)
- One long-lasting thermal impact
- ➢ Some influencing factors could be neglected

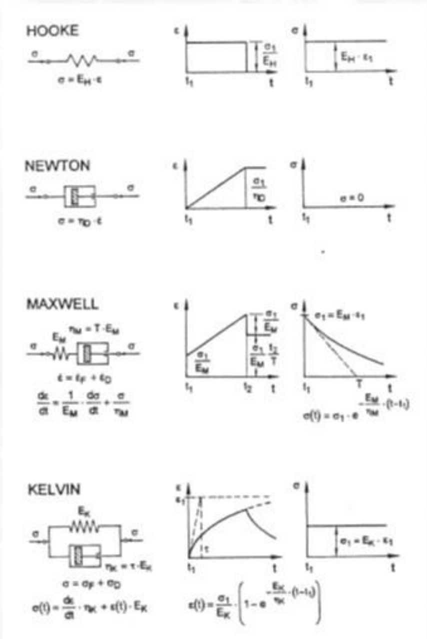


Byfors 1980

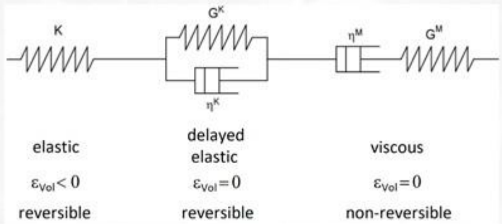
7

Selection of Rheological Model

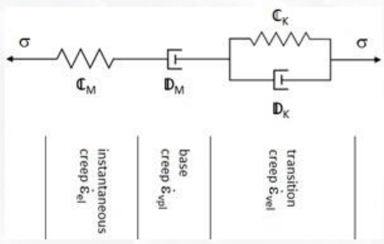
- Basic rheological models used for concrete



- Rheological model used for salt



- First choice of rheological model for MgO-concrete with crushed salt aggregate



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MgO-Concrete - Laboratory Investigations

- Challenge: Test specimens of high concrete age kept at constant climate
  - ➢ Availability of test specimens of MgO-concrete that were produced in the context of the building of flow barriers in the Asse mine

- Definition of the load-temperature conditions of laboratory tests conjointly with GRS taking into account conditions of the VSG drift seals
  - ➢ Triaxial tests starting at 30 °C heating up to 60 °C, loading condition 22 MPa axial stress and 2 MPa radial stress but well below MgO-concrete´s strength
  - ➢ Triaxial tests were performed twice under nearly similar conditions to control the reproducibility of test results

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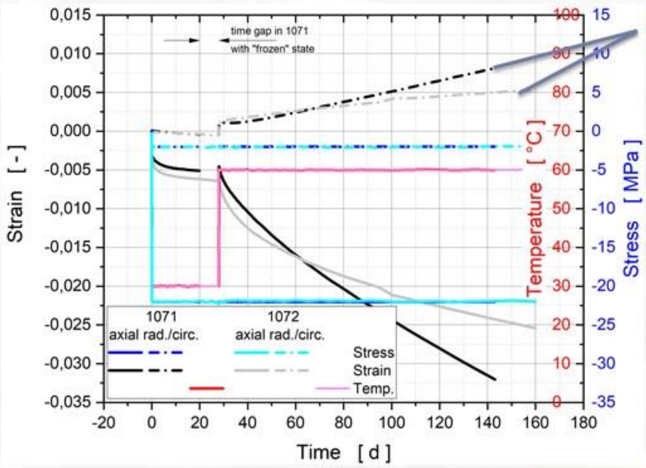
MgO-Concrete – Laboratory Test Results



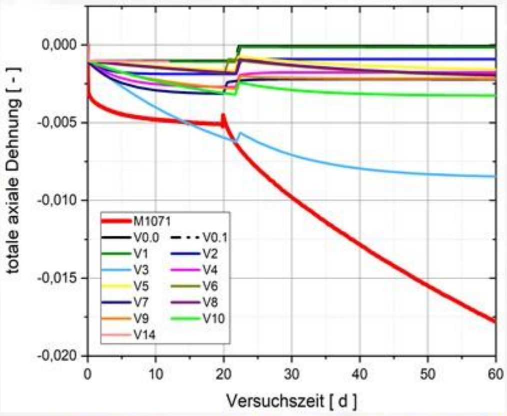
Different trends

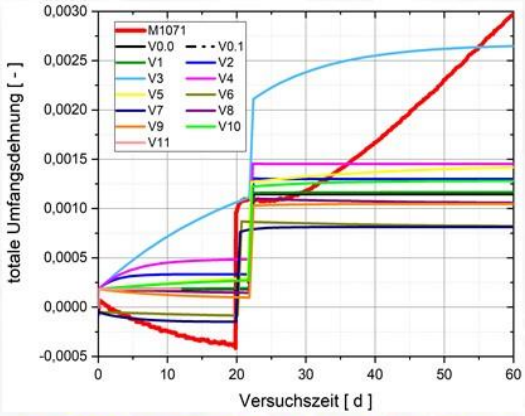
- The two tests were not sufficient
- ➢ GRS performed two additional tests
- ➢ Application of the recent test concept to distinguish mainly deviatoric and mainly spherical stress conditions

10

Experimental Results and Numerical Adjustments

Some numerical adjustments to available tests in the waiting period for additional test results





- Hein´s crushed salt approach for the Maxwell element supplemented by an Arrhenius term
- Linear Kelvin element with constant elastic module and constant viscosity supplemented by an Arrhenius term
- Accompanying checks whether parameter values remained within reasonable limits

- ➢ Numerical adjustments were too stiff
- ➢ The increasing trend in the lab test was assumed not to be plausible

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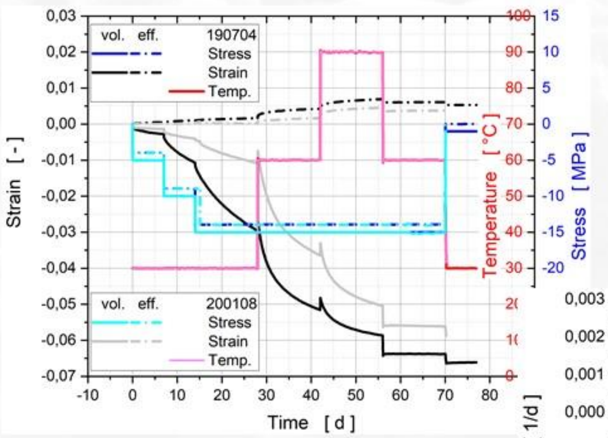
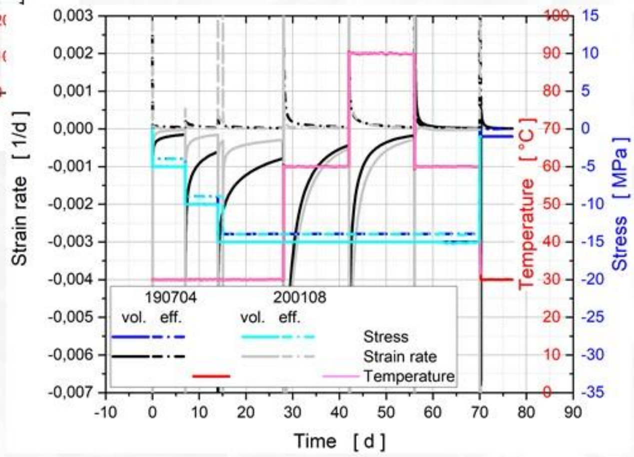
Results from (Additional) Mainly Spherical Tests



Decomposition of test regime in mainly spherical and mainly deviatoric tests utilizes the mathematical orthogonality of spherical tensor and deviator in the material model



GRS

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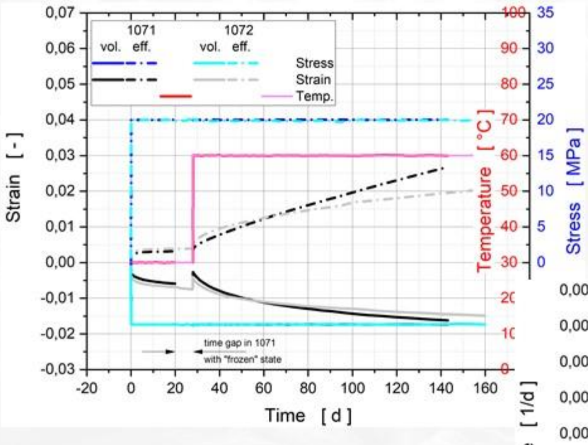
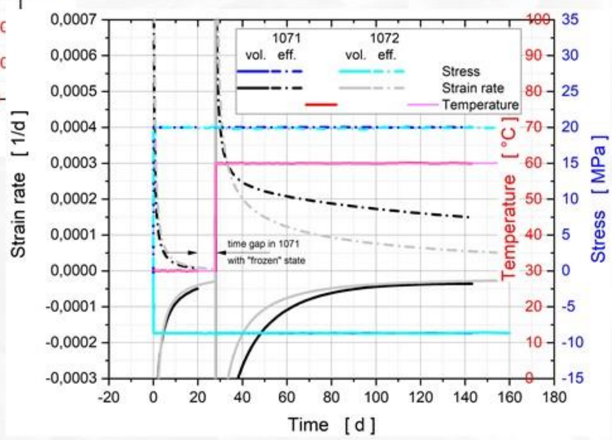
Results from Mainly Deviatoric Tests



Test results were also displayed and re-analyzed in the decomposed way



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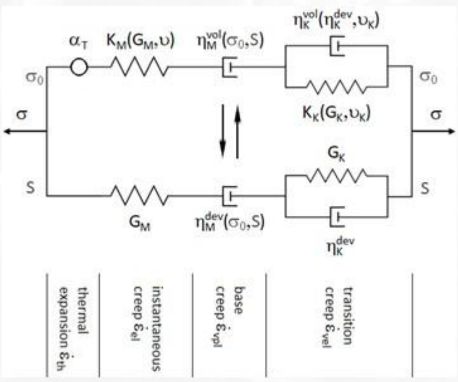
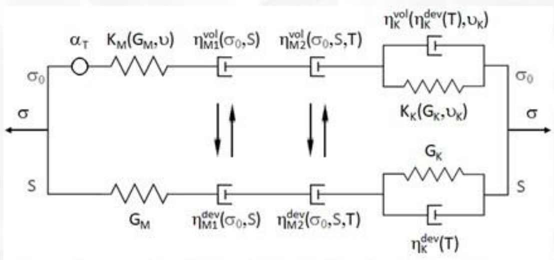
Material Model for high aged MgO-concrete

Initial state



Current state



Initial state:

$$\dot{\boldsymbol{\varepsilon}}_{th} = \alpha_{th} \dot{T}\, \boldsymbol{I} \qquad \dot{\boldsymbol{\varepsilon}}_{el} = \mathbb{C}^{-1} \dot{\boldsymbol{\sigma}}$$

$$\dot{\boldsymbol{\varepsilon}}_{vpl} = A\, F(\sigma_0, \hat{\sigma})\, \frac{\partial F}{\partial \boldsymbol{\sigma}}\, ; F = m|\sigma_0| + n\hat{\sigma}$$

$$\dot{\boldsymbol{\varepsilon}}_{vel} = \mathbf{D}^{-1} \boldsymbol{\sigma} - \mathbf{D}^{-1} \mathbb{C}\, \boldsymbol{\varepsilon}_{vel}$$

Current state:

$$\dot{\boldsymbol{\varepsilon}}_{th} = \alpha_{th} \dot{T}\, \boldsymbol{I} \qquad \dot{\boldsymbol{\varepsilon}}_{el} = \mathbb{C}^{-1} \dot{\boldsymbol{\sigma}}$$

$$\dot{\boldsymbol{\varepsilon}}_{vpl} = \sum_{i=1}^{2} A_i e^{-\frac{Q_{M,i}}{RT}} F_i^q(\sigma_0, \hat{\sigma})\, \frac{\partial F_i}{\partial \boldsymbol{\sigma}}\, ; F_i = m_i|\sigma_0|^{p_i} + n_i \hat{\sigma}^{p_i}$$

$$\dot{\boldsymbol{\varepsilon}}_{vel} = e^{-\frac{Q_K}{RT}}\, \mathbf{D}^{-1} (\boldsymbol{\sigma} - \mathbb{C}\, \boldsymbol{\varepsilon}_{vel})$$

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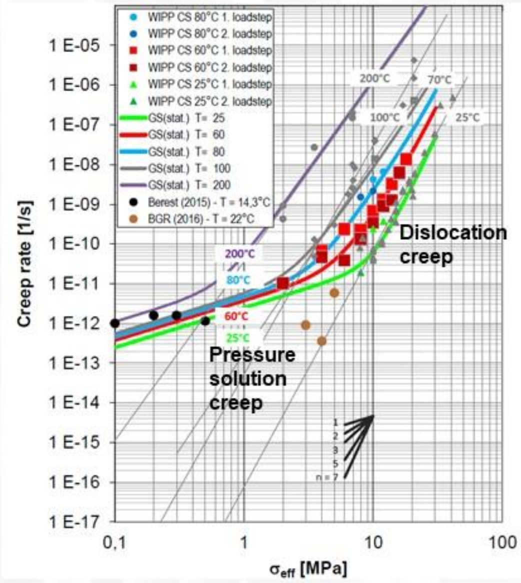
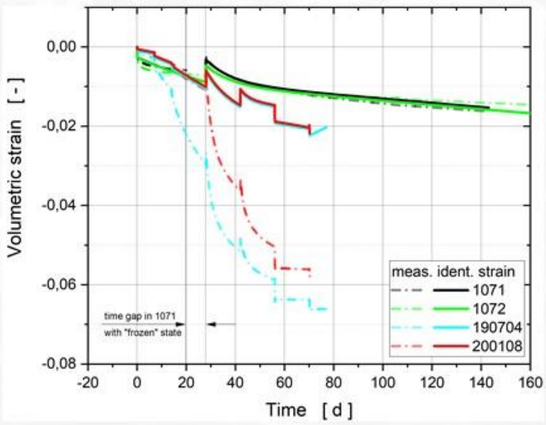
Maxwell Element and Successive Parameter Identification

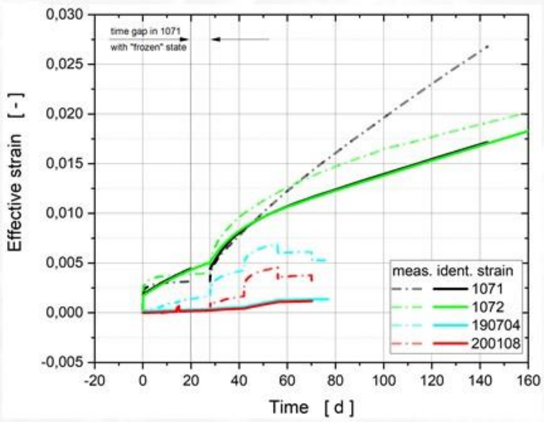
- Parameter values and their explanation:
- Exponents: 1 - 3
- Indicating main influence of pressure solution creep
- Spherical activation energy shows negligible dependency on temperature
- Deviatoric activation energy shows dependency on temperature in the range of salt



Salt

Kelvin Element and Parameter Identification



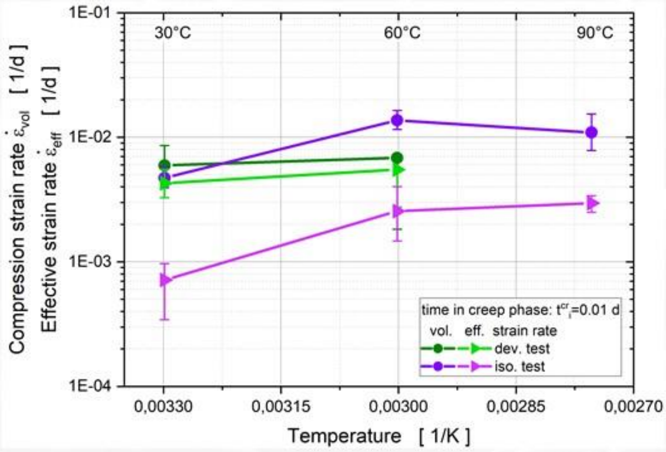


- Requiring that all experiments should be captured by the same set of parameters the identified parameter set is unsatisfactory as the Kelvin element remains too stiff
- Typically, thermal activation plays a role of „softening" the material

➢ Consequently, temperature dependency of strain rate immediately after mechanical/thermal load step was investigated in detail (assuming that in this time period the Kelvin element dominates the strain rate)

Influence of Temperature

Temperature dependency of strain rate decomposed in deviatoric and spherical part shortly after temperature rise



- Result: None or very low temperature dependency

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Process Understanding and Conclusions

- The short term process seems to be governed by viscoelasticity (like concrete)
  - ➢ Due to the limitations of engineering concrete models further applications of viscoelasticity were considered
- Literature from modeling of polymers was included
  - ➢ The finding: The viscoelastic behavior of polymers is described by a spectrum
  - ➢ This issue is explained by the internal structure of the polymers being composed of different molecular chains
- This argumentation also holds for concrete being a multi-aggregate material
  - ➢ The argumentation explains the stiff behavior of one Kelvin element (missing internal degrees of freedom to represent the spectrum)
  - ➢ The Maxwell and Kelvin chains applied in concrete models on a semi-empirical basis are an adequate approach, the parameters of the chains, however, are not independent (as they treated) but belong to a spectrum
  - ➢ The parameters of the spectrum must be identified, experimentally
  - ➢ The mathematics to describe these relationships is non-standard

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Summary and Outlook

- A material model for MgO-concrete was established consisting of rheological elements - Maxwell and Kelvin type - and being able to capture thermal activation
- Experimental results gained from complex experiments formed the basis for parameter identification
- The Maxwell element shows thermally activated behavior and seems to capture mainly the salt aggregate´s influence
  - The range of exponents identified indicates the dominance of pressure solution creep
- The Kelvin element did not agree well with the experimental results – too stiff
- Surprisingly, the Kelvin element shows low temperature dependency indicating that a different (unexpected) type of process is acting
- Based on further information the conclusion is drawn that an internal “dynamic” process may act that is characterized by a spectrum
  - Due to the “dynamics” of the process potentially it might be neglected in long-lasting processes with small changes on the time scale

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Acknowledgement

Many thanks to our colleagues from GRS for precise experimental results constituting the basis for our investigations and to

The German Federal Ministry for Economic Affairs and Energy (BMWi) managed by the Project Management Agency Karlsruhe (PTKA) for funding the project (FKZ 02E11678)

Casting of MgO-Concrete

PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

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RANGERS:
Methodology and Numerical Applications

11th US/German Workshop on Salt Repository Research, Design, and Operation

Eric Simo, Philipp Herold, Andreas Keller, Andree Lommerzheim, Paola Léon-Vargas

BGE TECHNOLOGY GmbH

Edward Matteo, Kristopher Kuhlman, Teklu Hadgu, Richard Jayne, Melissa Mills

SANDIA National Laboratories

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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-NA-0003525. SAND2021-10982 C. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

What is RANGERS?

- **RANGERS stands for:**
  - (german) Entwicklung eines methodischen Ansatzes zu**r** **A**uslegung und zum **N**achweis von **g**eo-technischen Barrieren für ein HAW **E**ndlage**r** in **S**alzformationen Design
  - (english) Methodology for design and performance assessment of geotechnical barriers in a HLW repository in salt formations
- **Joint-Project between BGE TECHNOLOGY and SANDIA National Lab**
- **Project duration: 2020 - 2022**

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Project Goals

- **Main goals:**
  - Compilation of existing knowledge and experience for the design geotechnical barriers and compilation of new concepts and technologies on the subject of geotechnical barriers.
  - Development of a methodology based on the state of the art in science and technology for the design and verification of geotechnical barriers.
  - Preliminary design and verification of the geotechnical barrier system for the selected repository system based on the developed methodology.
  - Comparison of design results according to the new methodology with results of previous design and assessment.

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Project Goals

- **Secondary goals:**
  - Estimation of the optimization potential of EBS in salt repositories
  - Analysis of the impact of gases on EBS in salt
  - Exploiting synergy effects between BGE TEC and SANDIA in the numerical treatment of EBS in the course of the overall safety assessment of salt repositories:
    - The expertise of BGE TEC on numerical based design of EBS will be used for the dimensioning of the components of the EBS.
    - The expertise of SNL in the performance assessment of large repository systems will serve to analyze the geochemical evolution and radionuclide transport through the EBS

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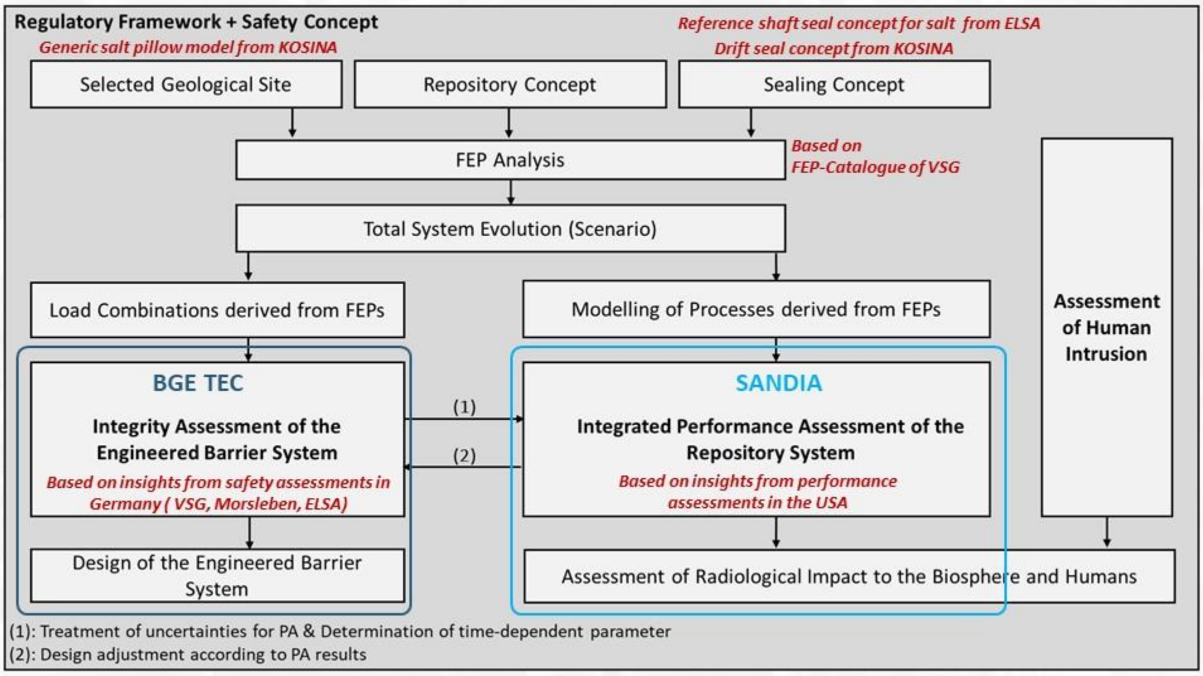
RANGERS Methodology



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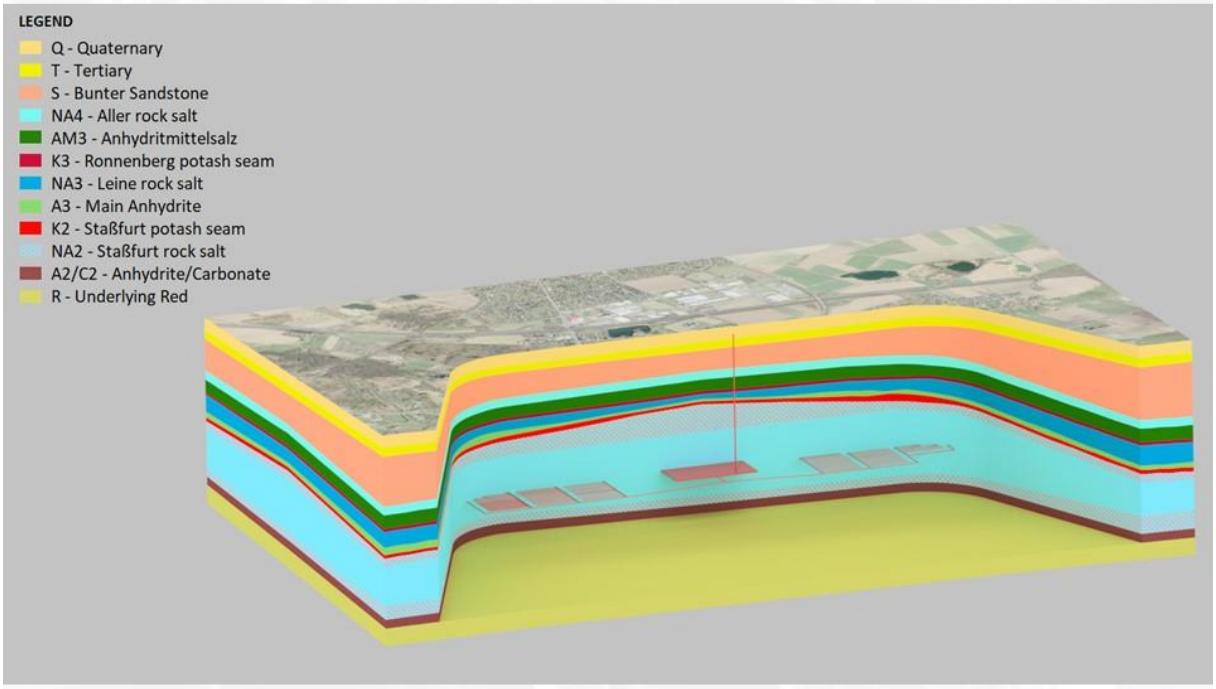
Repository in the selected geological site



with courtesy of BGR

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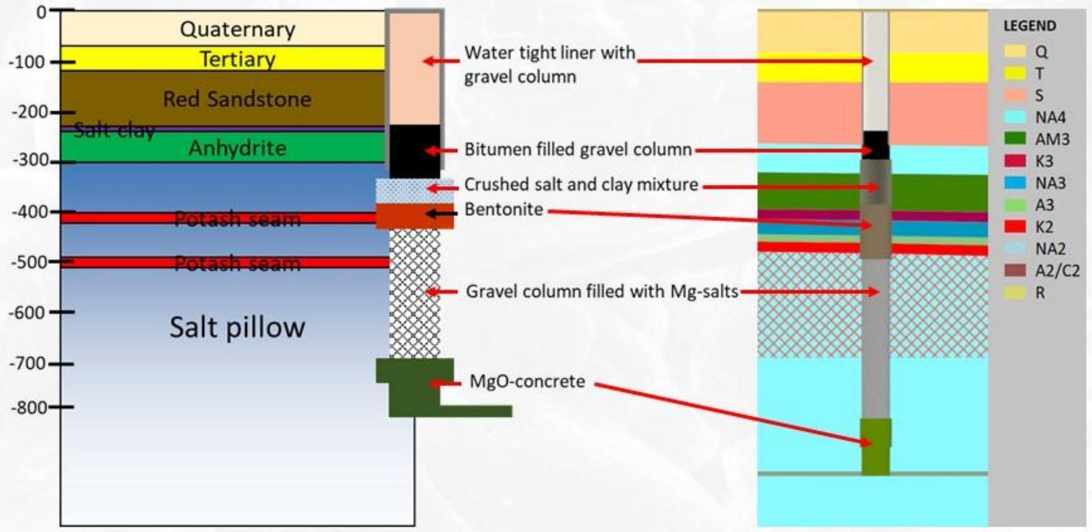
Sealing concept: Shaft seals



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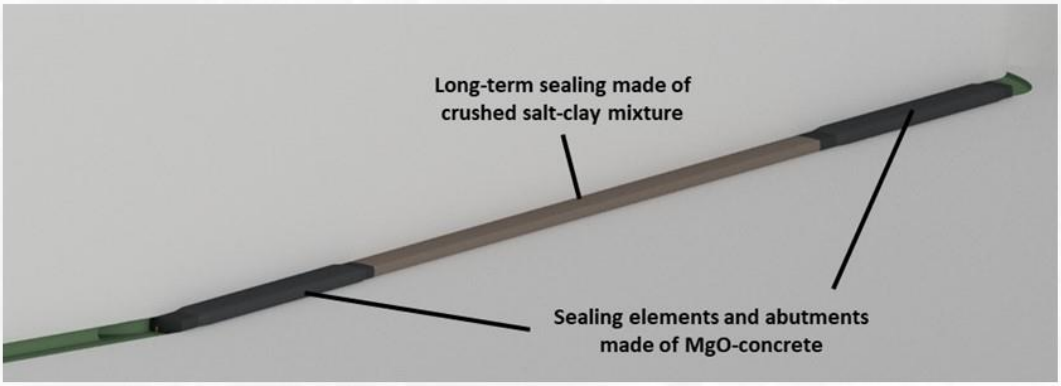
Sealing concept: Drift seals



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Preliminary FEPs for EBS in salt formation

Sub-system: Drift	Process Group	FEP	Description	Impact on EBS	Components affected by process														
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Components		1: Drift seal																	
		3: Drift Backfill																	
		10: Concrete injection																	
		7: EDZ																	
		XX: ...																	
Processes/ Events	Mechanical	Example: Earth quake	The release of accumulated geologic stress via rapid relative movements within the earth's crust usually along existing faults or geological interfaces.	tectonic movements resulting from an earth quake may yield in fractures in the drift seal. The drift lining may collapse.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Hydraulic	Example: Gas flow processes	Describes the gas flow due to potential gradients. Gas flow is responsible for transport of volatile compounds.	Gas flow transport is important for chemical processes and radio-nuclide spreading.									x						x
	Thermal	Example: Heat flow	Means the energy transport as a result of temperature differences. There are 3 main sources for heat flow: climate, geothermic and radionuclide decay of the waste	The impact of waste produced heat on geotechnical barriers depends on the distance between barrier and empla-cement field.	x	x	x	x	x		x	x	x	x	x	x	x	x	x
	Chemical	Example: Concrete corrosion	Describes the chemical degradation of concrete	The corrosion processes will impair the function of all concrete components in the drifts	x	x	x	x				x		x	x				

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Scenario relevant for EBS

- **Reference Scenario**: The EBS retains its function over 50000 years
  - Case 1: Water flow from overburden through the shaft to the disposal zones
  - Case 2: Gas production inside the repository from corrosion of the casks
  - Case 3: Water source inside the repository from inter-/ intragranular salt solutions
- **Alternative Scenario 1**: Shaft seal loses its function and drift seals retain their function
  - Same cases
- **Alternative Scenario 2**: Shaft seal retains its function and drift seals lose their function
  - Same cases

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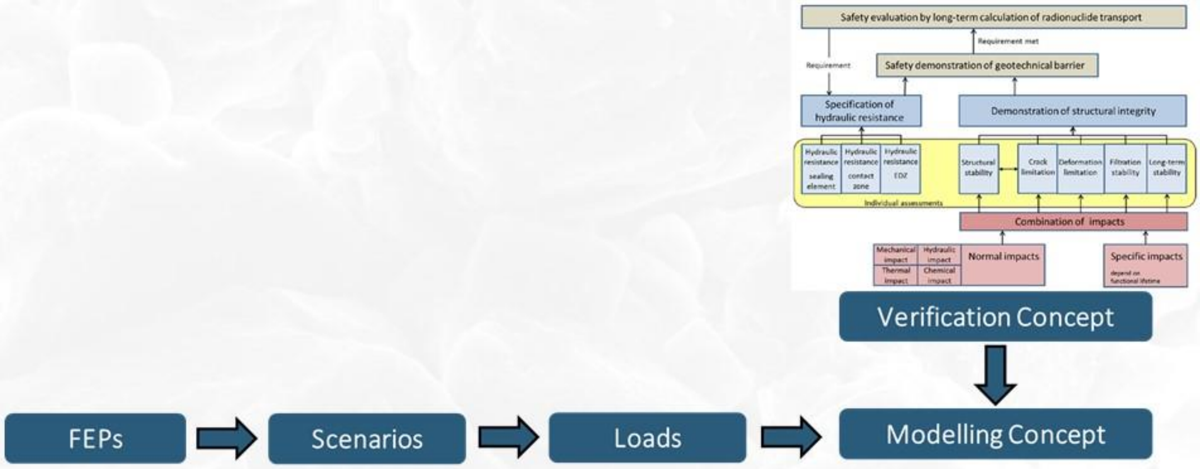
Modelling Concept

- **Integrity assessment:**



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Modelling Concept

- **Integrity assessment:**

	Hydraulic resistance -sealing element	Hydraulic resistance -contact zone	Hydraulic resistance -EDZ	Structural stability	Crack limitation	Deformation limitation	Filtration stability	Long-term stability
Reference Scenario: The EBS retains its function over 50000 years								
Case 1: Water flow from overburden through the shaft to the disposal zones	**H**: determination of flow rate and passing time. **HM:** including compaction of crushed salt, swelling of bentonite (shaft) and related kf-development **THM:** compaction and kf-development at drift seal			**TM:** structural analysis of components inside the shaft (gravel column, concrete elements)			No numerical modelling needed, design and assessment based on existing standards	**Geochemical analysis:** determination of geochemical stability of the sealing elements against water/brine, a) theoretically unlimited water reservoir b) limited reservoir or in combination with kf-development
Case 2: Gas production inside the repository from corrosion of the casks	**H:** gas pressure development inside repository (backfill)/at the drift seal, permeation condition pg<sig min **HM:** Interaction between gas pressure evolution and compaction of crushed salt in the drifts			Not relevant			Not relevant	Not relevant
Case 3: Water source inside the repository from inter-/ intragranular salt solutions	**H:** determination of flow rate and passing time. **HM:** including compaction of crushed salt, swelling of bentonite (shaft) and related kf-development **THM:** compaction and kf-development at drift seal			**TM:** structural analysis of components inside the drift (concrete abutments)			Not relevant	**Geochemical analysis:** determination of geochemical stability

(purple)	BGE TEC
(green)	SANDIA

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Modelling Concept

- **Performance assessment**

$$RGI = \frac{\sum_i S_i \cdot DKF_i}{W \cdot K_{RGI}}$$

Verification Concept ↓ Modelling Concept

FEPs → Scenarios → Processes → Modelling Concept

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Modelling Concept

- **Performance assessment**

	Processes							Target Criteria
	Nuclide decay	Advection	Diffusion	Convection/ conduction	2-Phase-flow	Boiling	Recon-densation	Dose constraints
Reference Scenario: The EBS retains its function over 50000 years								
Case 1: Water flow from overburden through the shaft to the disposal zones								
Case 2: Gas production inside the repository from corrosion of the casks								
Case 3: Water source inside the repository from inter-/intragranular salt solutions								

BGE TEC | SANDIA

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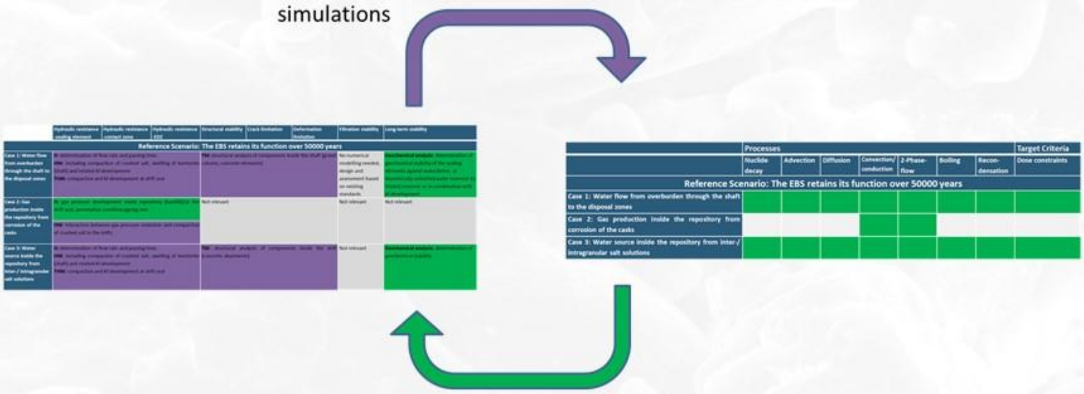
Modelling Concept

- **Interactions between integrity and performance assessment**

Interaction with performance assessment: Determination of permeability/porosity-functions of EBS-components for the PA simulations



	Processes							Target Criteria
	Nuclide decay	Advection	Diffusion	Convection/ conduction	2-Phase-flow	Boiling	Recon-densation	Dose constraints
Reference Scenario: The EBS retains its function over 50000 years								
Case 1: Water flow from overburden through the shaft to the disposal zones								
Case 2: Gas production inside the repository from corrosion of the casks								
Case 3: Water source inside the repository from inter-/ intragranular salt solutions								

Interaction with Integrity assessment: Sensitivity analyses – Optimization of the EBS-parameters in the PA simulations

BGE TEC SANDIA

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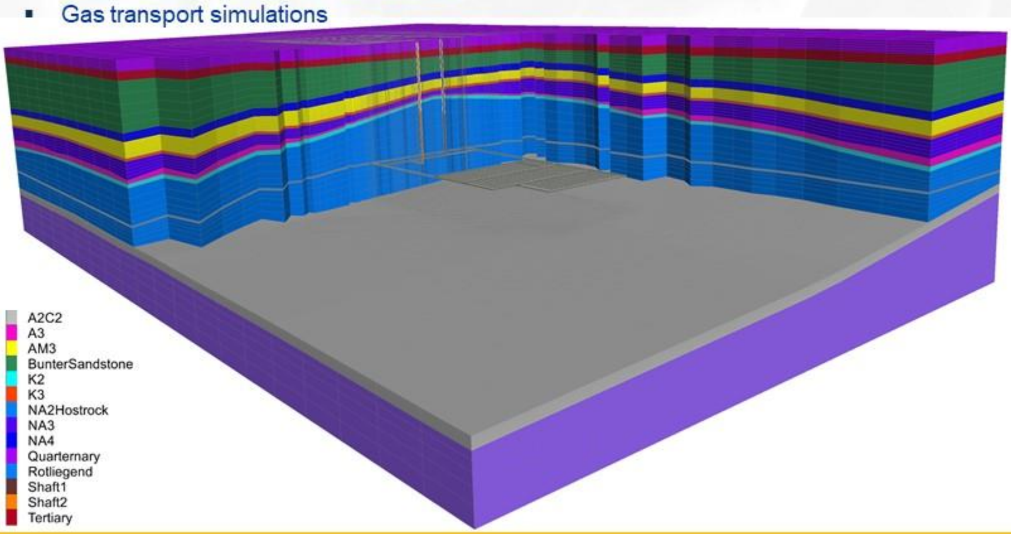
Numerical Model

- **BGE TEC:**
  - T: Analysis of the thermal evolution in the EBS components
  - H: 1-phase hydraulic evolution of the repository
  - TM-compaction of crushed salt in the repository – determination of permeability function
- **SANDIA:**
  - Performance Assessment Simulations
  - Gas transport simulations



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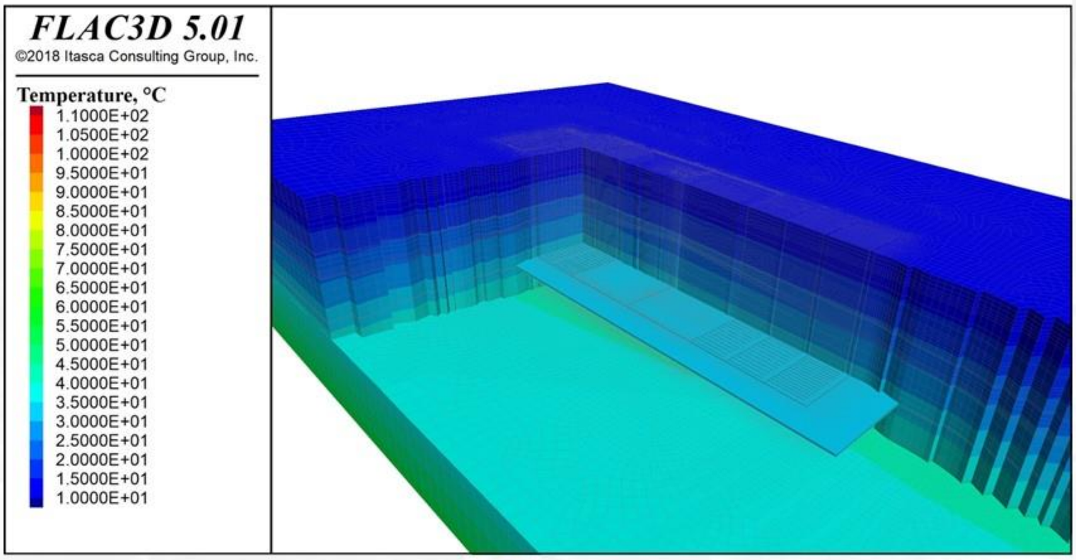
Thermal evolution in the repository (BGE TEC)

- Goal: Determination of the temperature increase in the EBS

5 a



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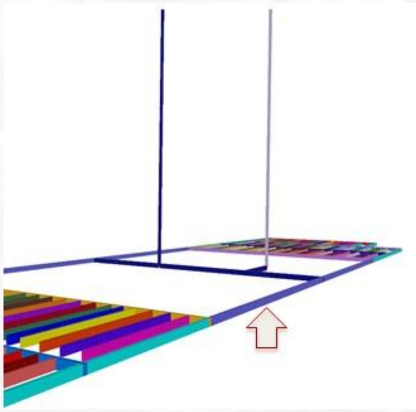
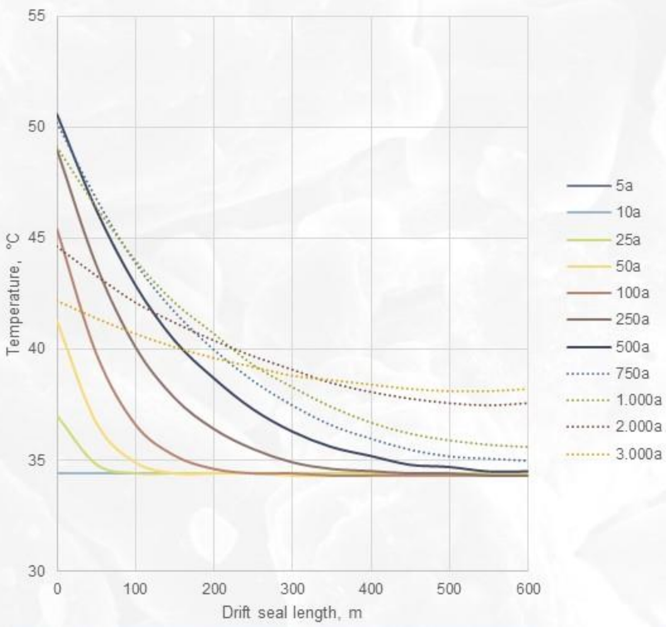
Thermal evolution in the repository (BGE TEC)

- Temperature evolution in the drift seal





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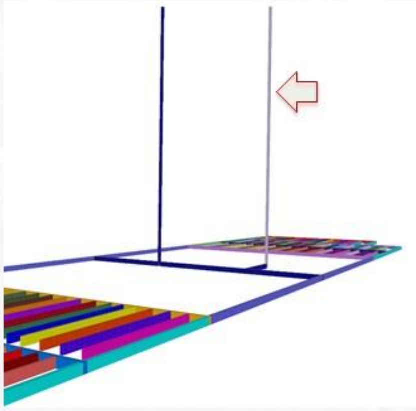
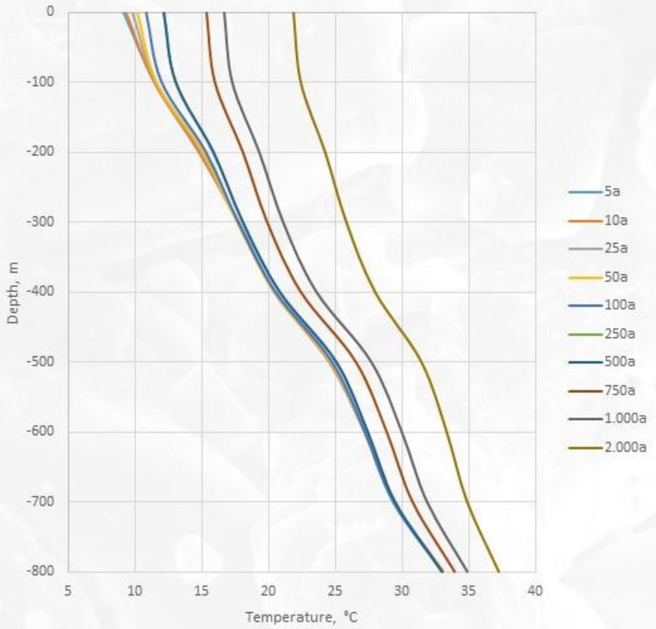
Thermal evolution in the repository (BGE TEC)

- Temperature evolution in the shaft





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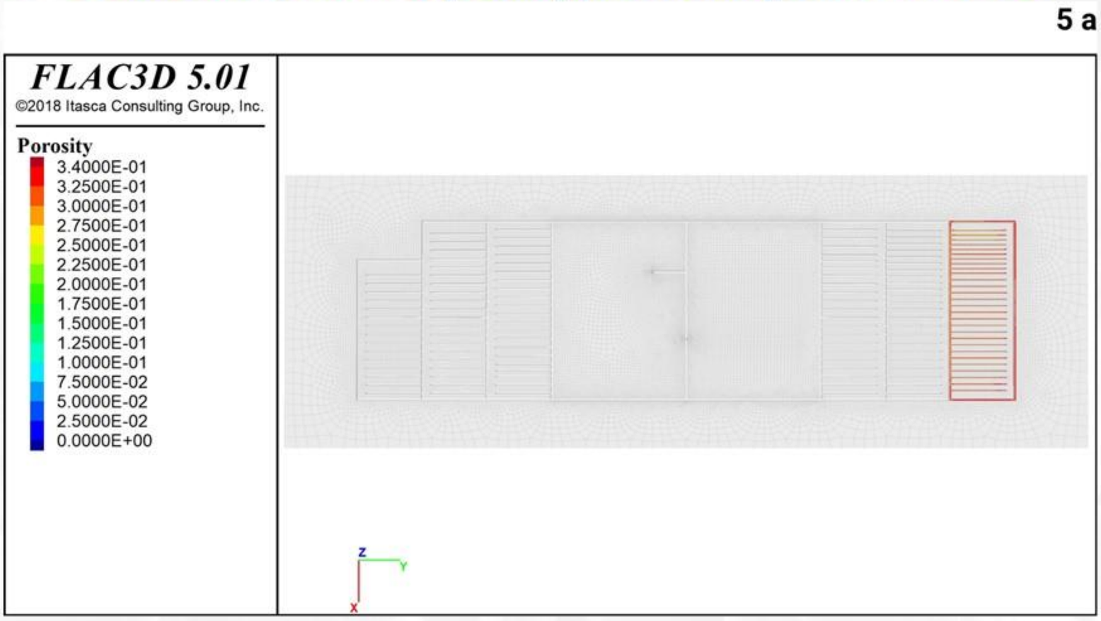
Thermomechanical compaction of crushed salt in the repository (BGE TEC)

- Goal: Determination of porosity/permeability-function for PA



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Demonstration PFLOTRAN Simulations (SANDIA)

- **Goal: Test of the capacity of PFLOTRAN to simulate the relevant processes considered in the scenario evolution**
- Assumption for the test case:
  - Two-phase flow of air and water
  - Drifts, seals, and shafts are initially air-filled
  - Host rock is initially water-filled
  - 20 years pressure equilibration, then heating
  - Small inventory: 765 Pollux-10 and 279 Pollux-9 canisters
  - Individual waste packages not resolved
  - Assumed fuel 100 years out-of-reactor
- Next step: more realistic scenarios

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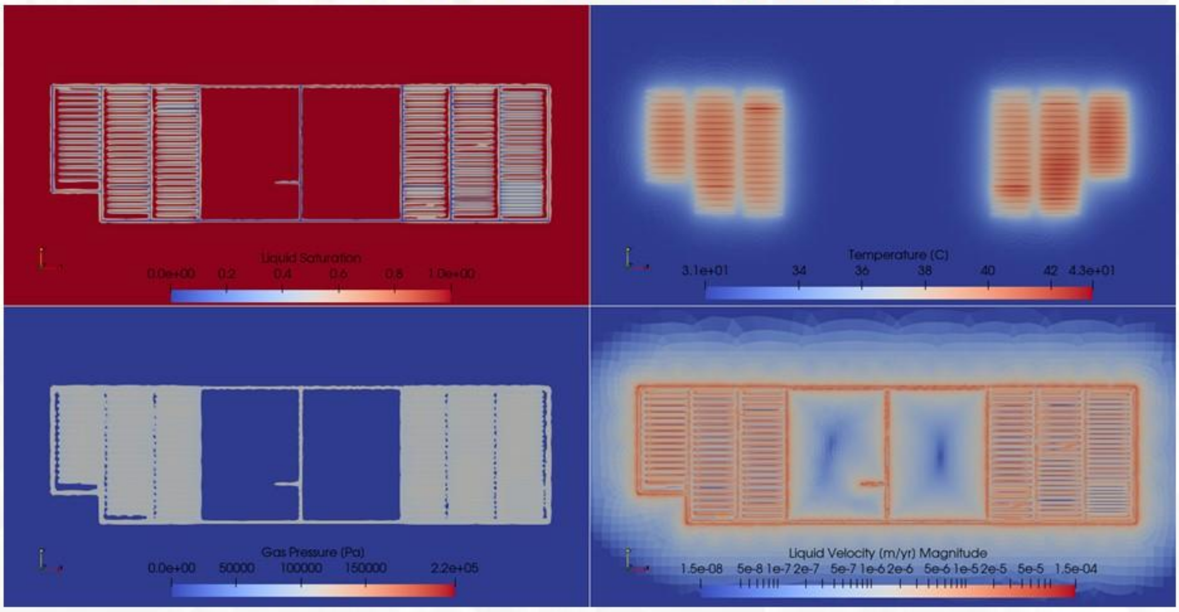
PFLOTRAN Simulations (200 yr)

- Seals re-saturating and gas pressure increasing
- Flow in hostrock confined to near repository



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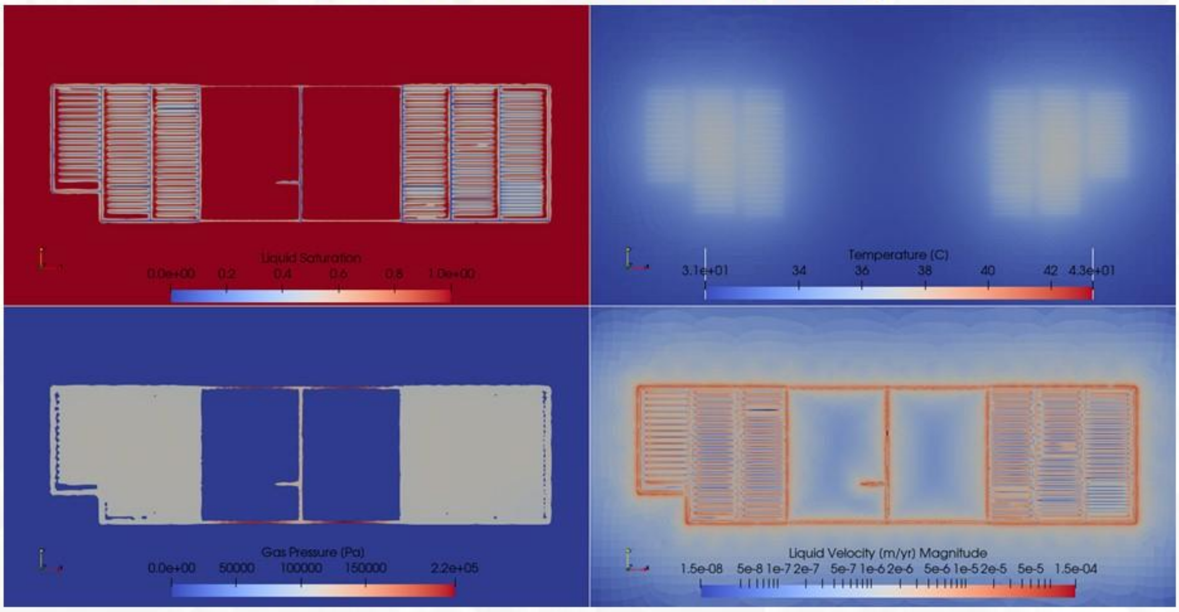
PFLOTRAN Simulations (2000 yr)

- Seals re-saturating and gas pressure increasing
- Flow in host rock confined to near repository



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Conclusions

- A methodology for the for design and performance assessment of EBS in a HLW repository in salt formations has been developed
- The methodology has been applied for the preliminary design of the EBS of a generic repository system in Germany based on the generic salt pillow model developed in the KOSINA project
- The methodology is now being used to assess the integrity of the EBS and the long term evolution of the repository system:
  - A unique numerical model used at BGE TEC and at SANDIA has been developed for this purpose
  - First results show that the temperature evolution in the EBS remain transient in the first 2000 years
  - The evolution of the compaction of crushed salt in the repository will be used to derive the time dependent permeability in the repository mine
  - The capabilities of PFLOTRAN to analyze all relevant processes occurring in the near- and far-field of the repository system have been successfully shown

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Next steps

- Structural integrity of the drift seals
- Structural integrity of the shaft seals
- Performance Assessment Simulations of the whole repository using the realistic geological material parameters and the actual waste inventory available in Germany
- Model optimizations and several case studies

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Questions?

Thank you for your attention!

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BEN VASIM
Benchmarking Results for
Heterogeneous H²M and TH²M Models
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH
Michael Rutenberg et al.
Clausthal University of Technology et al.
Part 4 of the online workshop
September 9, 2021


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Clausthal University of Technology
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Confédération suisse
Confederazione Svizzera
Confederaziun svizra
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Jonny Rutqvist, Mengsu Hu
Antonio P. Rinaldi
2

Contents

- Considered TH²M processes and applied simulators
  (H²: two-phase flow – liquid and gaseous phases with water and air)
- Some simulation results for a H²M-coupled model
- Some simulation results for a TH²M-coupled model
- Conclusions of the work

3

Processes and Simulators

→ THM processes – models and equations

- mechanical process:
  equation of motion *(no gravity, small strains)*, Hooke's model
- hydrological processes:
  mass-balance equation *(for each phase φ)*, Darcy's model
- thermal processes:
  heat-balance equation *(int. energy/enthalpy)*, Fourier's model
- no M→T coupling
- T→M coupling:
  thermal expansion of the solid skeleton: $\dot{\varepsilon}^{th} = -\alpha^{th}\dot{T}I$

4

Processes and Simulators

→ THM processes – models and equations

- H→M coupling:
  Biot's effective-stress definition: $\sigma_{eff} = \sigma_{tot} - \alpha p_{eq} I$
  with $p_{eq} = \sum_{\varphi} S_{\varphi} p_{\varphi}$
- M→H coupling part: $\frac{1}{\breve{M}_{\varphi}} \dot{p}_{\varphi} + \frac{\phi}{S_{\varphi}} \dot{S}_{\varphi} = \alpha \dot{\varepsilon}_{vol}$
- H→T coupling:
  advective transport of energy, saturation-dependent thermal parameters of the bulk (λ and c)
- T→H coupling:
  temperature-dependent hydraulic properties

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Processes and Simulators

→ Simulators used by the partners

- BGR → OpenGeoSys
- ENSI → TOUGH-FLAC, OpenGeoSys, COMSOL Multiphysics
- GRS *(2 teams)* → CODE_BRIGHT, TFC
- LBNL → TOUGH-FLAC
- TUC → FTK

Kolditz et al. (2012)
Rutqvist (2011); Rinaldi et al. (2018)
COMSOL (2012)
UPC (2017)
Hotzel (2014)
Lux et al. (2015)
Pruess et al. (2012); Jung et al. (2018); Itasca (2009/2012)

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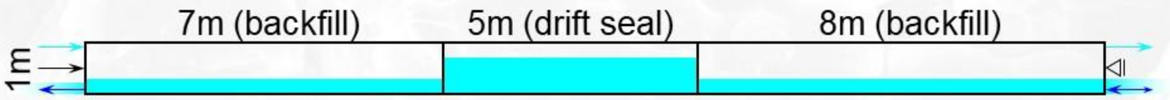
H²M Model: Basic Scenario



$\sigma_{tot;lhs} = 5\ MPa$
$p_{g;lhs} = 4\ MPa$
$S_{l;lhs} = 0.20$

backfill: $\sigma_{tot0} = 5\ MPa$, $p_{g0} = 0.25\ MPa$, $S_{l0} = 0.25$

drift seal: $p_{g0} = 0.2\ MPa$, $S_{l0} = 0.70$

$u_{rhs} = 0\ m$
$p_{g;rhs} = 0.25\ MPa$
$S_{l;rhs} = 0.25$

parameters			
Poisson's ratio	ν	0	
Biot's coefficient	α	1	
residual gas saturation	S_{gr}	0	
pore connectivity parameters	$\tilde{\varepsilon}$ & $\tilde{\gamma}$	0.5	
gas viscosity	η_g	$1.8 \cdot 10^{-11}$	$MPa \cdot s$
liquid viscosity	η_l	10^{-9}	$MPa \cdot s$
liquid bulk modulus	$\breve{K}_l$	$2{,}220$	MPa

Mualem (1976); van Genuchten (1980); Parker et al. (1987)

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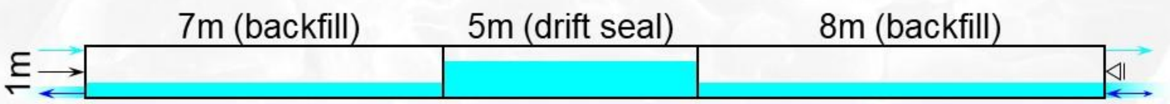
H²M Model: Basic Scenario



$\sigma_{tot;lhs} = 5\ MPa$
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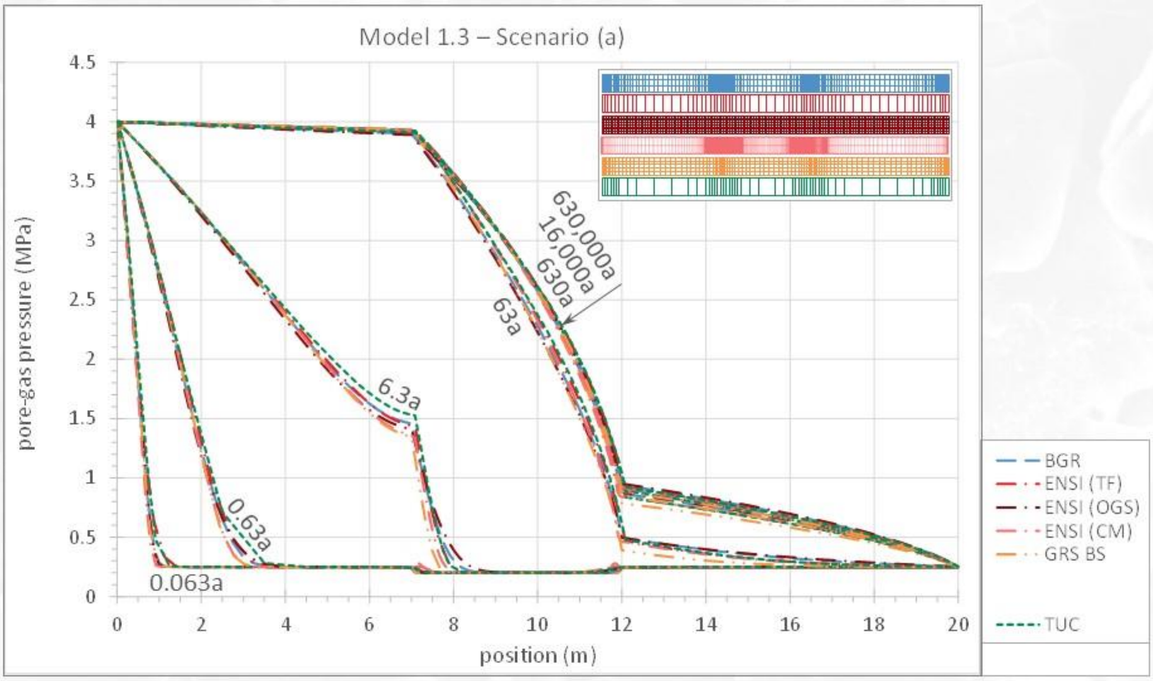
$u_{rhs} = 0\ m$
$p_{g;rhs} = 0.25\ MPa$
$S_{l;rhs} = 0.25$

parameters				
		backfill	drift seal	
Young's modulus *(drained)*	E	200	600	MPa
porosity	ϕ	0.4	0.3	
intrinsic permeability	K	$2 \cdot 10^{-19}$	10^{-20}	m^2
residual liquid saturation	S_{lr}	0.01	0.05	
van Genuchten parameter	m	0.47	0.37	
van Genuchten pre-factor	p_{cap0}	15	35	MPa

Mualem (1976); van Genuchten (1980); Parker et al. (1987)

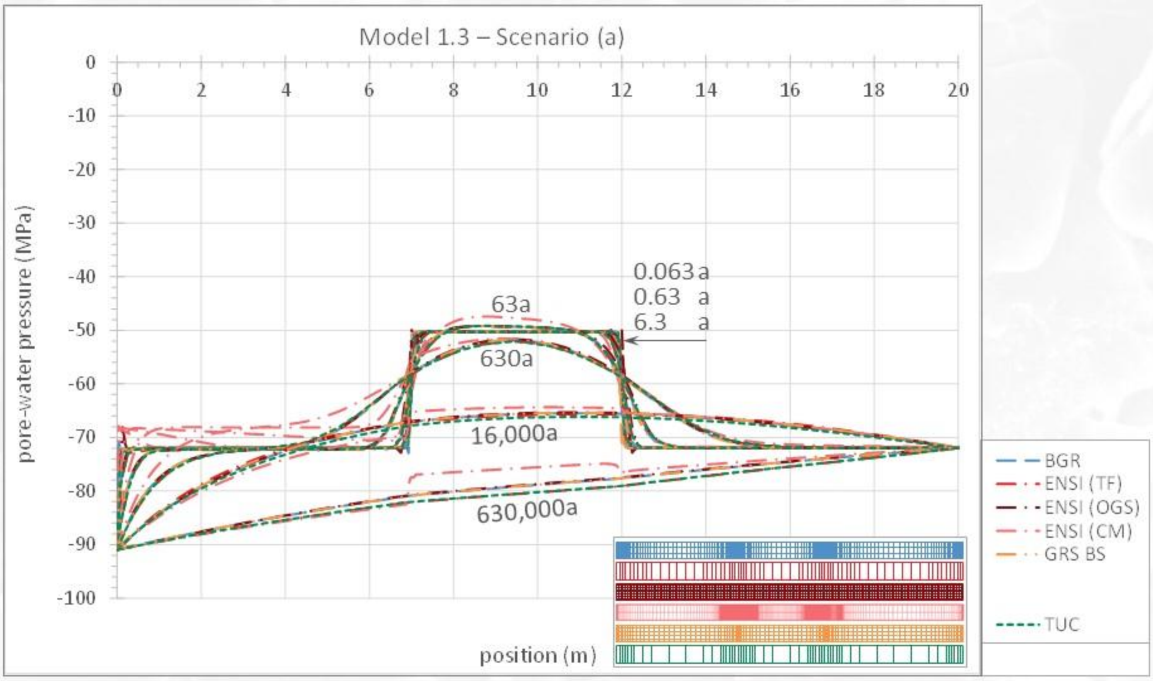
8

H²M Model: Basic Scenario



9

H²M Model: Basic Scenario



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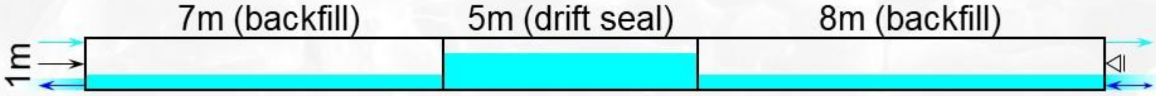
H²M Model: Mobile Phases



$\sigma_{tot;lhs} = 5\,MPa$
$p_{g;lhs} = 4\,MPa$
$S_{l;lhs} = 0.20$

backfill: $p_{g0} = 0.25\,MPa$, $S_{l0} = 0.25$

$\sigma_{tot0} = 5\,MPa$

drift seal: $p_{g0} = 0.2\,MPa$, $S_{l0} = 0.70$

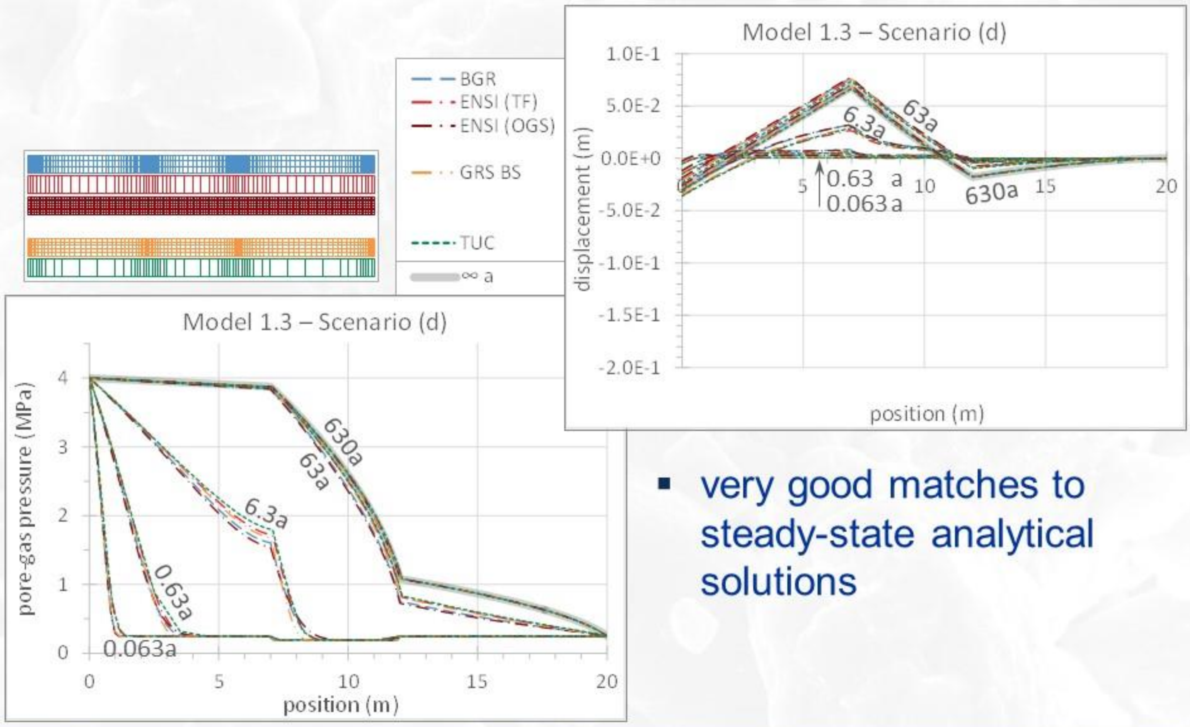
$u_{rhs} = 0\,m$
$p_{g;rhs} = 0.25\,MPa$
$S_{l;rhs} = 0.25$

$K_{rel;\varphi} \equiv 1$

in place of Mualem/van Genuchten's relative permeability

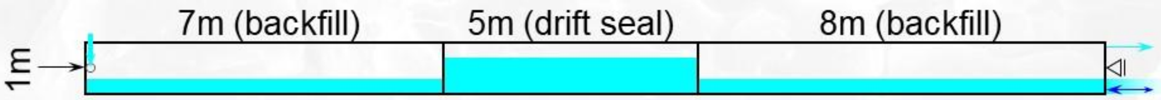
other parameters and functions as before

H²M Model: Mobile Phases



- very good matches to steady-state analytical solutions

H²M Model: Constant Gas Source



$\sigma_{tot;lhs} = 5\ MPa$

$\hat{Q}_{m;g;lhs} = 6 \cdot 10^{-9}\ kg/s$

backfill: $\sigma_{tot0} = 5\ MPa$, $p_{g0} = 0.25\ MPa$, $S_{l0} = 0.25$

drift seal: $p_{g0} = 0.2\ MPa$, $S_{l0} = 0.70$

$u_{rhs} = 0\ m$

$p_{g;rhs} = 0.25\ MPa$

$S_{l;rhs} = 0.25$

other parameters and functions as before

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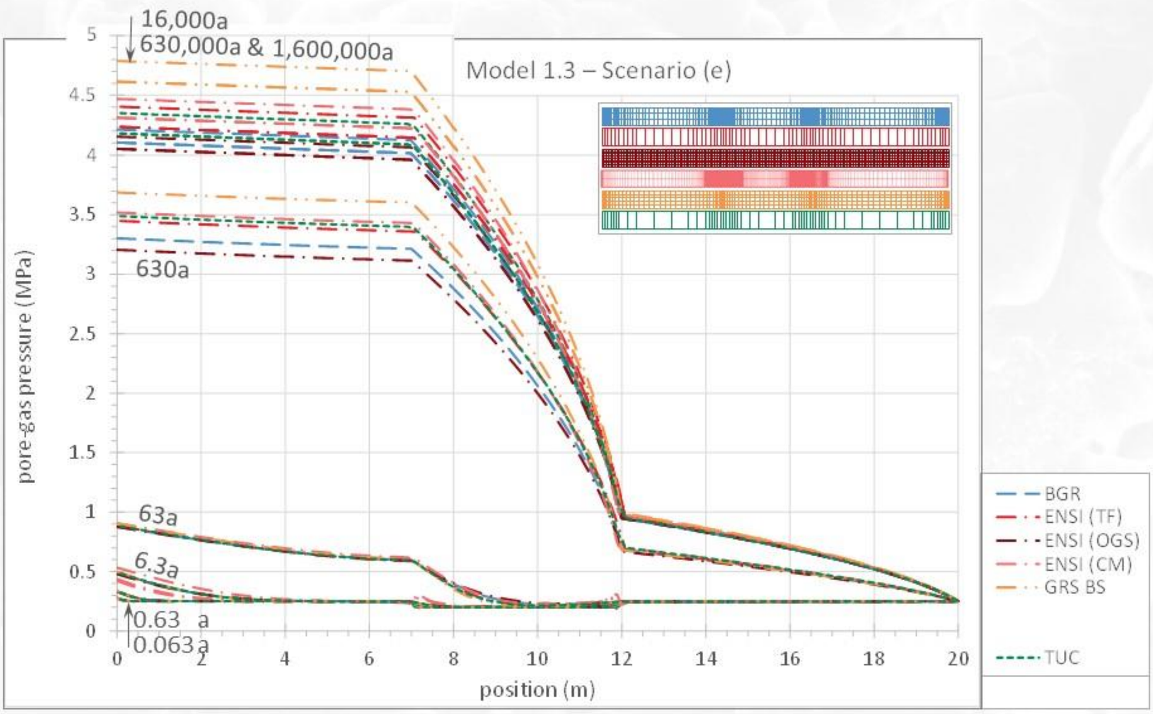
H²M Model: Constant Gas Source



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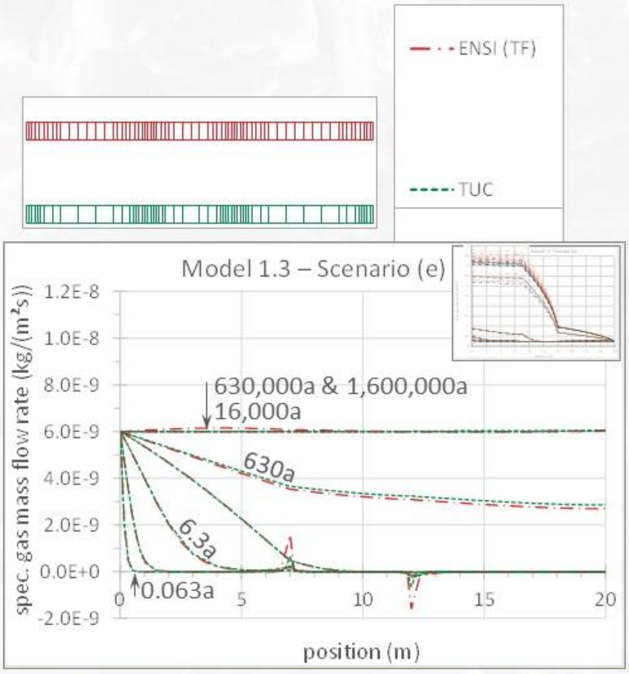
H²M Model: Constant Gas Source

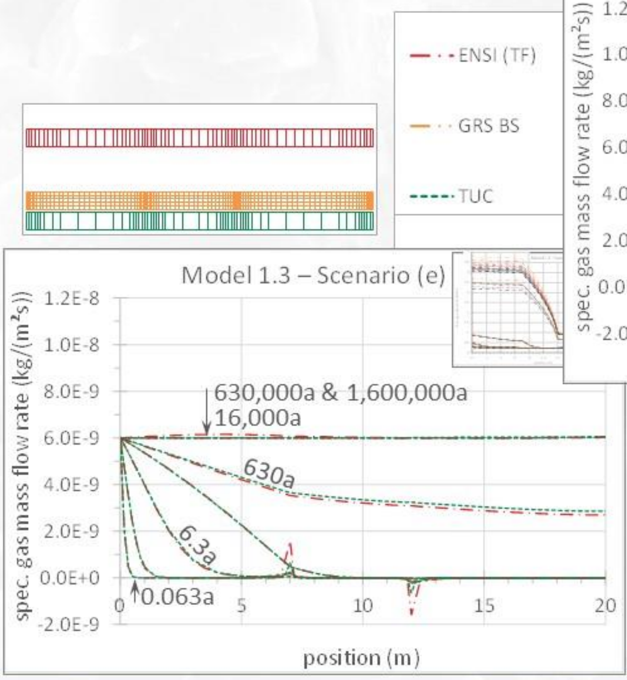


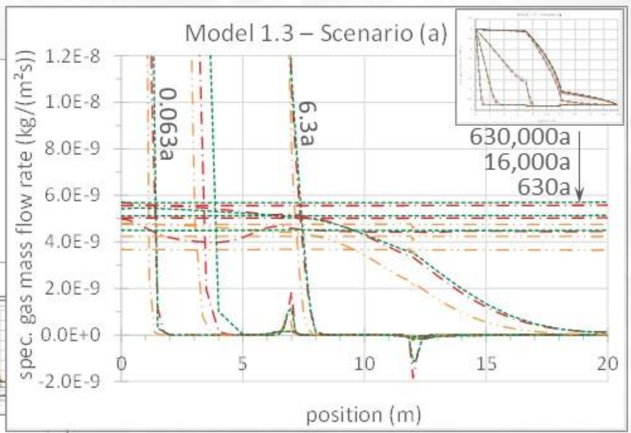
constant gas source:

- good agreements of gas-flow rates
- *as opposed to* scattered gas-pressure distributions

15

H²M Model: Constant Gas Source





basic scenario:
(with constant gas pressure b.c.)

- scattered gas-flow rates
- *as opposed to* well agreed gas-pressure distributions

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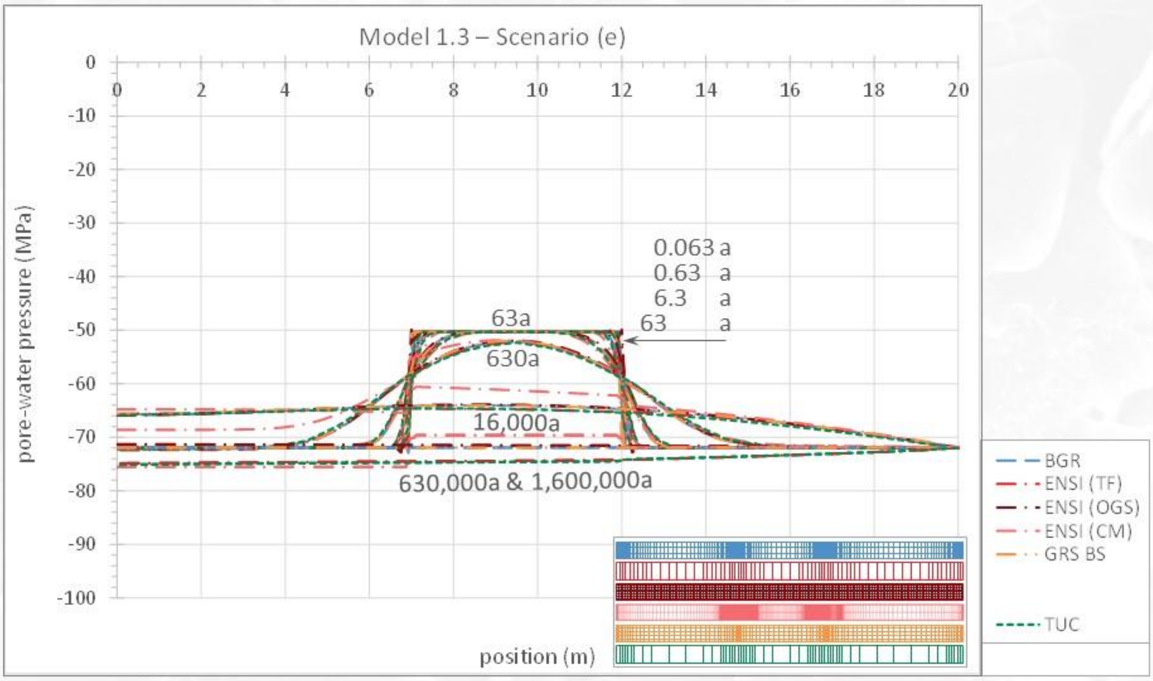
H²M Model: Constant Gas Source



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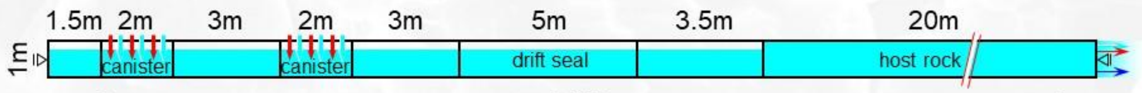
TH²M Model



$u_{lhs} = 0\ m$

$\sigma_{tot0} = 8\ MPa$

$u_{rhs} = 0\ m$

repo-sitory: $p_{g0} = 0.1013\ MPa$, $S_{l0} = 0.75$

host rock: $p_{g0} = 4\ MPa$, $S_{l0} = 1.00$

$p_{g;rhs} = 4\ MPa$

$S_{l;rhs} = 1.00$

$T_0 = 25\ °C$

$T_{rhs} = 25\ °C$

parameters						
		backfill	canister sections	drift seal	host rock	
Young's modulus *(drained)*	E	45	150	400	8,000	MPa
Biot's coefficient	α	1	1	1	0.8	
porosity	ϕ	0.42	0.37	0.35	0.17	
intrinsic permeability	K	$2 \cdot 10^{-18}$	$1.75 \cdot 10^{-18}$	$2 \cdot 10^{-20}$	$1 \cdot 10^{-20}$	m^2
residual liquid saturation	S_{lr}	0.03	0.03	0.1	0.16	
van Genuchten parameter	m	0.5	0.5	0.3	0.28	
van Genuchten pre-factor	p_{cap0}	12	12	26	30	MPa
thermal conductivity *(grains)*	λ_s	2.1	11.75	2.1	2.3	$W/(m\ K)$
specific heat capacity *(grains)*	c_s	1,100	830	950	900	$J/(kg\ K)$
density *(grains)*	ρ_s	2,500	3,450	2,500	2,700	kg/m^3
lin. th. exp. coeff. *(skeleton)*	α^{th}	$5 \cdot 10^{-6}$	$5.9 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	$3.6 \cdot 10^{-6}$	K^{-1}

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TH²M Model

$u_{lhs} = 0\ m$

$\sigma_{tot0} = 8\ MPa$

$u_{rhs} = 0\ m$

repo-sitory: $p_{g0} = 0.1013\ MPa$, $S_{l0} = 0.75$

host rock: $p_{g0} = 4\ MPa$, $S_{l0} = 1.00$

$p_{g;rhs} = 4\ MPa$

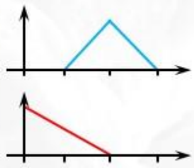
$S_{l;rhs} = 1.00$

$T_0 = 25\ °C$

$T_{rhs} = 25\ °C$

parameters		
Poisson's ratio	ν	0
residual gas saturation	S_{gr}	0
pore connectivity parameters	$\tilde{\varepsilon}$ & $\tilde{\gamma}$	0.5

source terms *(per canister section)*			
peak gas generation rate	$\max \hat{Q}_{m;g}$	10^{-9}	kg/s
peak heating power	$\max \hat{Q}_Q$	1.5	W



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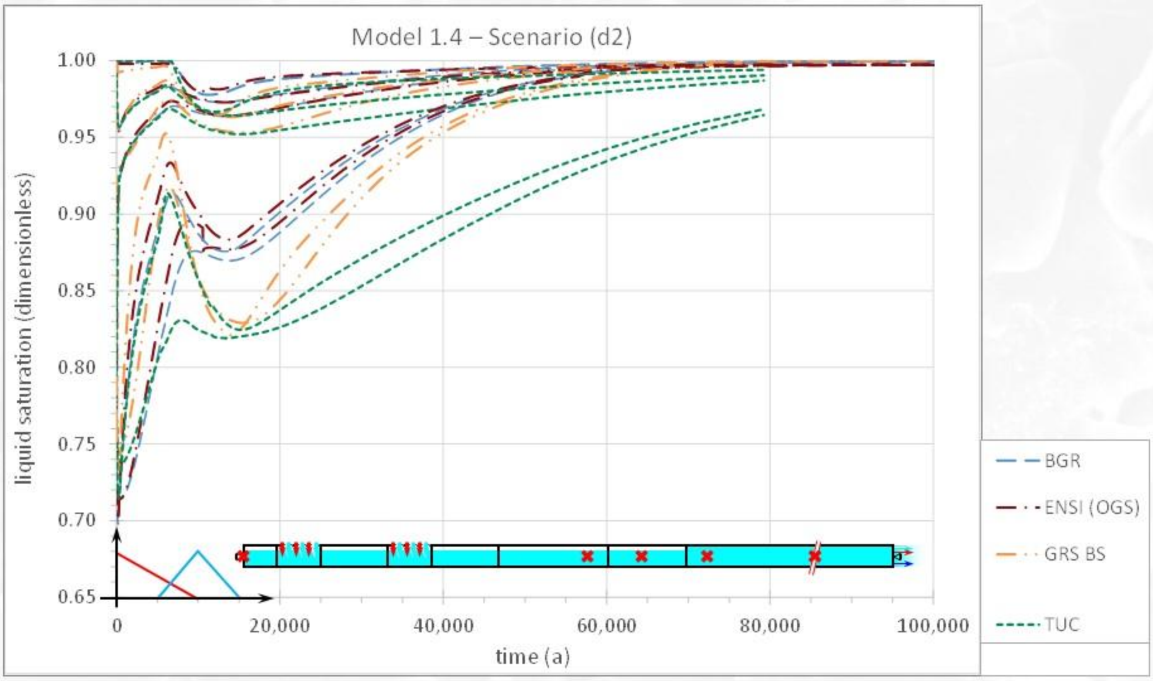
TH²M Model



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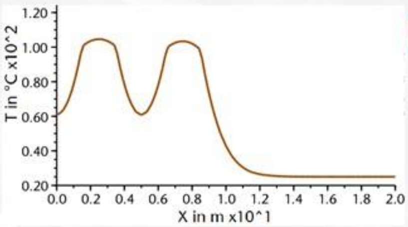
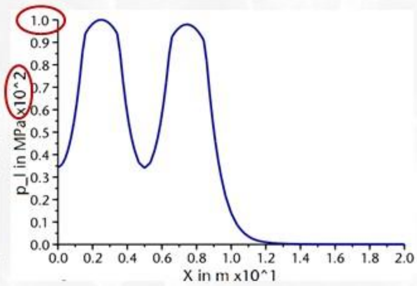
TH²M Model

→ Initial attempts *(with FTK)* – T processes

- in TOUGH2, there is no module without H processes
- fast temperature increase to over 100°C
  → pressure increase to 100 MPa *(S_l = 100%)*





(model yet without host rock area)

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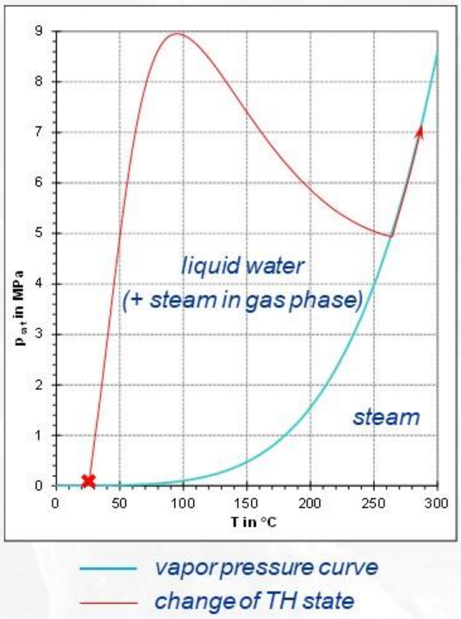
TH²M Model

→ Initial attempts *(with FTK)* – adding fluid flow

- before, high pressure kept water from boiling
- now: drainage
  → when pressure-dependent boiling point is attained, a gas phase develops



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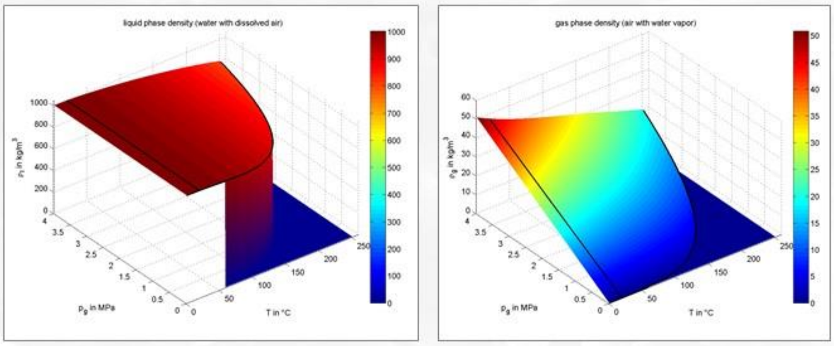
TH²M Model

→ it is expected that simulators treat the underlying thermo-dynamical processes differently so that discrepancies in results are stronger the more processes are involved

→ not the aim of this project



phase densities vs. p and T from TOUGH2 for two-phase states, might be implemented differently in the other simulators

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Conclusions

- models look simple, but simulating is not straightforward
- comprehension for TH²M processes and for simulators could be promoted and intensified by this project
- 1.3 results can be used as benchmarks by third parties
- differences in implemented equations and processes in the various simulators *(computation of phase densities and other properties, phase-extraneous components)*
  → not easy to guarantee equal framework conditions

Thank you for your attention!

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

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Brine Availability Test in Salt (BATS): Overview and Update

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

Sandia National Laboratories
PTKA Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
BGE TEC
BGE TECHNOLOGY GmbH

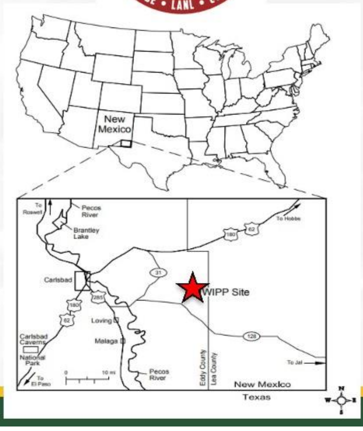
Melissa Mills
Sandia National Laboratories
Albuquerque, NM, USA

Part 3 of the online workshop
September 9, 2021
SAND2021-10966 PE

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.

Brine Availability Test in Salt at WIPP (BATS)

- Field test being conducted underground at WIPP
- Monitoring brine movement and production from heated salt using geophysics and sampling methods



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Multi-Lab Team

U.S. DEPARTMENT OF ENERGY
Office of Nuclear Energy

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WIPP Test Coordination Office (LANL)

Shawn Otto, Jon Davis, Brian Dozier*, Dave Guerin*

Lawrence Berkeley National Laboratory (LBNL)

Jonny Rutqvist, Yuxin Wu, Mengsu Hu, Jiannan Wang

*Retired March 2021

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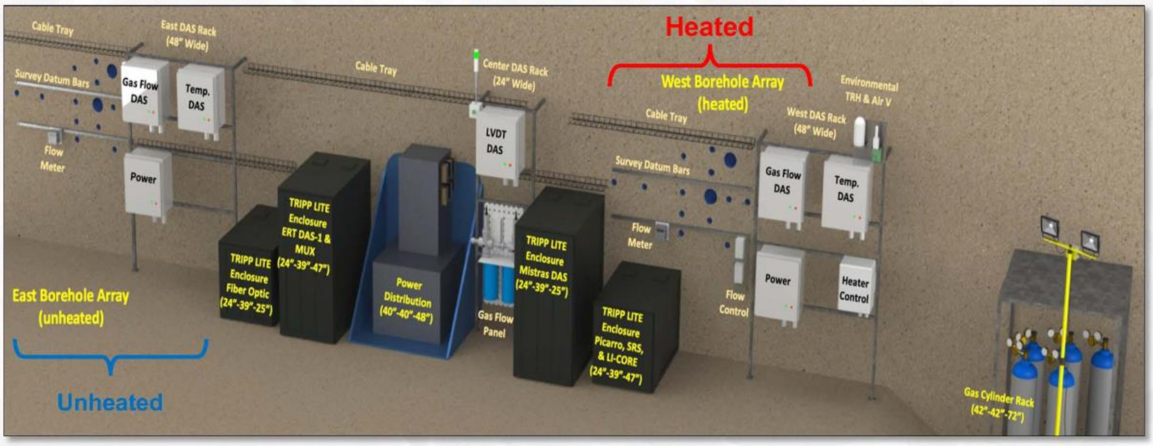
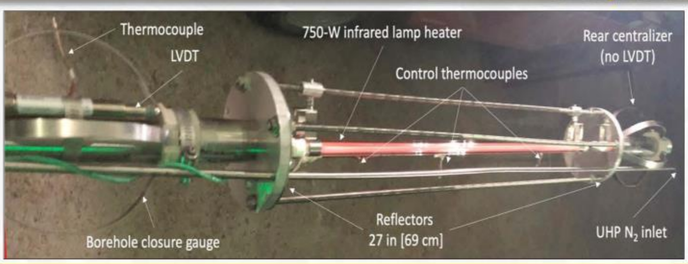
Test Overview: Phase 1

- Two Arrays mainly in Map Unit 3 (clean halite): Heated / Unheated



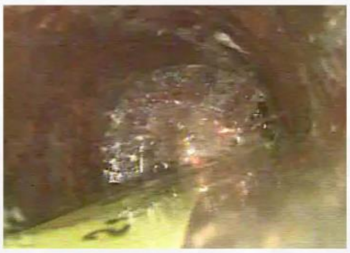
- Behind central packer
  - Circulate dry N_2
  - Quartz lamp heater (750 W)
  - Borehole closure gage (LVDT)

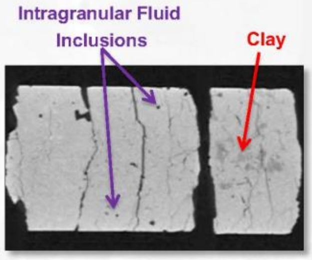


SFWST

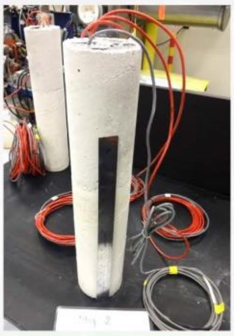
Test Overview: Data Being Collected

- Samples / Analyses
  - Gas stream (natural / applied tracers and isotopic makeup)
  - Liquid brine (natural chemistry and natural / applied tracers)
  - Cores (X-ray CT & fluorescence at NETL)





10.1 cm diameter core X-ray CT data from BATS (Betters et al., 2020)



- Cement Seals
  - Sorel cement + Salt concrete: strain & temperature
- Geophysics
  - 3 × Electrical resistivity tomography (ERT)
  - 3 × Acoustic emissions (AE)
  - 2 × Fiber optic distributed strain/temperature sensing

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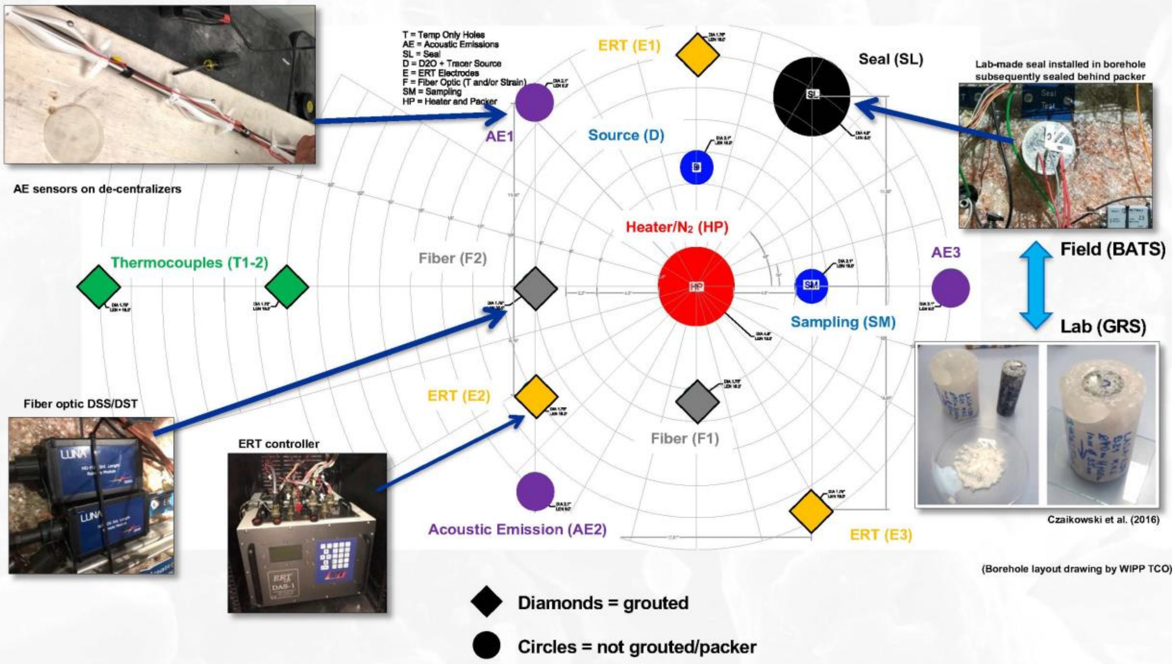
BATS 1 Borehole Array Schematic



SFWST

Data Collection Methods of Outflow

- Isotopic Composition of water
  - Picarro cavity ringdown spectrometer (CRDS): continuous measurement of isotopic makeup from humidity stream
  - Gives info on brine source (fluid inclusions vs. clays) and types
  - Useful for advection / diffusion / reaction information

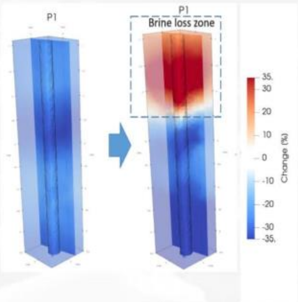
- Gas Stream Composition
  - SRS quadrupole mass spectrometer (QMS) gas analyzer
  - Types of gases interested in:
    - Dissolved in brine
    - Sorbed to salt (CO_2)
    - Geogenic gases within salt (e.g., He & Ar)
    - Added gas tracers (Ne, Kr & SF_6)

- Gas Stream Humidity
  - LI-COR 850 CO_2/H_2O
  - Drierite canisters weighed ~weekly

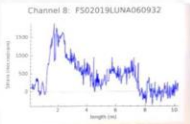
SFWST

Geophysical Methods

- Acoustic Emissions (AE)
  - Listening to salt cracking with piezoelectric transducers
  - AE correlated with increases in permeability
  - Informs when, where, and extent of damage



- Electrical Resistivity Tomography (ERT)
  - Measuring voltage from applied current at electrode pairs
  - Maps evolution of brine content

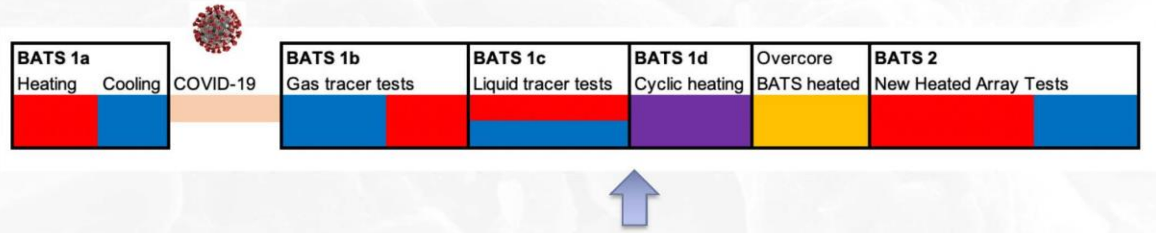


- Fiber Optics
  - Measuring temperature and strain
  - Sub-mm resolution in space

SFWST

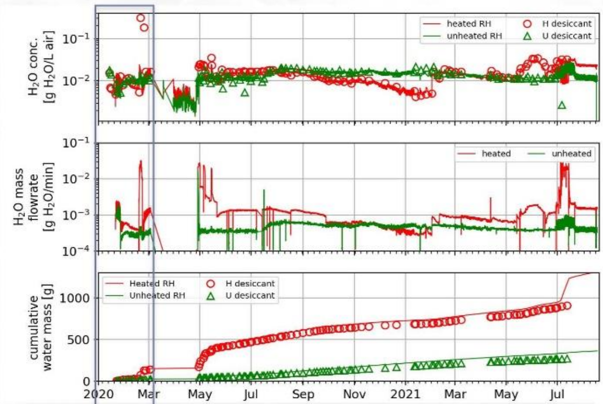
BATS Stages

- BATS 1 borehole drilling and install (2019)
- BATS 1a heated phase (Jan-Mar 2020)
- COVID-19
- Gas & liquid tracer tests (Jan-July 2021)
- Cyclic heating (summer-fall 2021)
- New BATS 2 boreholes (October 2021)
  - New array in argillaceous halite (MU-0)
  - Similar heater test in new boreholes

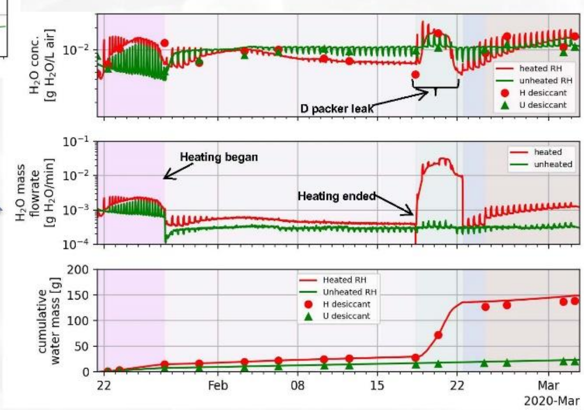


SFWST

Brine Inflow Data (Jan 2020 – Aug 2021)

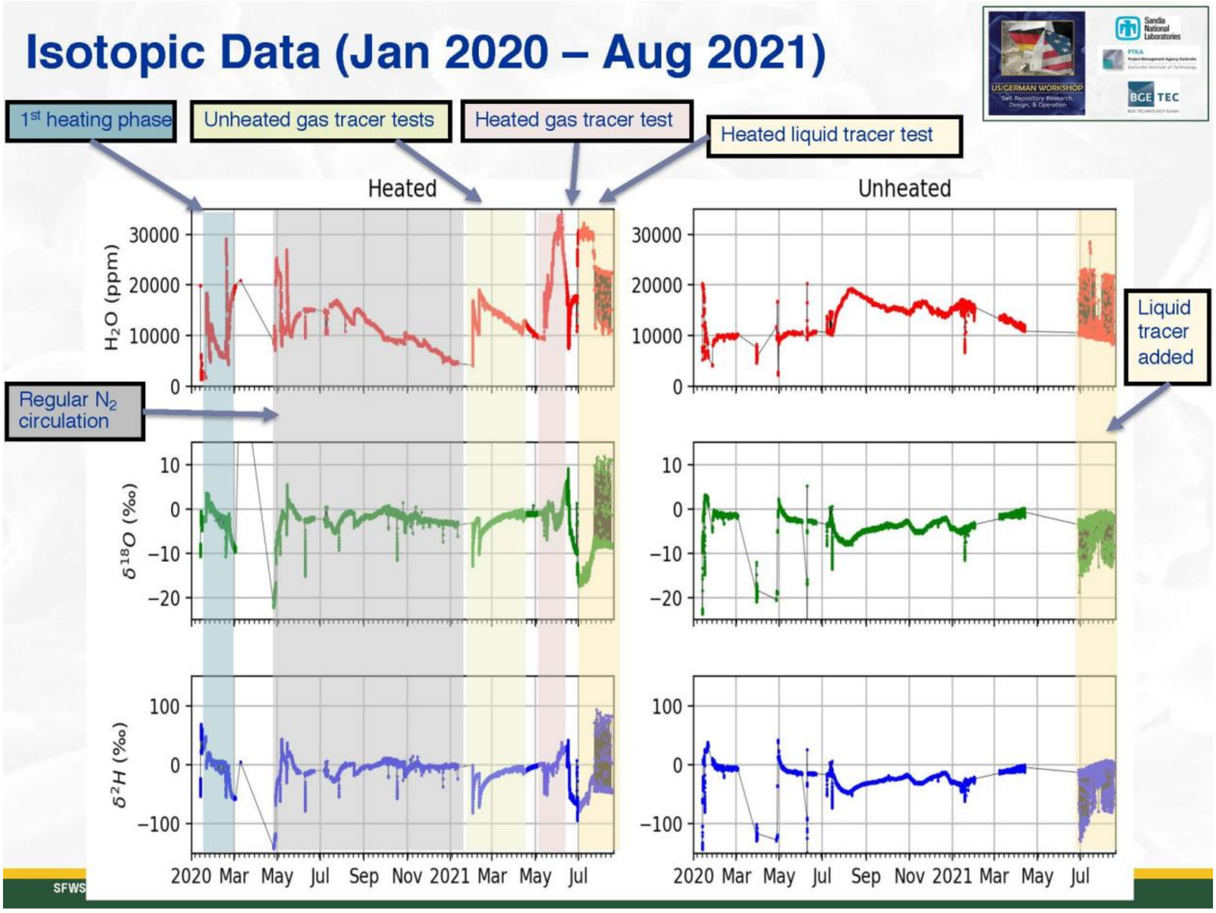


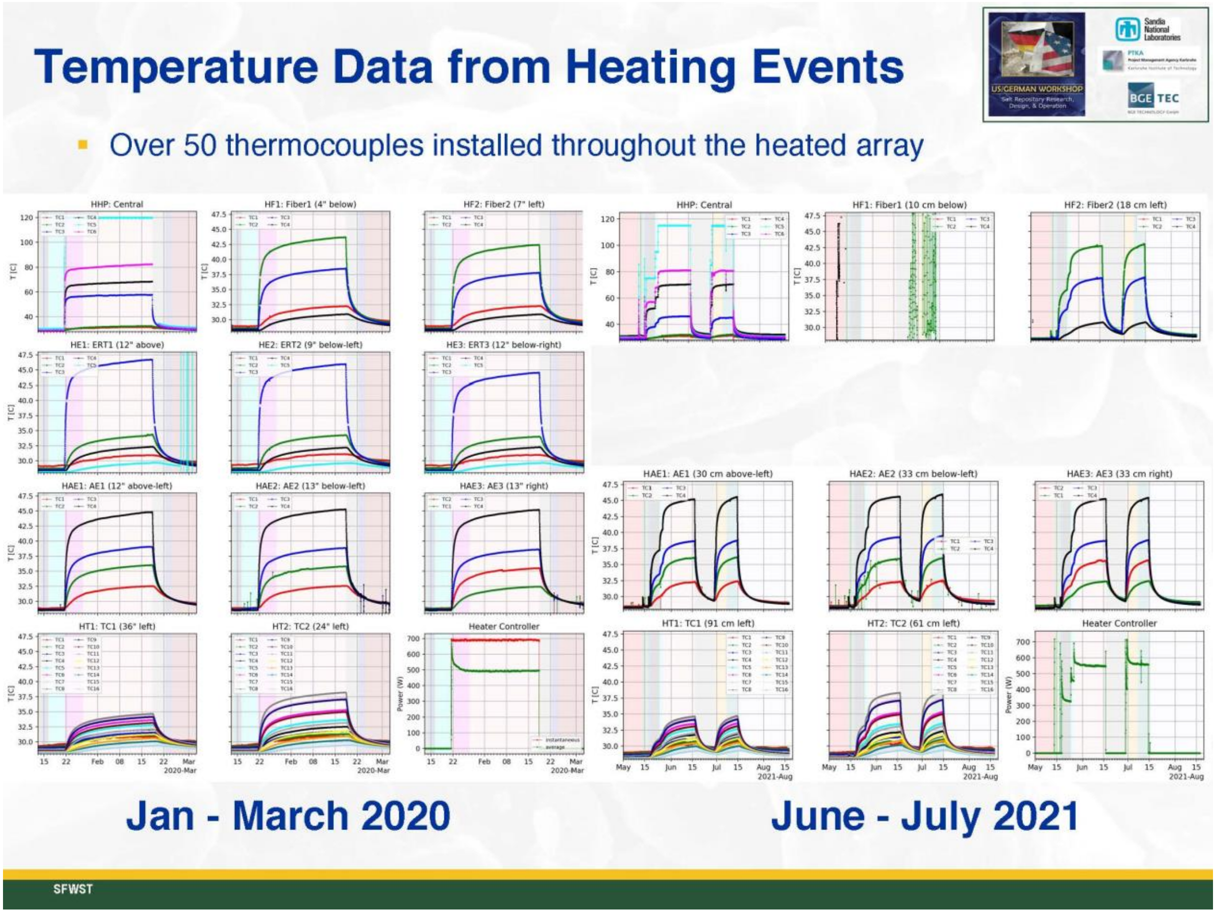
- Collected from outflow of borehole with relative humidity sensors and desiccant weights



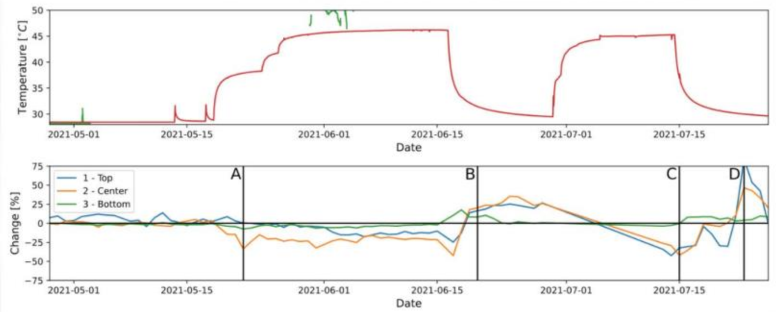
- First heating phase showed increase in brine production after heater turned off

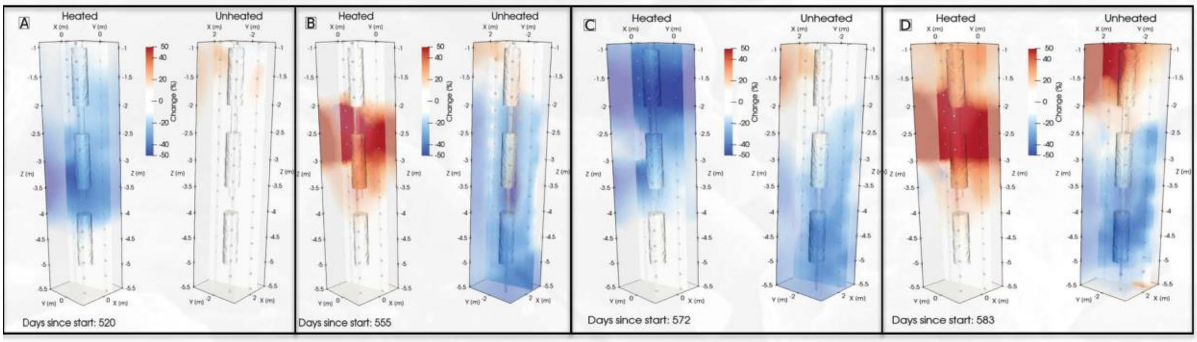
SFWST


Isotopic Data (Jan 2020 – Aug 2021)
1st heating phase
Unheated gas tracer tests
Heated gas tracer test
Heated liquid tracer test
Regular N2 circulation
Liquid tracer added
Heated
Unheated
H_2O (ppm)
$\delta^{18}O$ (‰)
$\delta^{2}H$ (‰)
2020 Mar May Jul Sep Nov 2021 Mar May Jul
SFWST


Temperature Data from Heating Events
Over 50 thermocouples installed throughout the heated array
HHP: Central
HF1: Fiber1 (4" below)
HF2: Fiber2 (7" left)
HE1: ERT1 (12" above)
HE2: ERT2 (9" below-left)
HE3: ERT3 (12" below-right)
HAE1: AE1 (12" above-left)
HAE2: AE2 (13" below-left)
HAE3: AE3 (13" right)
HT1: TC1 (36" left)
HT2: TC2 (24" left)
Heater Controller
HF1: Fiber1 (10 cm below)
HF2: Fiber2 (18 cm left)
HAE1: AE1 (30 cm above-left)
HAE2: AE2 (33 cm below-left)
HAE3: AE3 (33 cm right)
HT1: TC1 (91 cm left)
HT2: TC2 (61 cm left)
Jan - March 2020
June - July 2021
SFWST

ERT Data (May-July 2021)

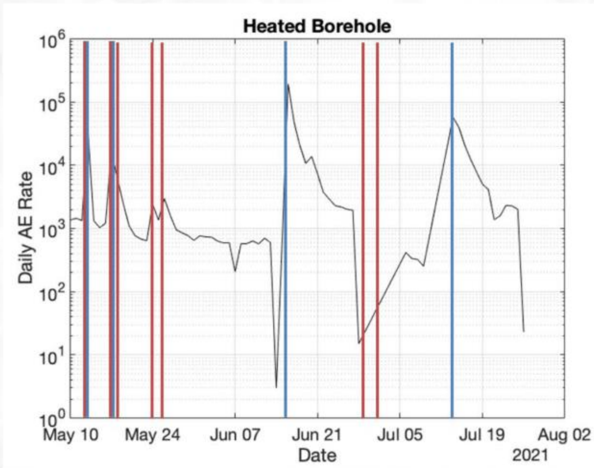




- Changes in both arrays during two heating phases and tracer tests

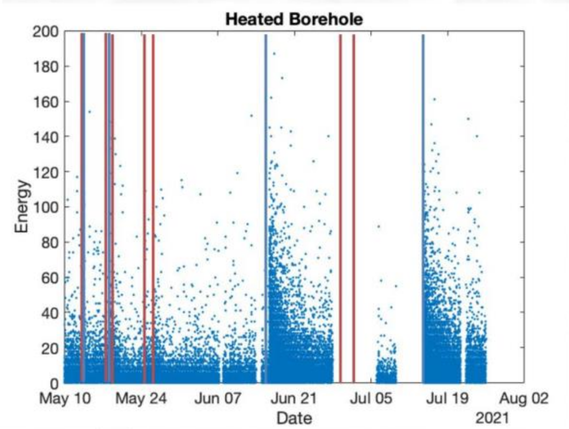
SFWST

AE Data from Heating Events (2021)

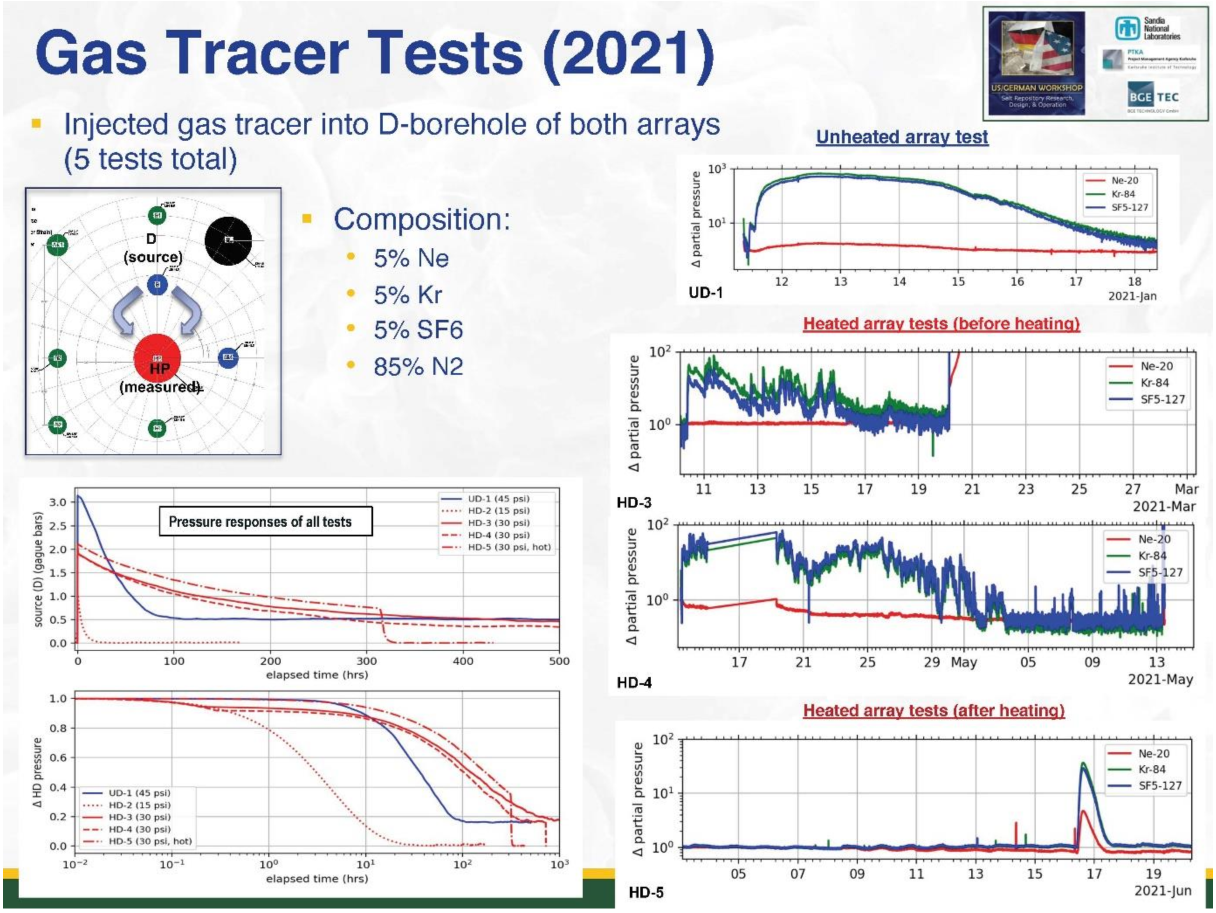


- Daily AE rates increase during heating (red) and cooling (blue) phases

- Large increases in AE energy during cooling (blue), with smaller observed during heating (red)



SFWST


Gas Tracer Tests (2021)
Injected gas tracer into D-borehole of both arrays (5 tests total)
D (source)
HP (measured)
Composition:
5% Ne
5% Kr
5% SF6
85% N2
Unheated array test
UD-1
Heated array tests (before heating)
HD-3
HD-4
Heated array tests (after heating)
HD-5
Δ partial pressure
Ne-20
Kr-84
SF5-127
Pressure responses of all tests
source (D) (gague bars)
Δ HD pressure
elapsed time (hrs)
UD-1 (45 psi)
HD-2 (15 psi)
HD-3 (30 psi)
HD-4 (30 psi)
HD-5 (30 psi, hot)
2021-Jan
2021-Mar
2021-May
2021-Jun
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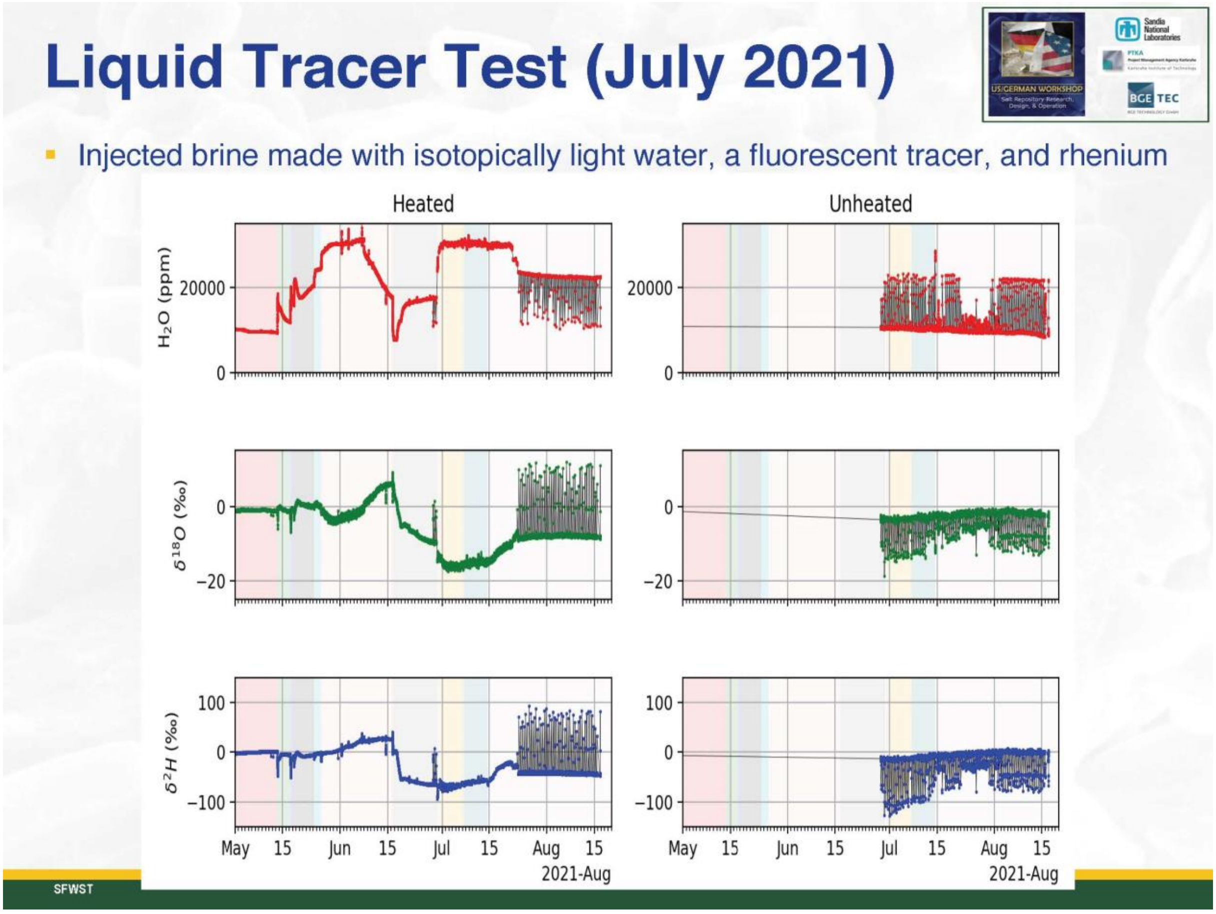
Liquid Tracer Test (July 2021)
Injected brine made with isotopically light water, a fluorescent tracer, and rhenium
Heated
Unheated
H_2O (ppm)
$\delta^{18}O$ (‰)
$\delta^{2}H$ (‰)
May 15 Jun 15 Jul 15 Aug 15
2021-Aug
SFWST
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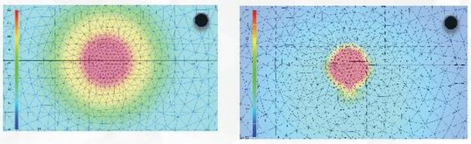
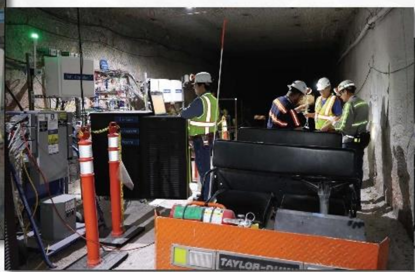
BATS Outcomes

- Generating field data for validating numerical models
  - Complex processes in a salt repository
  - Impacts of heat on amount of expected brine
  - Improve confidence in predictions to 10^6 years
  - New geophysical methods on hard problems



- New generation of repository scientists
  - Significant testing in 1980s (replace retired staff)

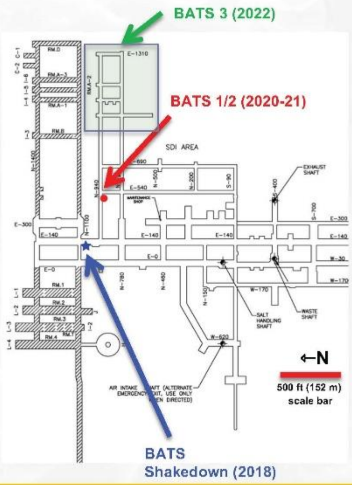


SFWST

BATS Future Plans

- BATS 1 & 2: coordinated around central borehole
  - Interference between tests (ERT vs. TC, ERT vs. AE)
  - EDZ from 14 boreholes

Layout of WIPP North End



- BATS 3 will be more "distributed"
  - New infrastructure
  - Decoupled smaller tests into SDI area
    - Long-term heated borehole
    - AE during drilling (EDZ development)
    - Cementitious EBS / seals experiments
    - Gas and brine permeability $k(\sigma, T)$

SFWST


Questions?

3D Numerical Study of BATS Field Test – Meshing and Modeling Complex Geometry

Richard Jayne
Sandia National Laboratories

Part 4 of the online workshop
September 9th, 2021

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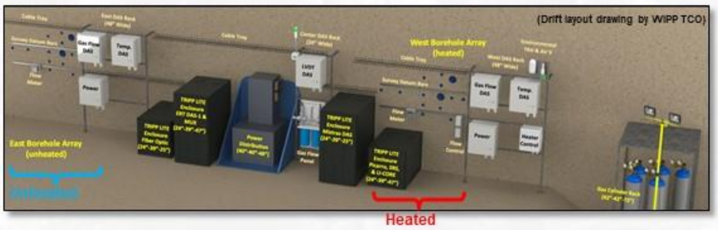
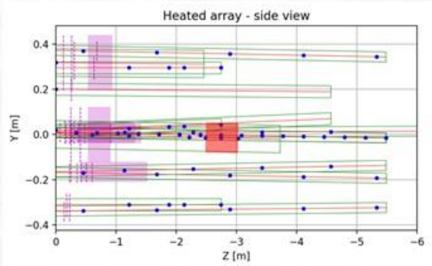
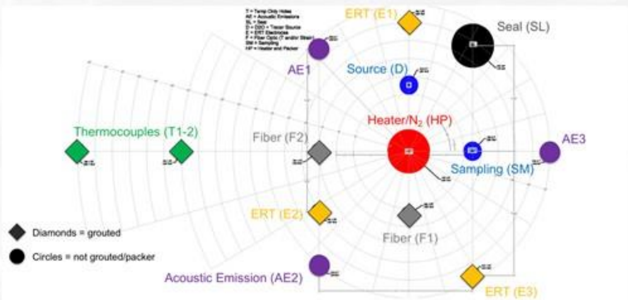
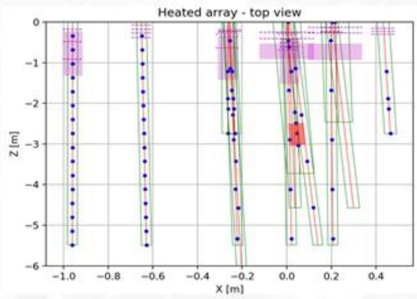
BATS Experimental Setup

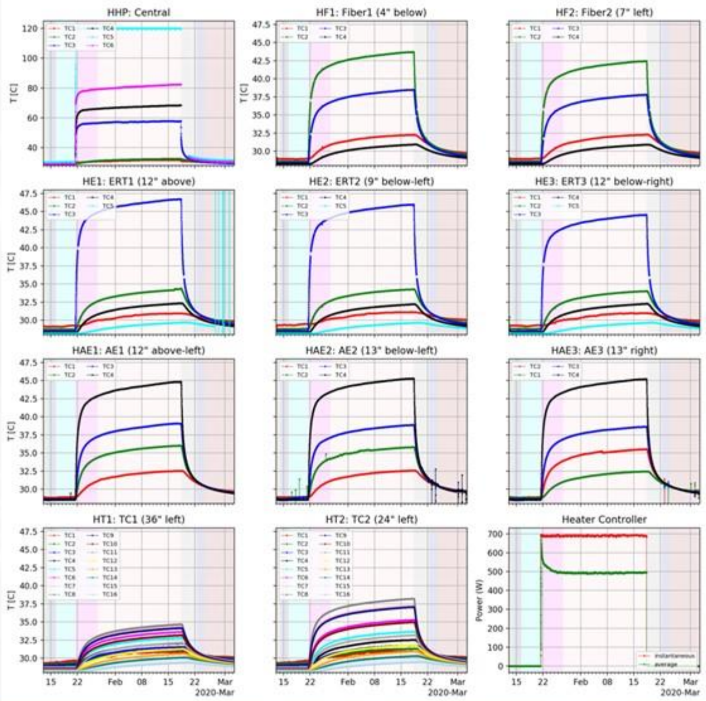








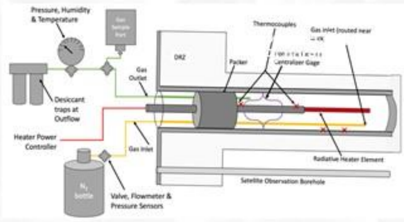
January - March 2020 BATS Test Data

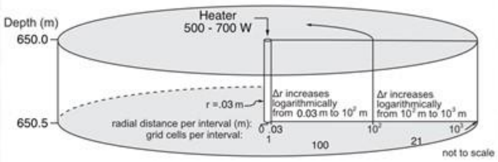


3

Previously Utilized 1-D Models to Match Field Test

- 1D radially symmetric
  - 121 grid cells
  - 1 km total model domain (0.03 – 150 m)
  - DRZ 0.03 – 1.75 m
- Heater in contact with salt
  - air causes issues with matching field data (radiative heating)
- Simulate 29 days of heating and 13 of cooling
  - On/off cycling in early test
  - Decreasing power input
- Matched temperatures measured at thermocouples





Reservoir Parameters

	Relative Permeability	Capillary Pressure
P_i = 0.1 - 12.4 MPa	λ = 0.412	λ = 0.412
T = 29.5 °C		
$k = 10^{-17} - 10^{-22}$ m^2	S_{lr} = 0.2	S_{lr} = 0.2
φ = 0.001 - 0.01	S_{ls} = 1.0	α (Pa^{-1}) = 6.5 x 10^{-5}
K = 2.0 - 7.0 W/m °C	S_{gr} = 0.2	S_{ls} = 0.999
c = 366 - 1000 J/kg °C		

(Jayne and Kuhlman, 2020)

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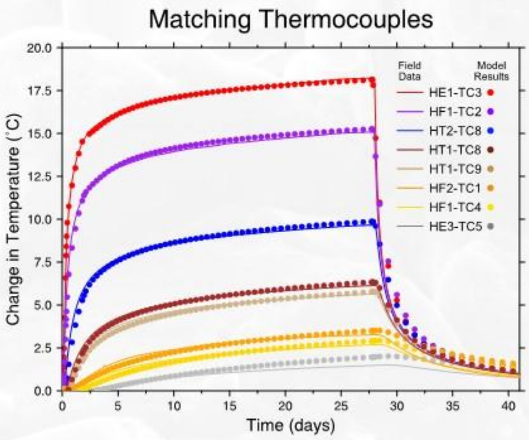
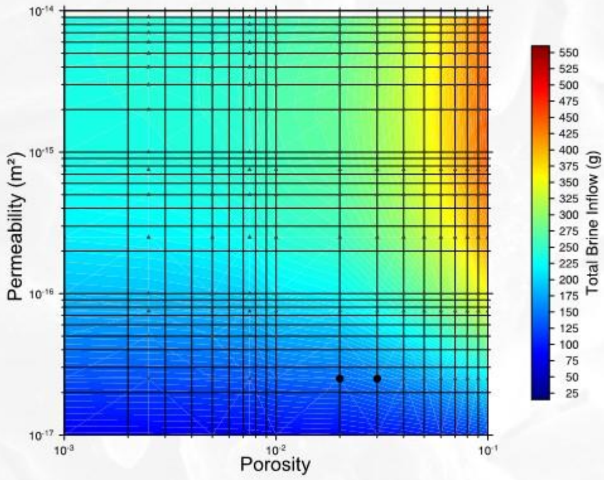
1-D Models Were Effective Matching BATS Field Data



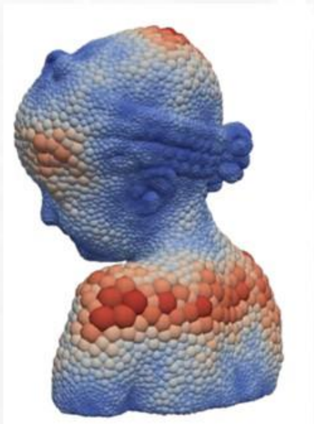


(Jayne and Kuhlman, 2020)

5

Meshing the Complex Geometry of BATS

- Create surfaces
  - Using LaGrit
- Input for Vorocrust = .obj
- Few required parameters
- Complex geometry with orthogonal discretization



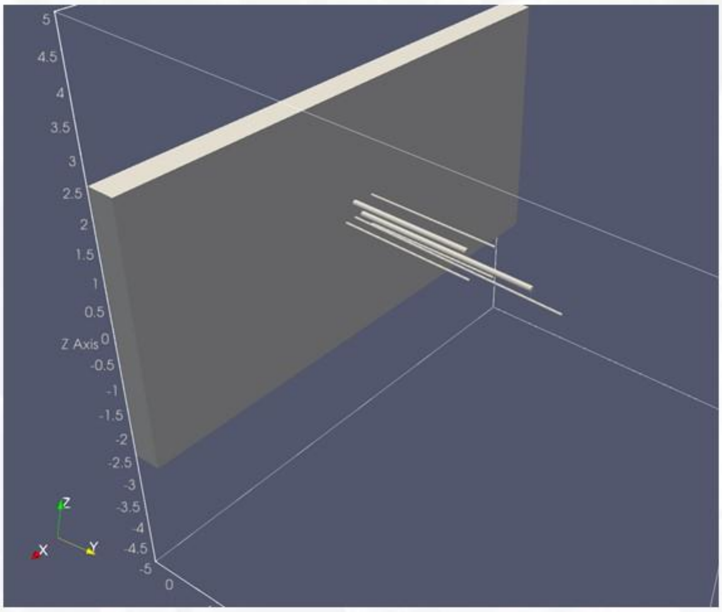
Surface spheres

Volumetric mesh

6

Meshing the Complex Geometry of BATS

- Create surfaces
  - E.g. LaGrit
- Input for Vorocrust = .obj
- Few required parameters
- Complex geometry with orthogonal discretization



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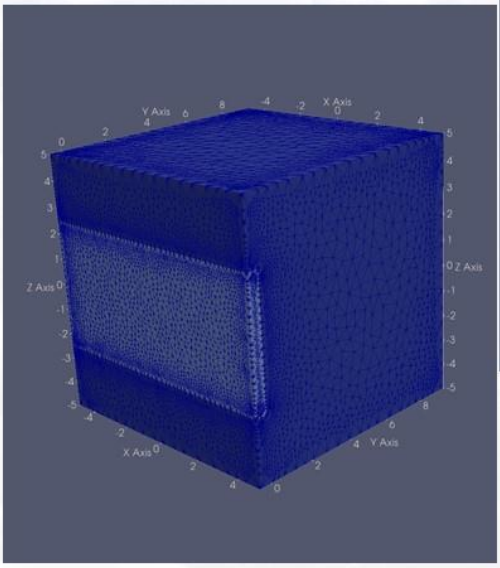
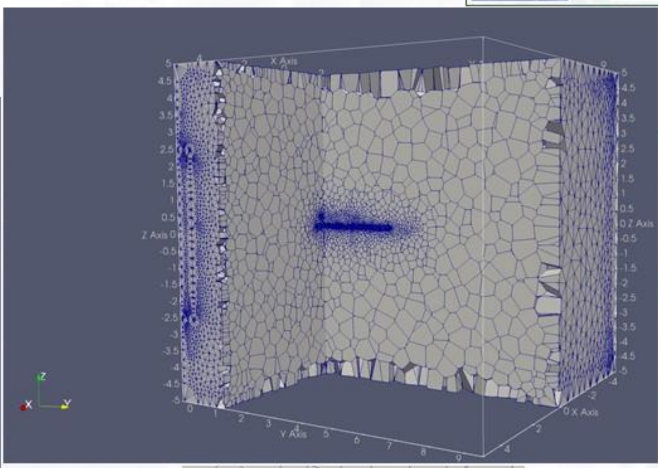
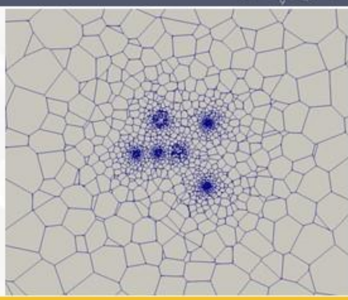
Meshing the Complex Geometry of BATS







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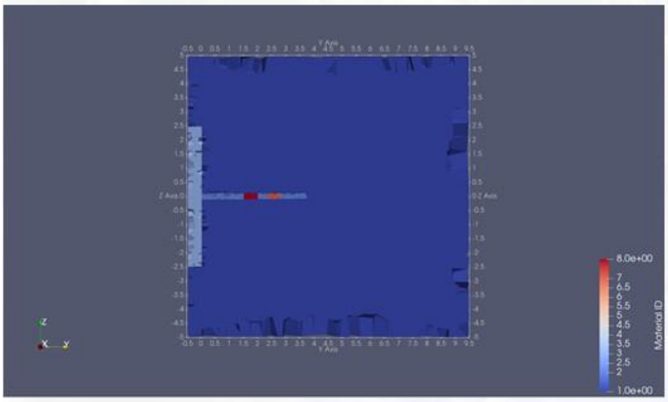
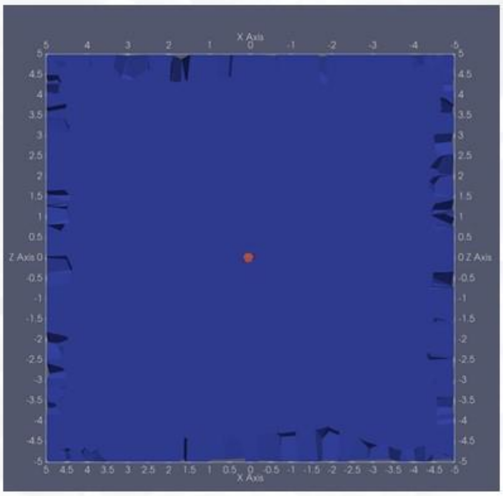
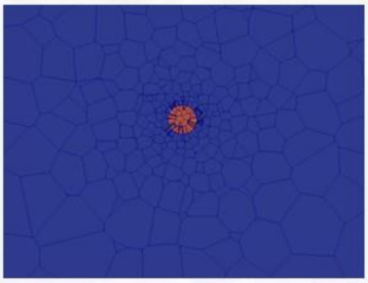
Starting with Only the Heater Borehole







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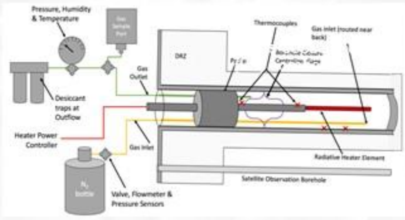
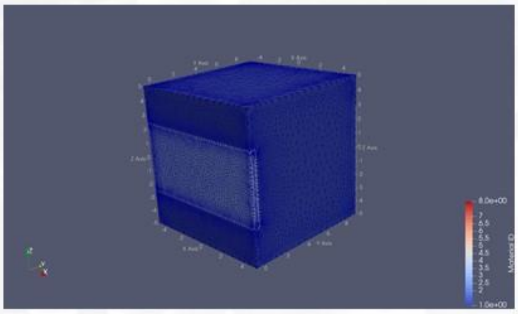
Building Complexity - Utilizing 3-D Models to Match Field Test

- 3D Model Domain
  - ~ 65,000 grid cells
  - 10 m × 10 m × 10 m
- Heater in contact with salt
  - air causes issues with matching field data (radiative heating)
- Simulate 29 days of heating and 13
  - Incorporates the on/off cycles in early time and gradual lowering of energy input
- Match temperatures measured at 3 thermocouples in-plane with heater
  - HE1 – TC3 – 0.4 m
  - HF1 – TC2 – 0.5 m
  - HT2 – TC1 – 1.68 m





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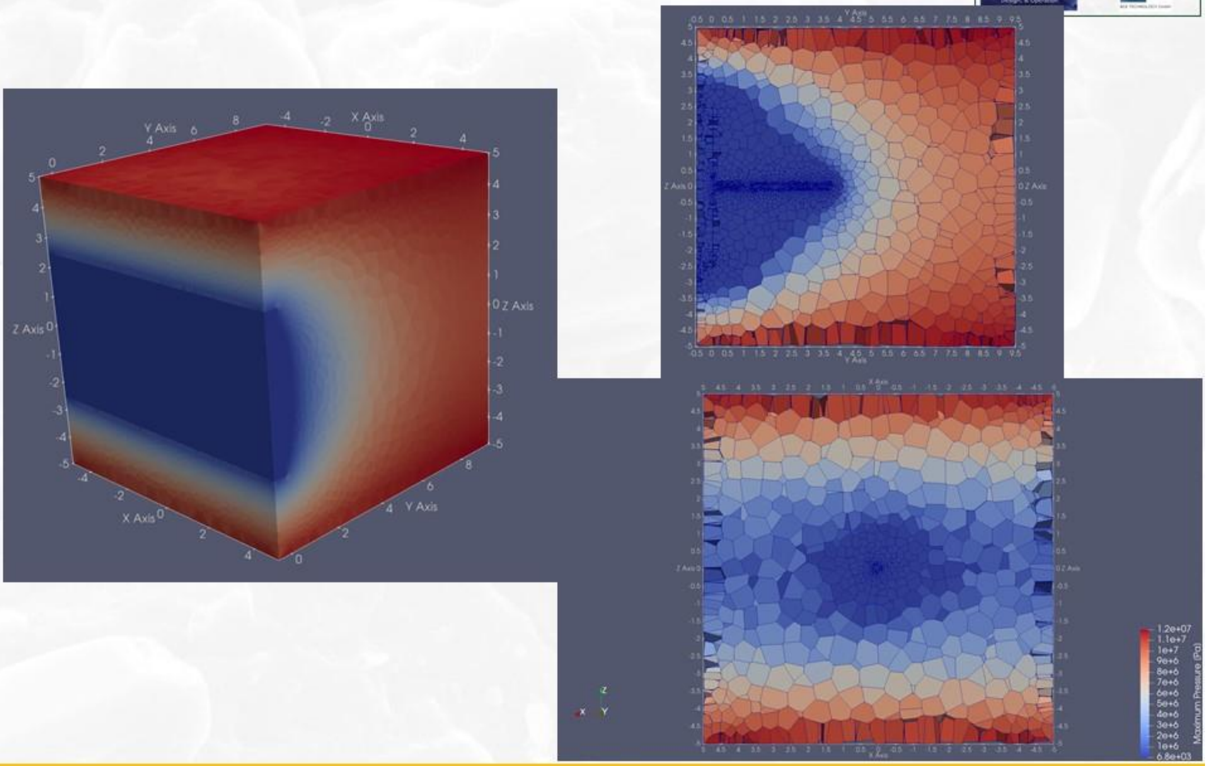
Initial Conditions - Fluid Pressure



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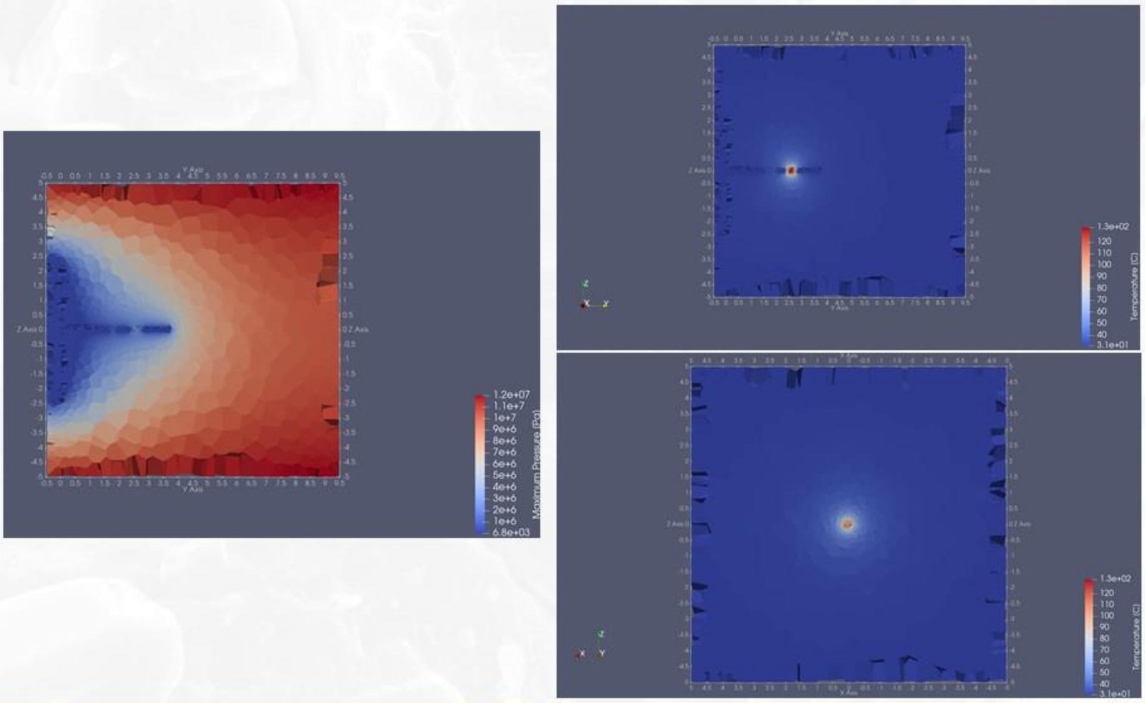
Temperature and Fluid Pressure at the End of Heating



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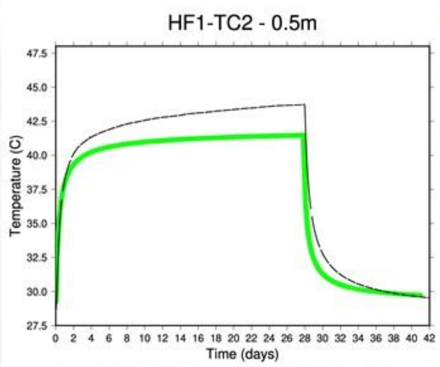
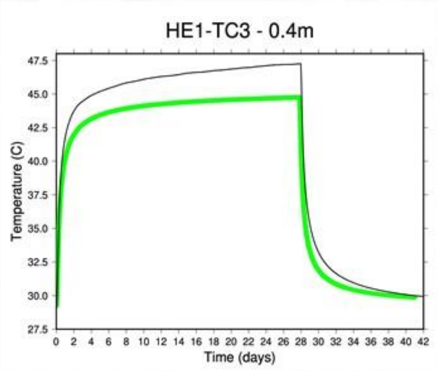
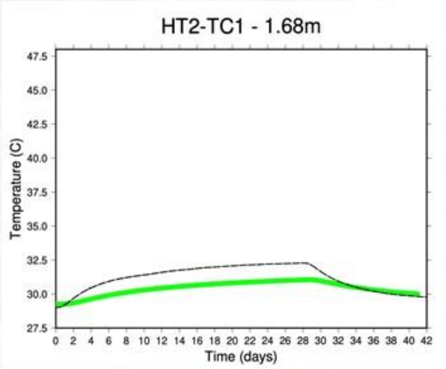
Modeled Temperature at Thermocouples







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Conclusions and Future Work

- Preliminary 3D Modeling – LaGrit + Vorocrust leads to a much more accurate representation of the BATS field test vs. a hex mesh
- Continue to build complexity
  - Add more wells
  - Add heterogeneity
  - Add DRZ

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BATS Field Test and Related Modeling

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[1]Los Alamos National Laboratory
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LA-UR-21-28810
Part 4 of the online workshop
September 9th, 2021

US/GERMAN WORKSHOP
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Stable Isotopes in Salt

3 Sources of brine at WIPP
- Fluid Inclusions
- Interstitial Water
- Water bound in clay

Stable isotopes have the potential to characterize the source of brine to heat generating waste

However this requires unique signatures from the different sources and the ability to accurately measure them.

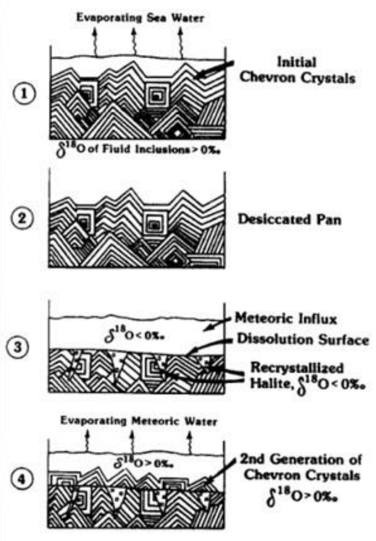


FIG. 10. Relationship between textures in halite and isotopic composition of fluid inclusions. Diagrams after SHEARMAN (1978).

From **Knauth & Beeanus, 1985**

Phase 1a Isotopes

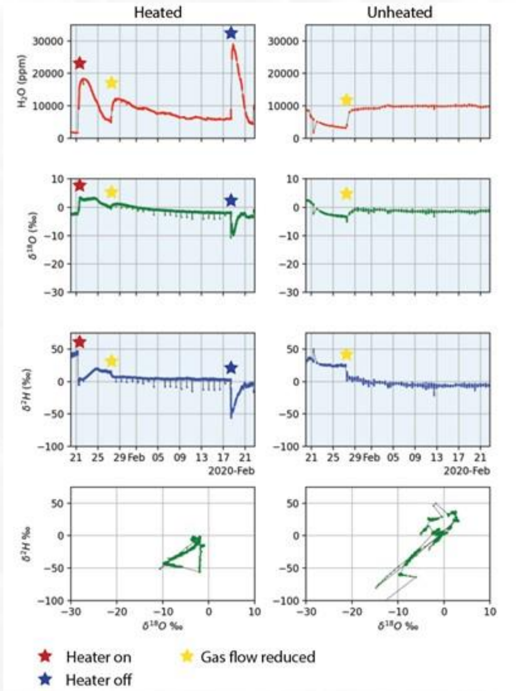
H_2O vapor concentration as well as $d^{18}O$ and d^2H in the heated and unheated boreholes as a function of time.

Jan-21-2020: heat on

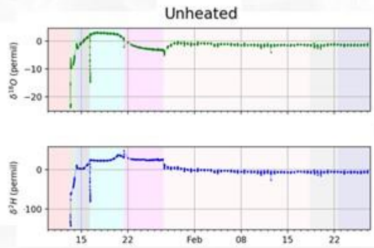
Jan-27-2020: gas reduced (H:50, U:25)

Feb-18-2020: heat off (leak)

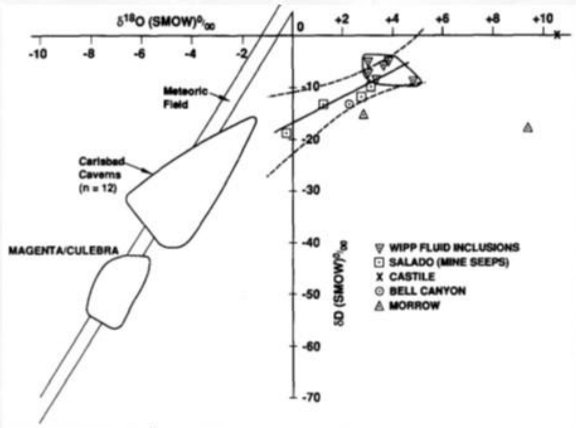
Feb-22-2020: gas spent, leak stops



Phase 1a Isotopes



Unheated array shows steady concentrations of d^2H -1.25 and $d^{18}O$ = -2



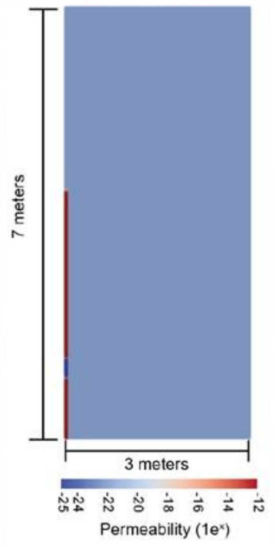
Literature values for isotopic values of local natural waters (including fluid inclusions in WIPP salt) from **Lambert, 1992**

Phase 1a Isotopes

2D Radial FEHM Model

Each isotope species treated as a liquid and vapor conservative tracer with different liquid and vapor diffusion coefficients.

Air is circulated behind the packer to remove water and stable isotopes which are monitored at an atm boundary at the packer.



Isotope species	Henry's Law Constant (Mpa)	Fractional Henry's Law Constant	Vapor Diffusion Coefficient	Liquid Diffusion Coefficient
$H_2{}^{16}O$	2.332×10^{-3}	1.0000	2.57×10^{-5}	2.23×10^{-9}
$H_2{}^{18}O$	2.309×10^{-3}	0.9903	2.50×10^{-5}	2.23×10^{-9}
$HD^{16}O$	2.149×10^{-3}	0.9217	2.51×10^{-5}	2.23×10^{-9}

Parameter (units)	Value
Salt initial porosity (-)	0.001
Salt initial permeability (m^2)	5×10^{-21}
Borehole permeability (m^2)	10^{-10}
Packer permeability (m^2)	10^{-26}
Salt thermal conductivity at 31.5 °C (W/m K)	5.25
Air thermal conductivity (W/m K)	0.03
Initial formation pressure (MPa)	12
Initial formation temperature (°C)	28.5
Air source behind heater (kg/sec)	3.06×10^{-6} / 1.06×10^{-6}
Residual saturation (-)	0.1
Maximum capillary pressure (MPa)	1.00
Saturation at which capillary pressure is zero (-)	1.00

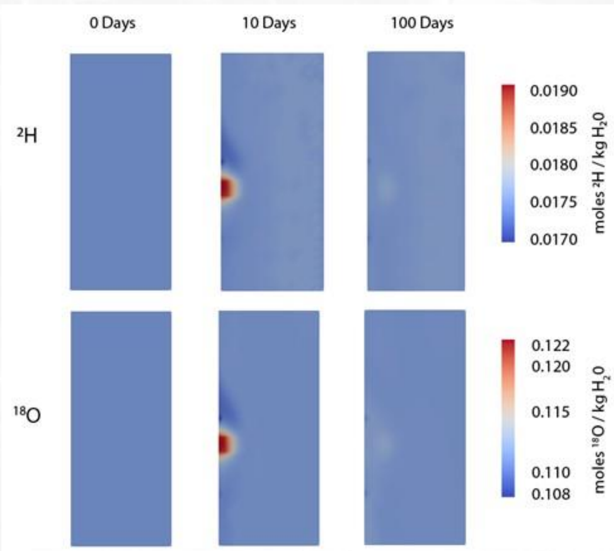
Molecular diffusion coefficients from **Smiles et al (1995)**
Henry's partitioning from **Friedman and O'Neil (1977)** and **Marilvate and Coantic (1975)**.

Phase 1a Isotopes

Model results through time.

The heater causes a lot of evaporation which leads to an enriching of ^{18}O and ^{2}H within the borehole and less ^{18}O and ^{2}H observed at the outlet

After the heater turns off the system returns to equilibrium



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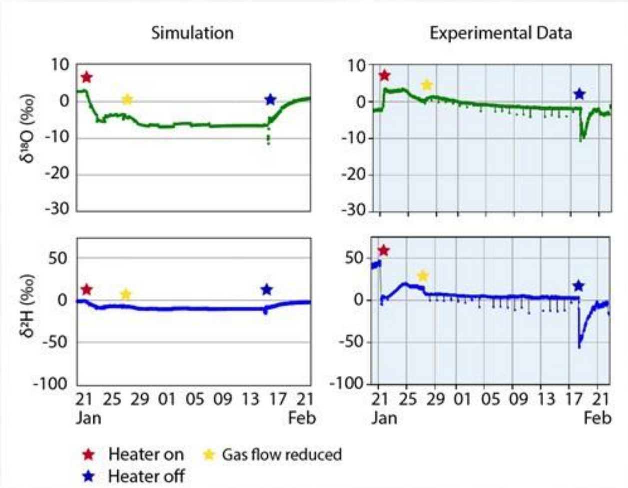
Phase 1a Isotopes

d18O and d2H behavior:

- Heater on – Water concentration rises and d2H and d18O equilibrate
- Air reduced – d2H falls / d18O rises
- Heater off - d2H/d18O fall sharply and then recover to new background
- FEHM model generally follows the d18O response but returns to background after heater off.

Different behavior between 2H and 18O is difficult to explain. Are we seeing a contribution of different sources?



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Laboratory Experiments

Laboratory experiments are underway to investigate the isotopic signature of each brine source within the WIPP formation:

- Pyrex capillary tube method is being targeted for fluid inclusion extraction
- Mechanical crushing in pyrex glass paired with heating is being considered for smaller volumes of clean salt
- Decrepitation via heating to 800 C followed by cryogenic collection

Laboratory experiments have been delayed due to Covid but are ramping up now.

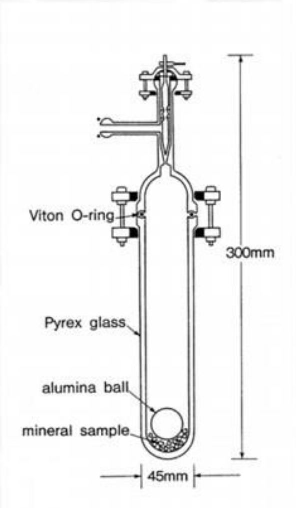


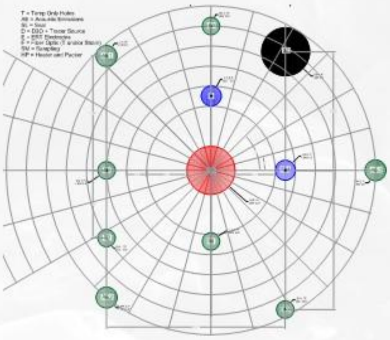
Fig. 1. Ball-mill made of Pyrex glass used in this study

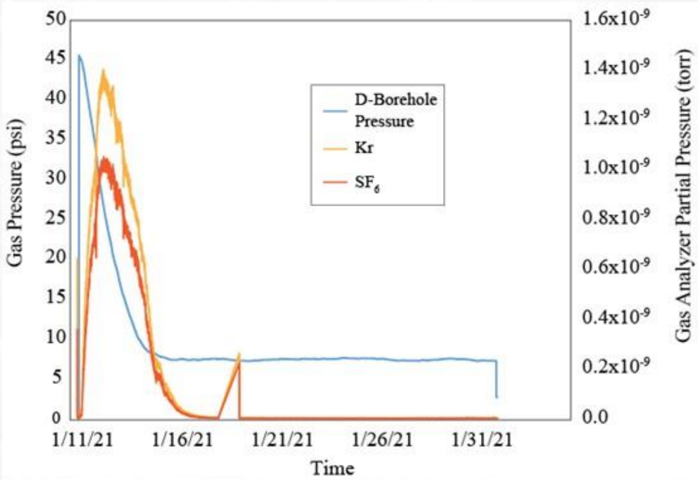
From **Horita, 1986**

Tracer Gas Experiments

Tracer gas experiment performed on the unheated array

D-Borehole pressured to 45 psi
Gas monitored at the HP Boreholes





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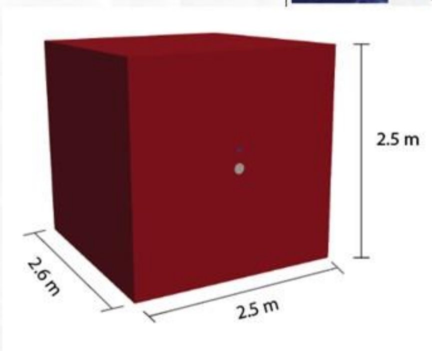
Tracer Gas Experiments

Parameter (units)	Value
Salt initial porosity (-)	0.01
Salt permeability (m^2)	1×10^{-17}
Borehole permeability (m^2)	10^{-12}
Formation pressure (MPa)	0.05
D borehole pressure (MPa)	0.31
Air source behind heater (kg/sec)	1.33×10^{-6}
Residual saturation (-)	0.1
Maximum capillary pressure (MPa)	1.00
Saturation at which capillary pressure is zero (-)	1.00
SF_6 Henry's Law Constant (mol/(kg*MPa)	2.4×10^{-3}
SF_6 Vapor Diffusion Coefficient m^2/s	9.1×10^{-7}
SF_6 Liquid Diffusion Coefficient m^2/s	1.2×10^{-8}



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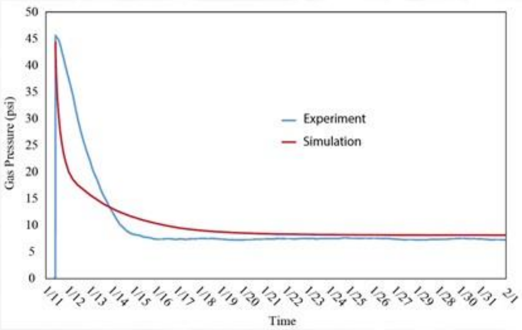
Tracer Gas Experiments

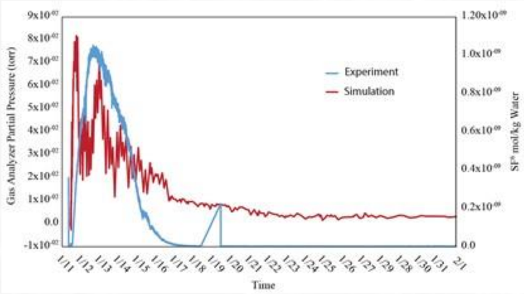
Results are still fairly preliminary.

In reality the area between the boreholes is more like a fracture network than it is porous media.

Long linear pressure decrease is difficult to match.

Need to consider appropriate relative permeability curves.





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Conclusions and Future Work

- Consider treating the DRZ as a fractured network which could potentially be characterized using the dual continuum model in FEHM
- Consider appropriate relative permeability curves for the fractured system
- Continue laboratory work to isolate the three separate brine sources in the vicinity of the BATS experiments

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