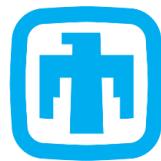




**PTKA**  
Project Management Agency Karlsruhe  
Karlsruhe Institute of Technology



**Sandia**  
**National**  
**Laboratories**



BGE TECHNOLOGY GmbH

## PROCEEDINGS

# 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation 2021

**BGE TEC 2021-19**





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# 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation 2021

**BGE TEC 2021-19**

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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 10<sup>th</sup> 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 12<sup>th</sup> 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 11<sup>th</sup> 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-Hoepppe, 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-Hoepppe, 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-Hoepppe) 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).



**Table of Contents**

Executive Summary	i
Acknowledgements	iii
Table of Contents	v
1       Introduction	1
2       National Programs and Site Selection Processes	3
2.1    Status of the United States Spent Fuel and High-Level Radioactive Waste Management Program	3
2.1.1   SNF/HLW Inventory	3
2.1.2   Fuel Cycle Research and Development (R&D)	3
2.1.3   Interim Storage/Nuclear Waste Fund Oversight	4
2.1.4   Summary	4
2.2    Status of Site Selection Procedure in Germany	4
2.2.1   Introduction	4
2.2.2   Interim Results of the Site Selection Procedure	4
2.2.3   Outlook	6
2.3    R&D program and Disposal Concept in the Netherlands	6
2.3.1   Introduction	6
2.3.2   Long-term research program	6
2.3.3   Disposal concept	7
2.4.1   Introduction	8
2.4.2   Siting Process	8
2.4.3   Concept of a Geological Disposal Facility	9
3       Compaction of Crushed Salt	11
3.1    The KOMPASS Project	11
3.2    Microstructural Investigations Presentation	11
3.3    Natural and Technical Analogues	13
3.4    Modelling-related Experimental Aspects	17
3.5    Future Work of Relevance for Long-term safety (LTS)	18
4       Engineered Barrier Systems – Towards Robustness and Reliability	19
4.1    Overview	19

4.2	Optimization of Drift Seals with Respect to Long-term Functionality	19
4.3	Mechanical and Hydraulic Zones of Weakness – Determination of Properties	21
4.4	Successful Improvement of a Technical Component	24
4.5	Summary	25
5	Modeling Challenges	27
6	Concluding remarks and outlook	29
	References	31
	Appendix A – Program and Presentations of Part 1 (February 2021)	33
	Appendix B – Program and Presentations of Part 2 (17 <sup>th</sup> June 2021)	69
	Appendix C – Program and Presentations of Part 3 (8 <sup>th</sup> September 2021)	137
	Appendix D – Program and Presentations of Part 4 (9 <sup>th</sup> September 2021)	199

## 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 10<sup>th</sup> 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 11<sup>th</sup> 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 11<sup>th</sup> US/German Workshop was a success and ties in with its predecessors.

The report in hand summarizes the 11<sup>th</sup> 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 includes 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**

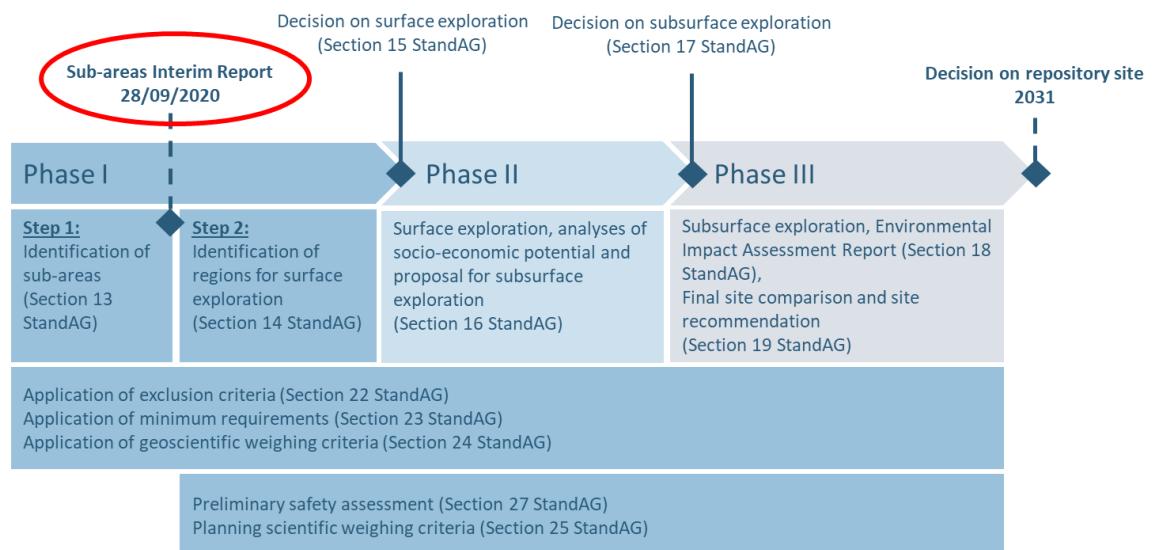
During the workshop, Astrid Göbel gave an overview of the status of the site selection procedure in Germany. The related presentation is included in the Appendix.

### **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 10<sup>th</sup> US-German-Workshop last year. During this year's workshop, first interim results could be presented.

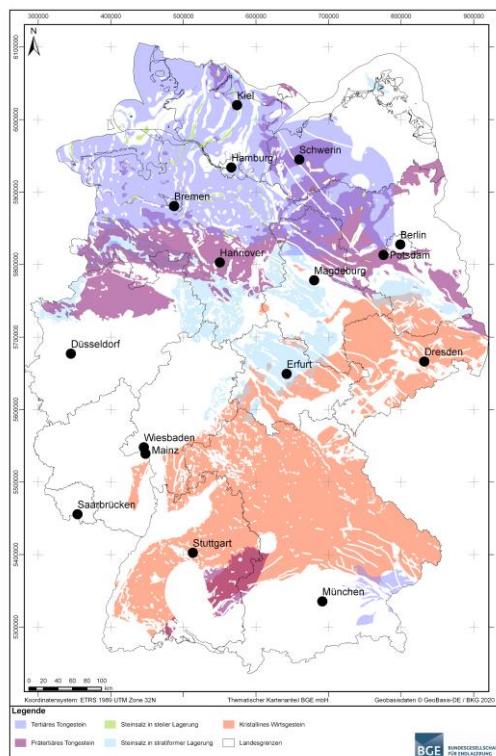
### **2.2.2 Interim Results of the Site Selection Procedure**

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 km<sup>2</sup>, 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 km<sup>2</sup>
- 7 sub-areas in crystalline host rock: surface of approx. 80 786 km<sup>2</sup>
- 74 sub-areas in salt host rock (60 steep salt rock structures + 14 stratiform salt formations): surface of approx. 30 450 km<sup>2</sup>

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**

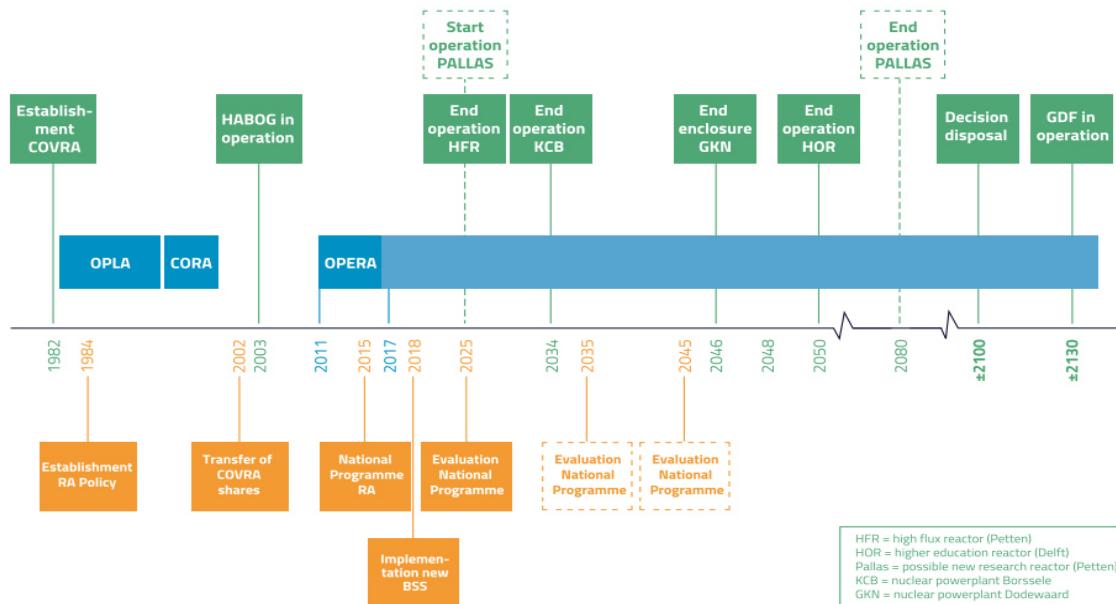
During the workshop, Jeroen Bartol gave an overview of the status of the R&D program and Disposal Concept in the Netherlands. The related presentation is included in the Appendices.

### **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 km<sup>2</sup>, while the underground part of a GDF may cover an area of up to 20 km<sup>2</sup>. 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.

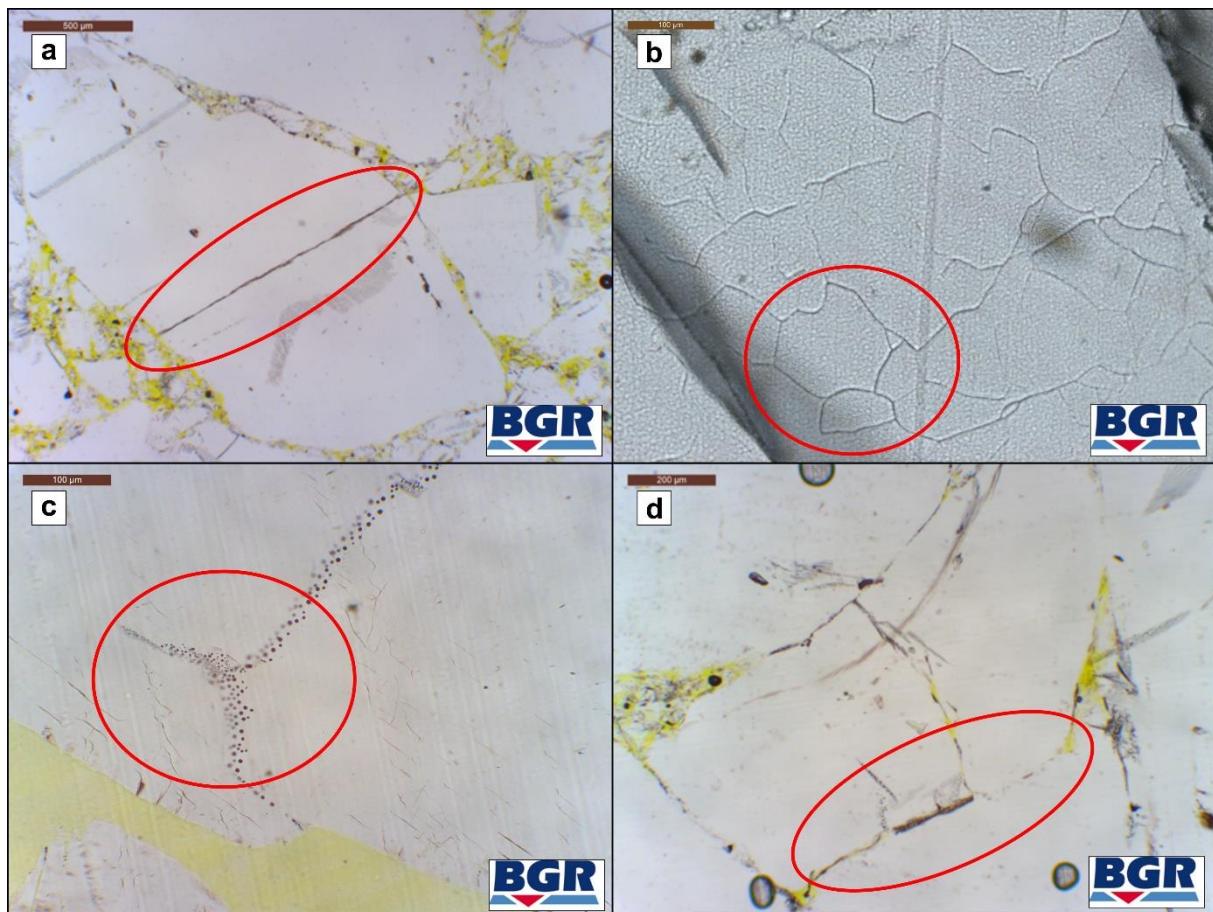
In general, three main types of deformation mechanisms were identified in rock salt (e.g. Jackson & Hudec, 2017): (1) cataclasis, (2) dislocation creep, and (3) solution-precipitation creep (Table 1). To some degree, the abundance of each indicator type provides the corresponding mechanism's contribution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

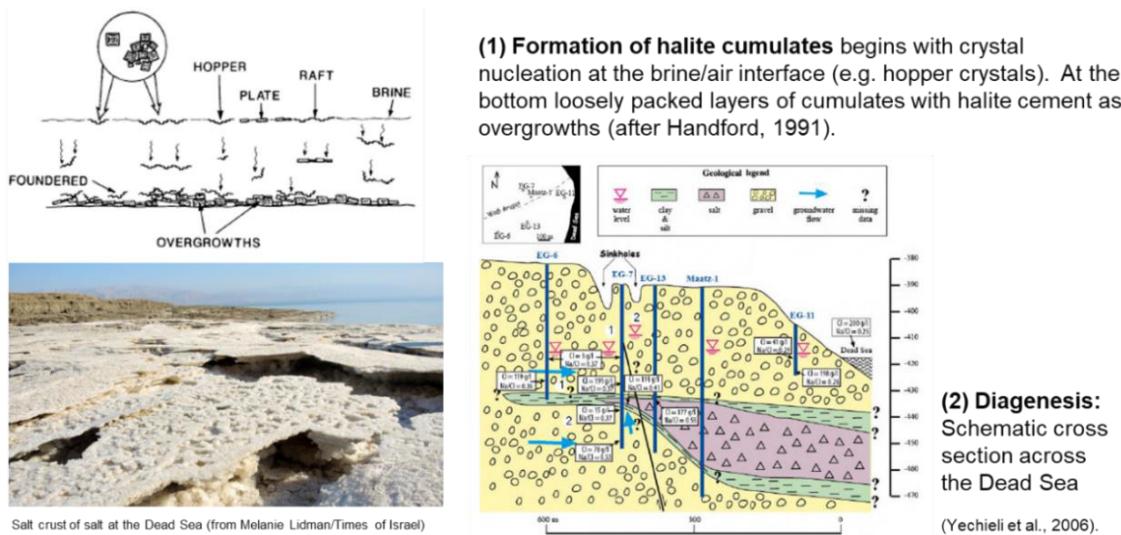
Yet, we still see the potential in identifying the indicators' abundancies and strive for better analysis in our upcoming work (KOMPASS-II). For this improvement, we plan to investigate samples from compaction tests with more stable environmental controls. This way, we may be able to successfully assign 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

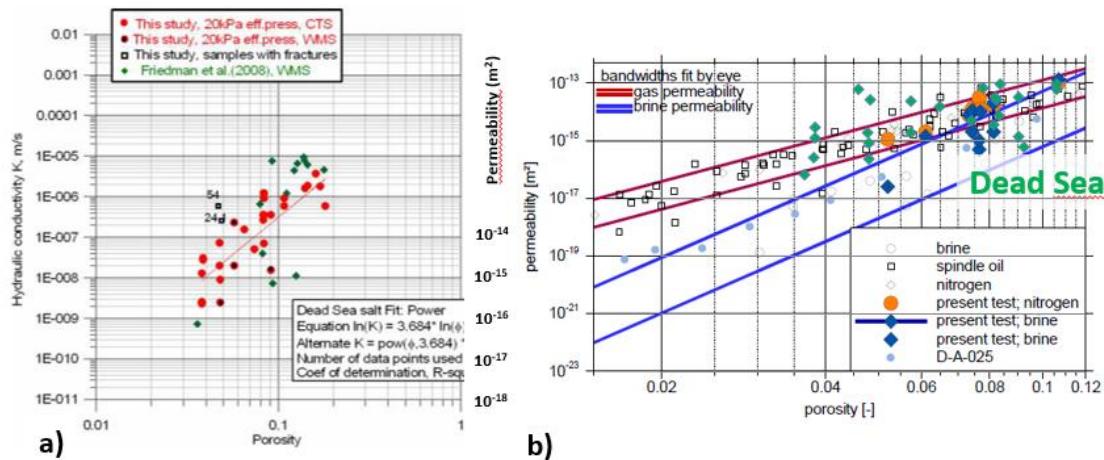
shown for Dead Sea sediments in Figure 6, the diagenetic modification of halite begins contemporaneously with deposition, is most intense within the upper few meters of deposition, and is essentially complete within the first 45 m of deposition or, at least, within 100 m. At the same time, the pore space 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.

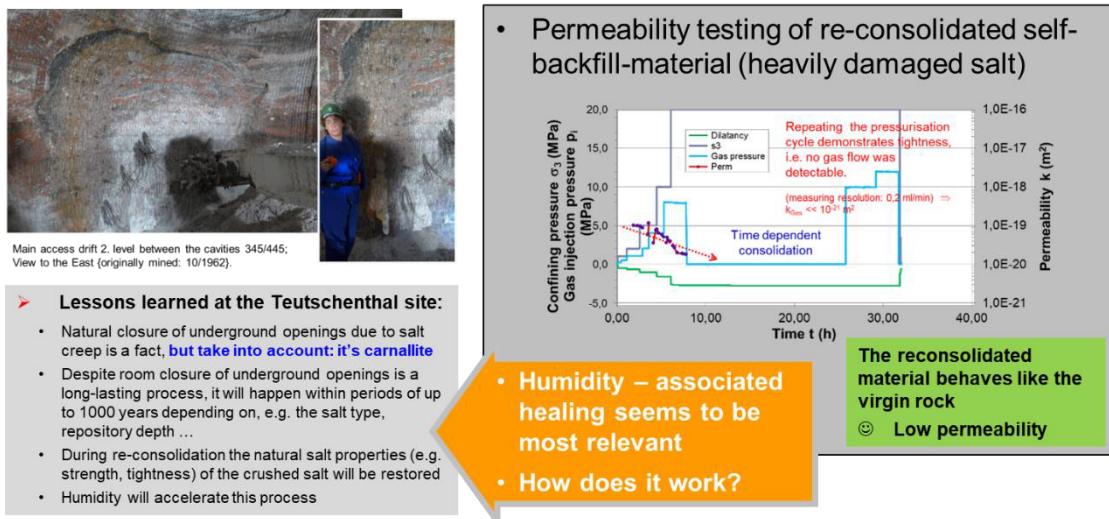
The diagenetically induced loss of porosity result mainly from chemical changes such as changes of the mineralogical/ (cementation). Textural effects (mechanical induced compaction), in the pore space of deposited salt aggregates is also documented as origin of loss of porosity. From all the effects changes of petrophysical properties are expected, e.g. compression wave velocities ( $V_p$ ), shear waves ( $V_s$ ), and electrical resistivity ( $\rho$ ) 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.



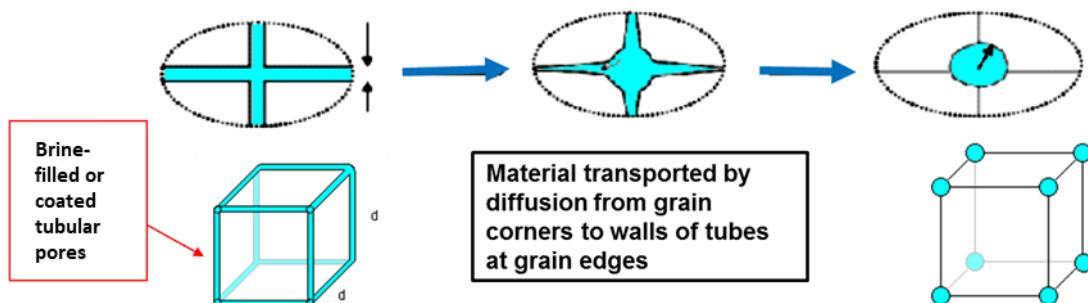
**Figure 8:** Synthesis of observations from drift closure in the Teutschenthal mine, where permeability measurements on compacted material demonstrated that the original tightness of the disturbed salt is restored (modified, after Popp et al., 2018)

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  $\theta$ . In the case of  $\theta > 60^\circ$ , the fluids will be present inside isolated inclusions, whereas for  $\theta < 60^\circ$ , 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.

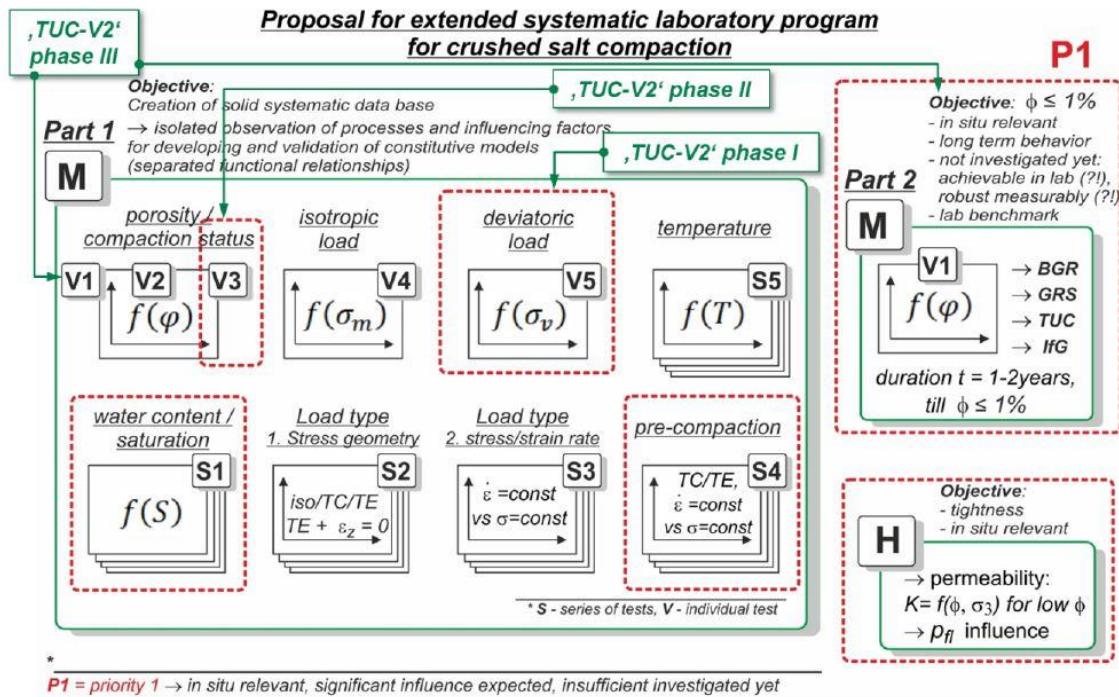


Figure 10: Proposal for an extended laboratory program for the systematic determination of the THM-coupled long-term behavior of crushed salt with prioritization (red) and allocation of the TUC-V2 test phases I, II and III (green), based on Friedenberg et al. (2021)

### 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 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.

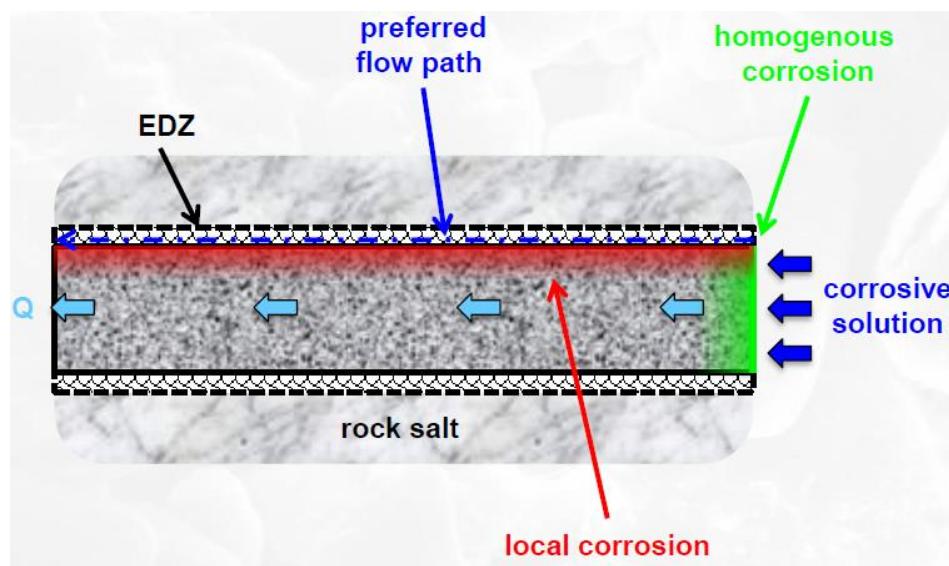
Regarding long-term robustness and reliability, two presentations were provided by technical staff of BGE and GRS. SNL contributed investigations on bedding planes, which constitute natural zones of weakness. A technical procedure to assess mechanical properties of clay seams in salt was presented. TUC 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**

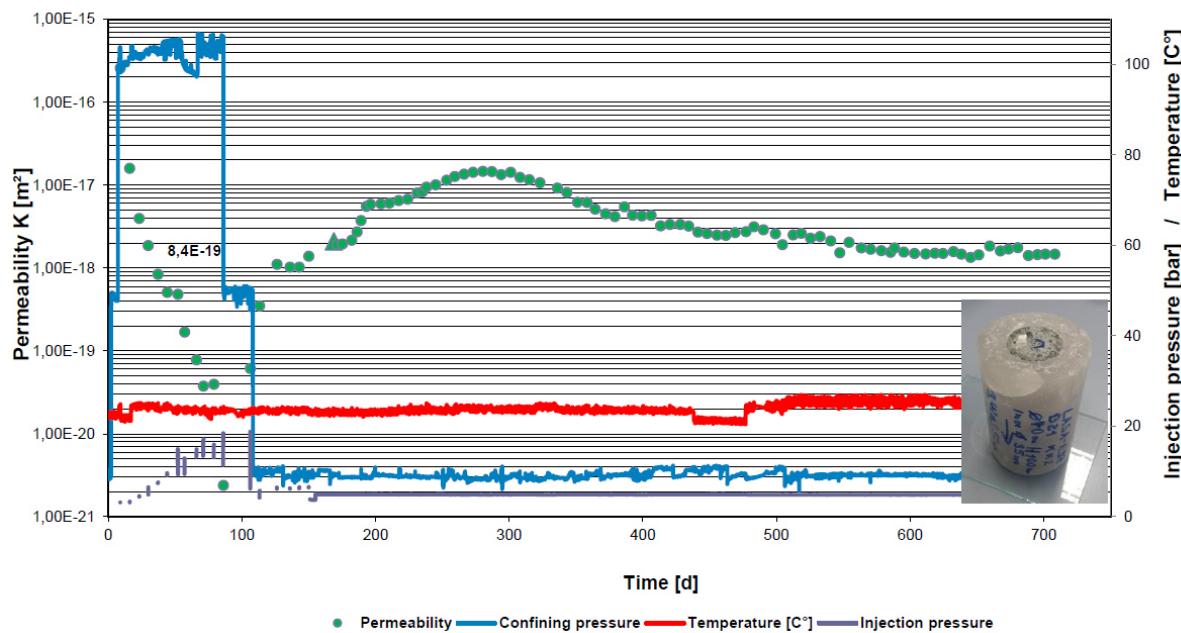
Within the closure concept of the Morsleben repository, drift seals were planned in the past that were mainly made of salt concrete M2. Meanwhile, experience has been gained on MgO-based construction materials, and different emplacement technologies are available. In order to increase robustness and 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  $10^{-18} \text{ m}^2$  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<sub>2</sub>-rich brine is expected whose MgCl<sub>2</sub> 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.

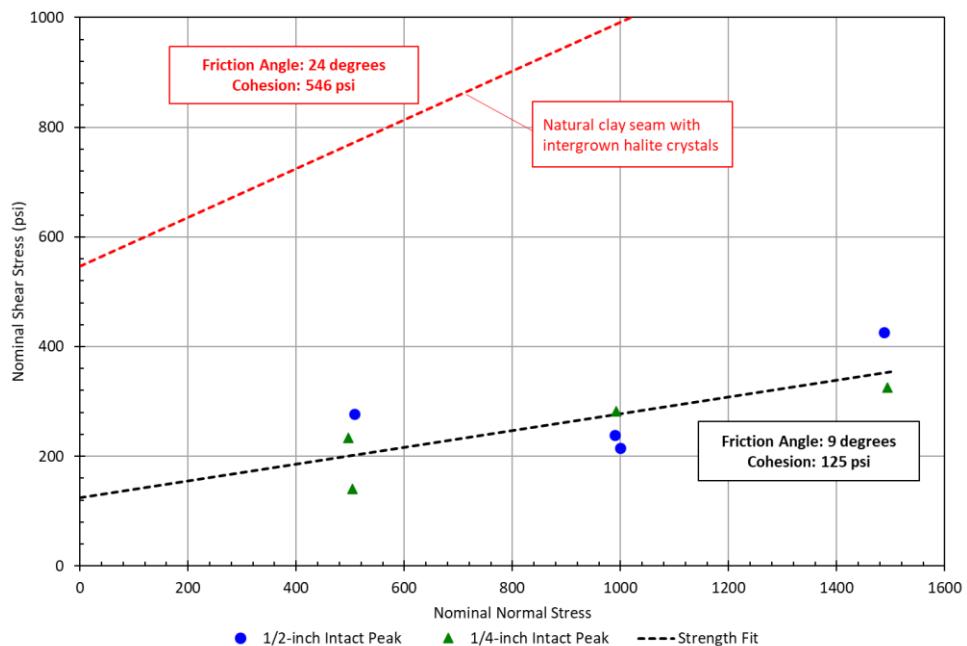
The artificial clay seam test specimens were manufactured as follows:

- 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.



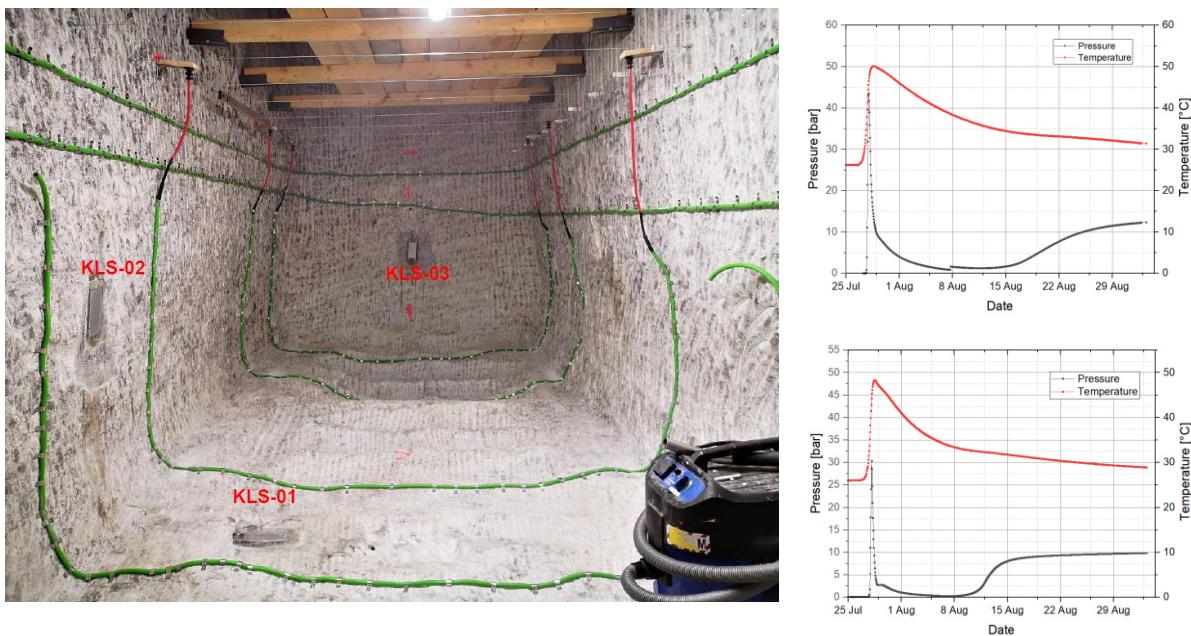
Figure 13: Decisive details of artificial clay seam, based on Sobolik et al. (2021)



**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)

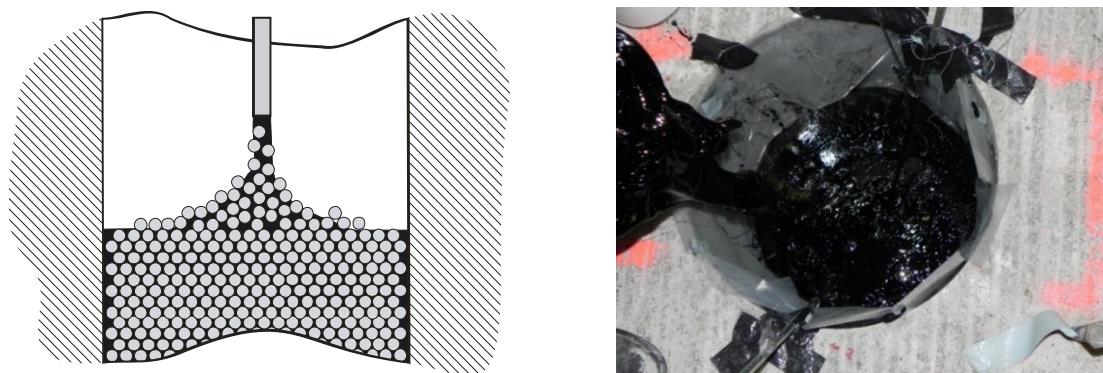
#### 4.4 Successful Improvement of a Technical Component

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.

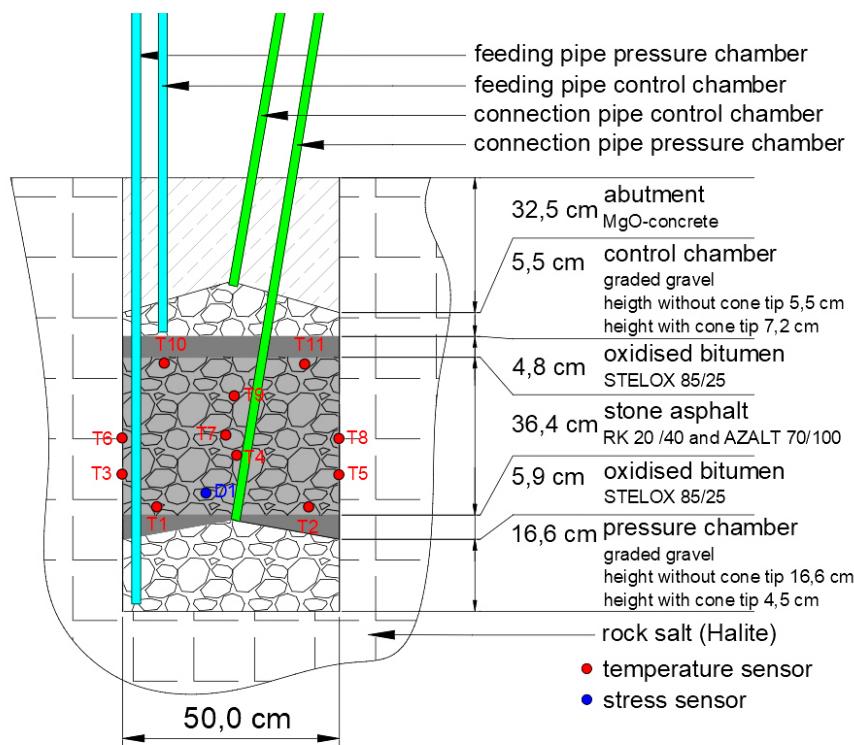
An alternative to the bitumen-filled gravel column would be the dense stone asphalt newly developed within the joint R&D project ELSA II (Figure 16). The sealing capability of the stone asphalt was tested at a medium scale by means of borehole tests (Figure 17). For stone asphalt, the gravel aggregate (=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-Hoepppe 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 12<sup>th</sup> 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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**Appendix A – Program and Presentations of Part 1 (February 2021)**

Berlin time		2 <sup>nd</sup> 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
<b>NATIONAL PROGRAMS</b> 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**



## Sources of Nuclear Waste



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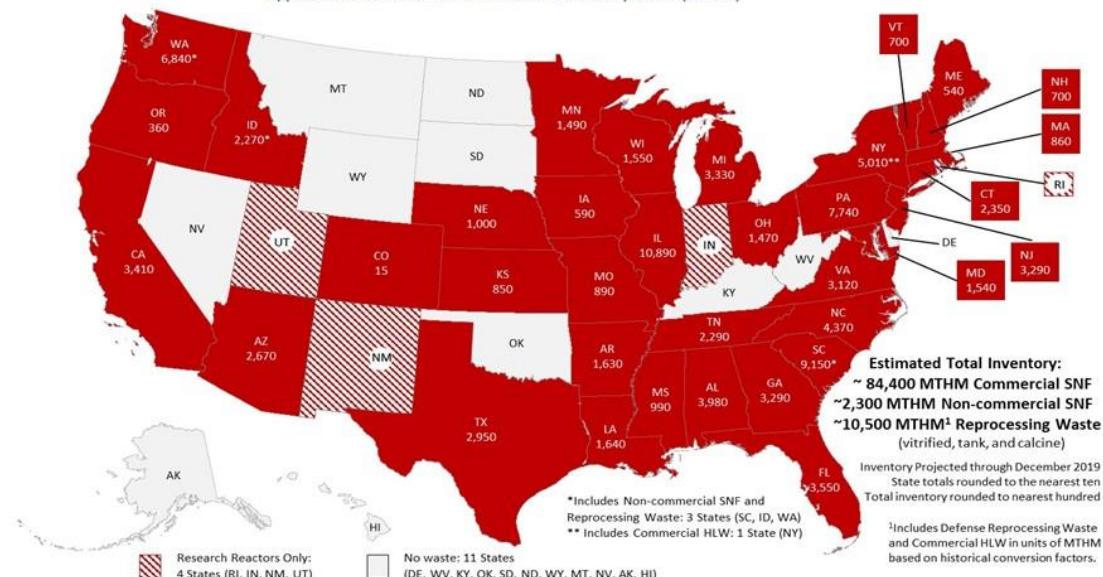


## SNF/HLW Inventory

Nuclear Energy

### 39 States with SNF/Reprocessing Waste

Approximate amounts shown in Metric Tons Heavy Metal (MTHM)

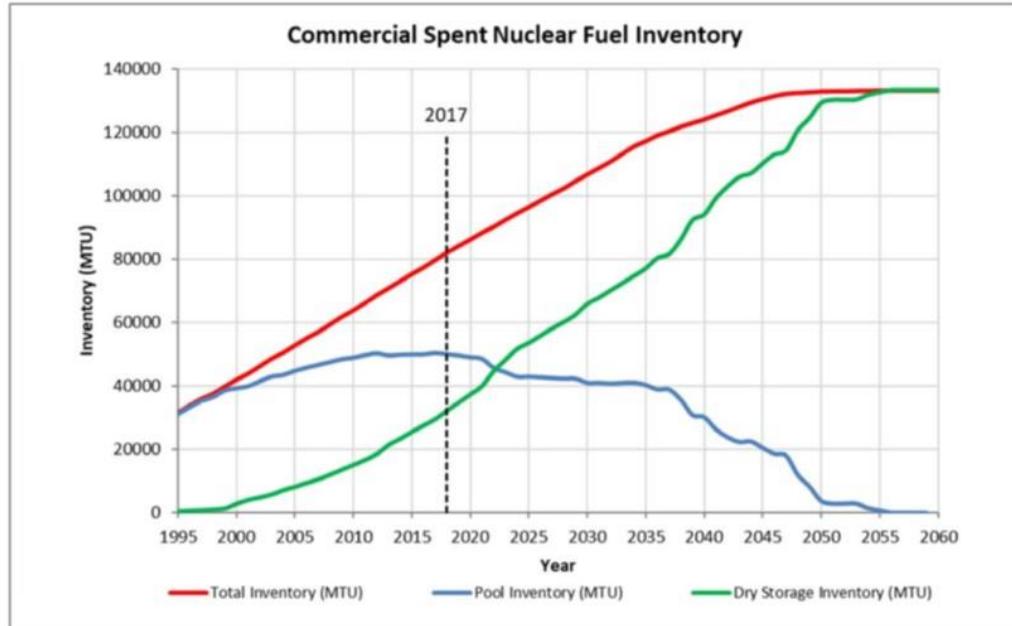


Source: SRNL 2020

4



## Spent Fuel Inventory Projection



Source: Modified from Figure 1-5, SNL 2019

5



## 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.

6



## 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



## 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

8



## 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

9



## 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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## Summary

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

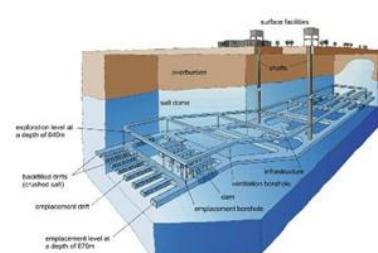
- Continue R&D in areas of storage and transportation, generic geologic disposal, and direct disposal of dual-purpose canisters
- Continue development of transportation capabilities (railcar and programmatic elements)
- Planning for possible interim storage

11



## Questions

### Questions/Comments?



**Additional information at**

**[www.energy.gov](http://www.energy.gov)**

12



## References

- SNL (Sandia National Laboratories) 2014. *Evaluation of Options for Permanent Geologic Disposal of Used Nuclear Fuel and High-Level Radioactive Waste Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*. FCRD-UFD-2013-000371. SAND2014-0187P; SAND2014-0189P. Revision 1. Albuquerque, New Mexico: Sandia National Laboratories.
- 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



## 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation



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)

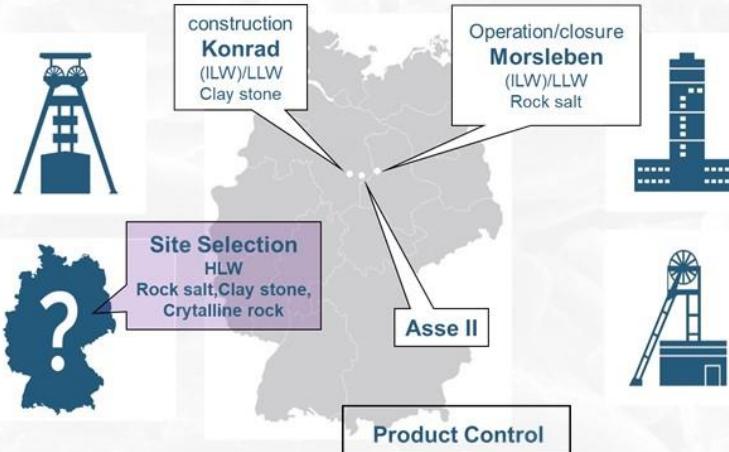
2013 **restart** The 'StandAG' (Repository Site Selection Act) comes into force. The aim of the site selection procedure is to find a site for a geological repository for mainly high-level radioactive waste (HLW) by means of a science-based and transparent procedure.

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.



# BGE as German implementer

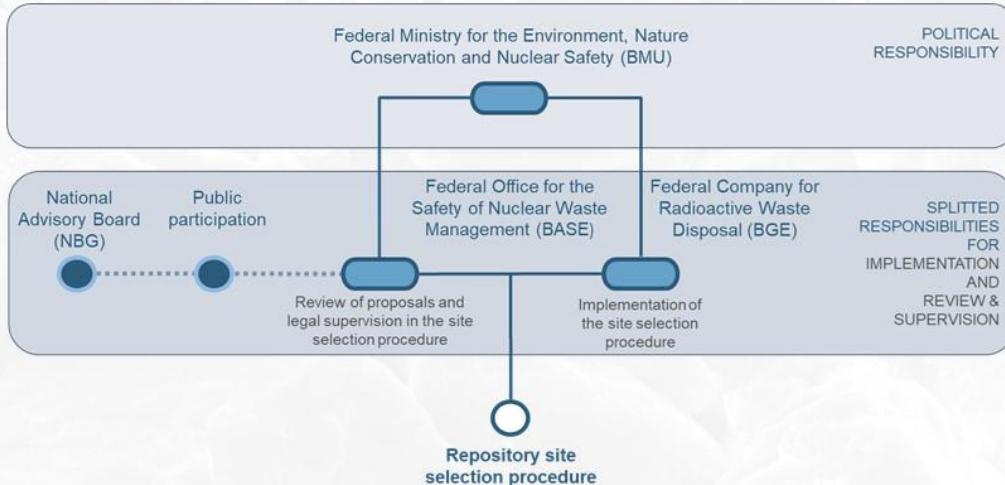


## Profile of the BGE:

- 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

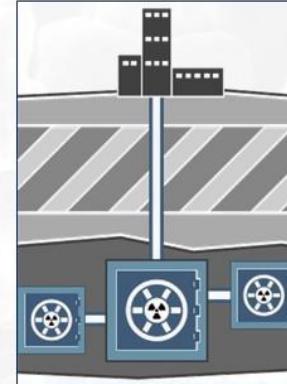


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# Regulatory framework

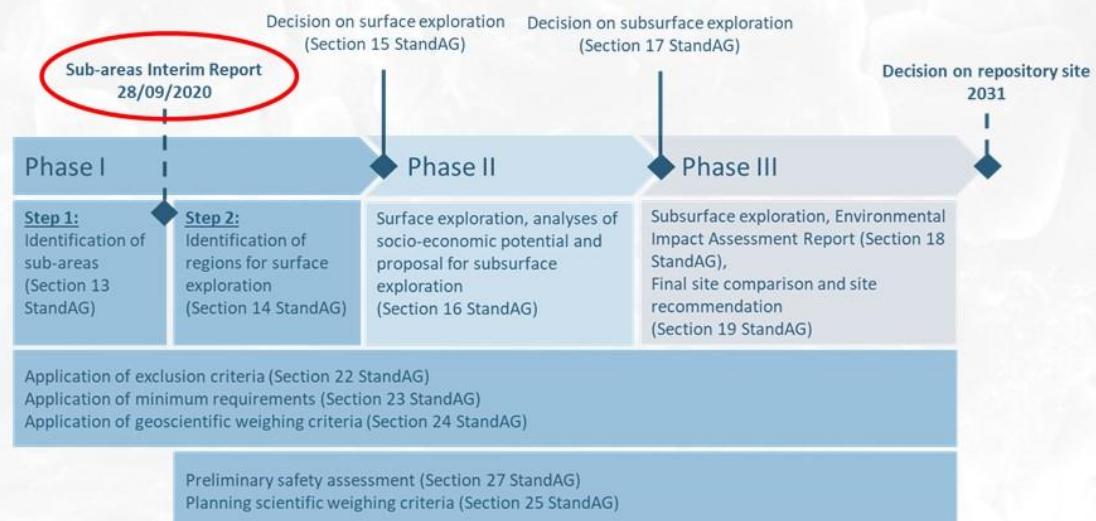


- Best possible safety conditions for the storage of HLW
- Repository location must be within the Federal Republic of Germany
- Deep geological disposal mine
- Best possible safety for a period of 1 million years
- Retrievability during operating phase
- Recoverability (Bergbarkeit) for 500 years after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



5

# 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
- Consultations
- 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

**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

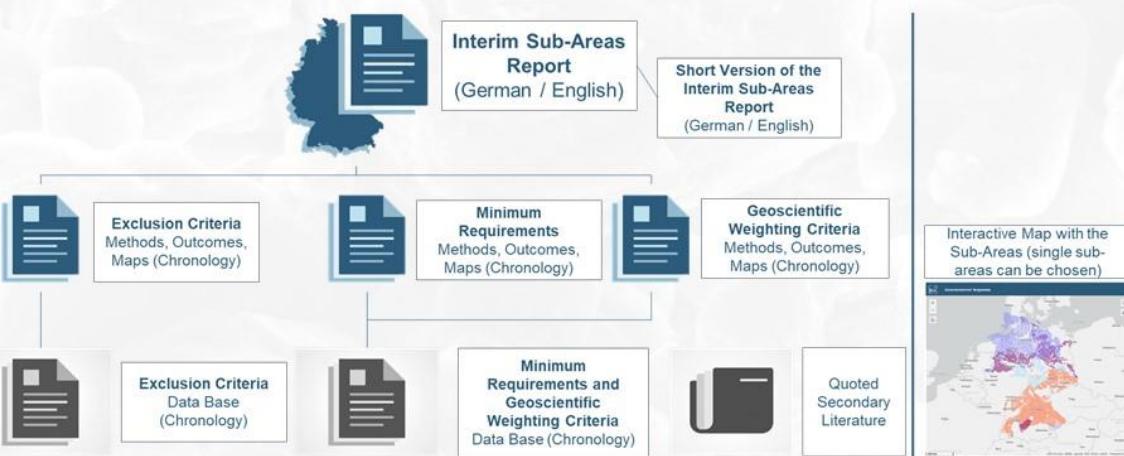


Identified areas



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# Milestone – sub-areas interim report



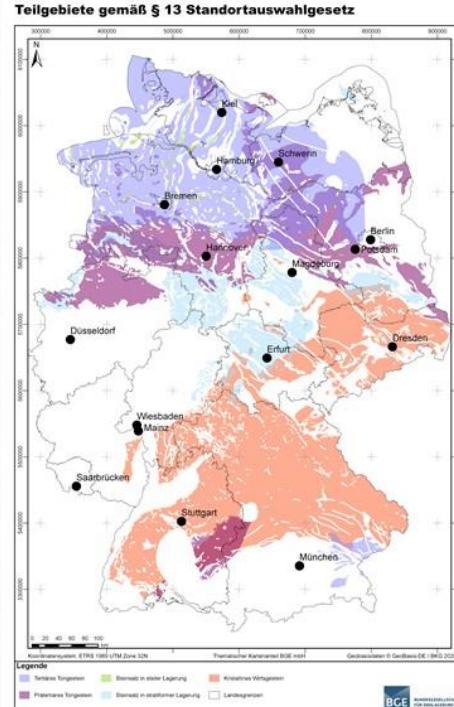
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# Sub-areas interim report



## 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 km<sup>2</sup>** 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**



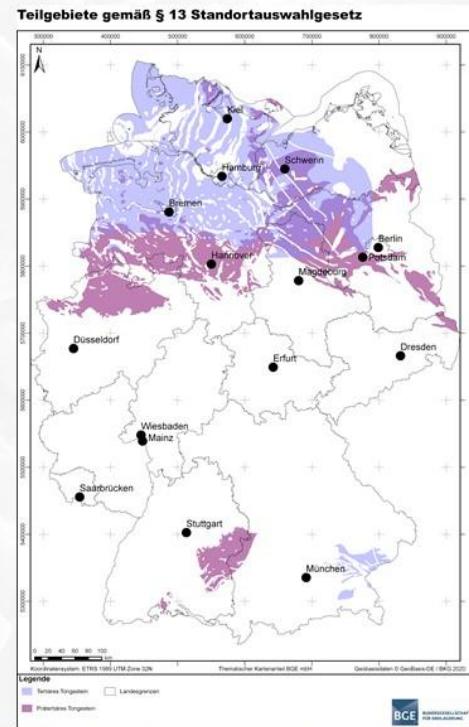
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## Identified sub-areas 1 - claystone



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

- 9 sub-areas** with a surface of approx. **129 639 km<sup>2</sup>** are identified in claystone host rock

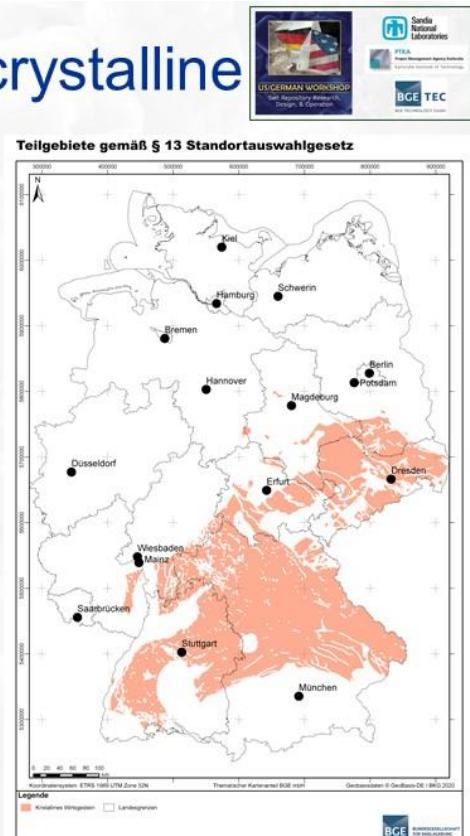


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## Identified sub-areas 2 - crystalline

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

- **7 sub-areas** with a surface of approx. **80 786 km<sup>2</sup>** were determined in **crystalline** host rock

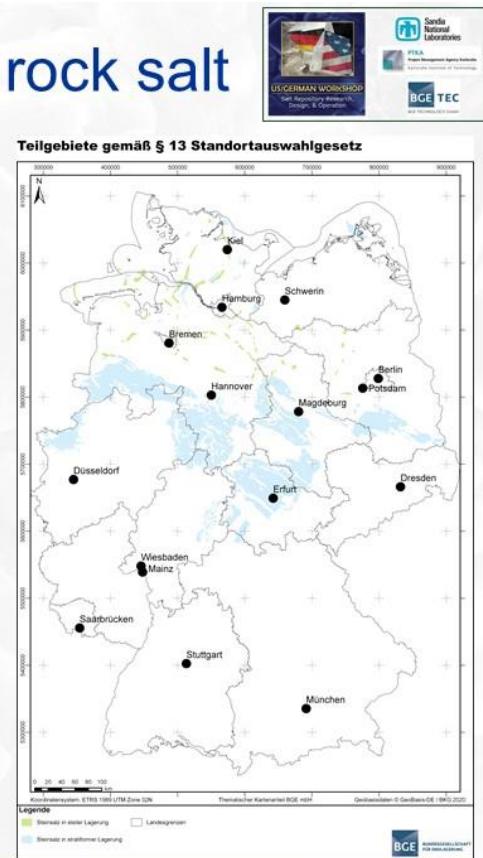


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## Identified sub-areas 3 – rock salt

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

- **74 sub-areas** with a surface of approx. **30 450 km<sup>2</sup>** were identified in salt host rock
- 60 are located in steep rock salt structures
- 14 sub-areas are in stratiform salt formations



12

# 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\_001G\_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.**

13

# 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)



14

# 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



15

# 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
  - Continuous 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

16

# 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

17

## Thank you for your attention



 Sandia  
National  
Laboratories

 PTKA  
Project Management Agency Karlsruhe  
Karlsruhe Institute of Technology

 BGE TEC  
BGE TECHNOLOGY GmbH

### Contact

Bundesgesellschaft für Endlagerung mbH (BGE)  
Eschenstr. 55  
31224 Peine  
+49 (0)5171 43-0  
dialog@bge.de  
www.bge.de

18





## 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation



Jeroen Bartol  
COVRA, the Netherlands

Part X of the online workshop  
02 02, 2021

## Content



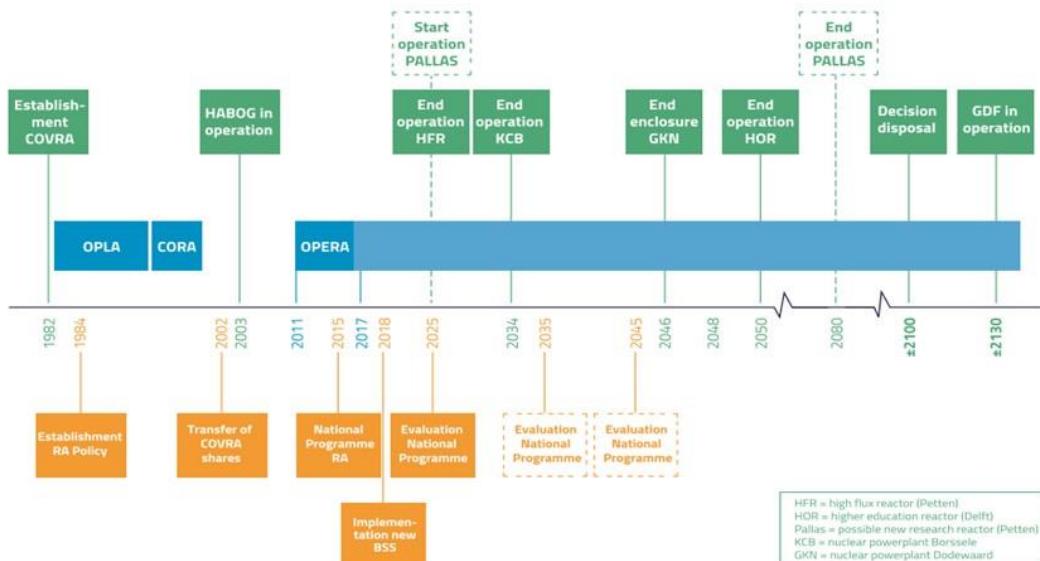
### Long term research programme

- Overview of the new long-term programme
- Research questions

### Disposal concept

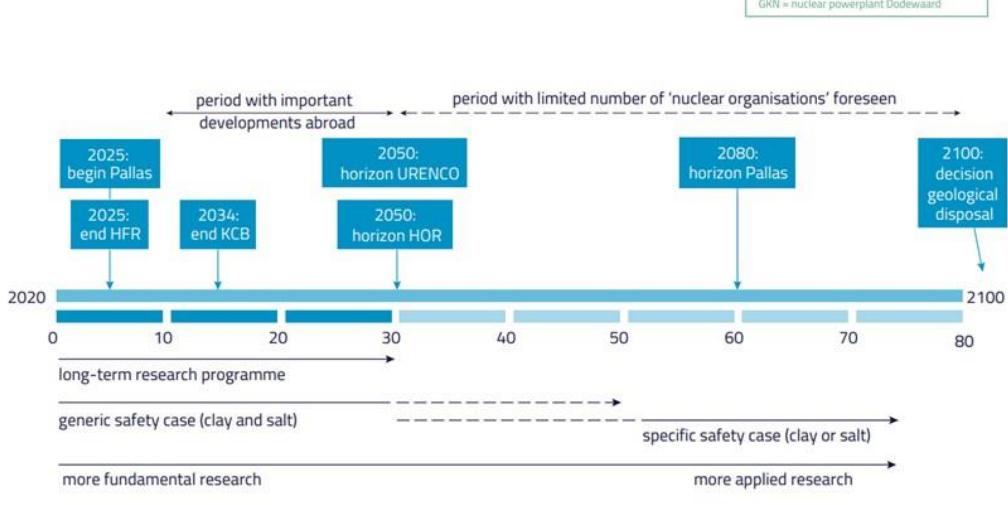
- Overview of the disposal concept
- HLW disposal
- LILW & (TE)NORM

# Research programme



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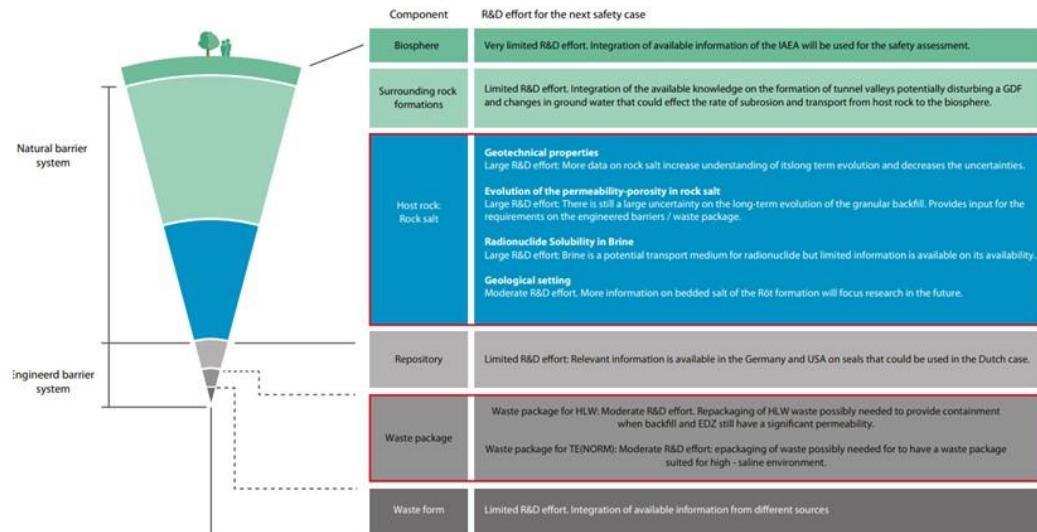
# Research programme



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# Research programme





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



US-GERMAN WORKSHOP  
Salt Repository Research,  
Design & Operation

Sandia National Laboratories  
PTB  
BGE TEC

### 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



US-GERMAN WORKSHOP  
Salt Repository Research,  
Design & Operation

Sandia National Laboratories  
PTB  
BGE TEC

## COVRA NV

# LONG-TERM RESEARCH PROGRAMME

FOR GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

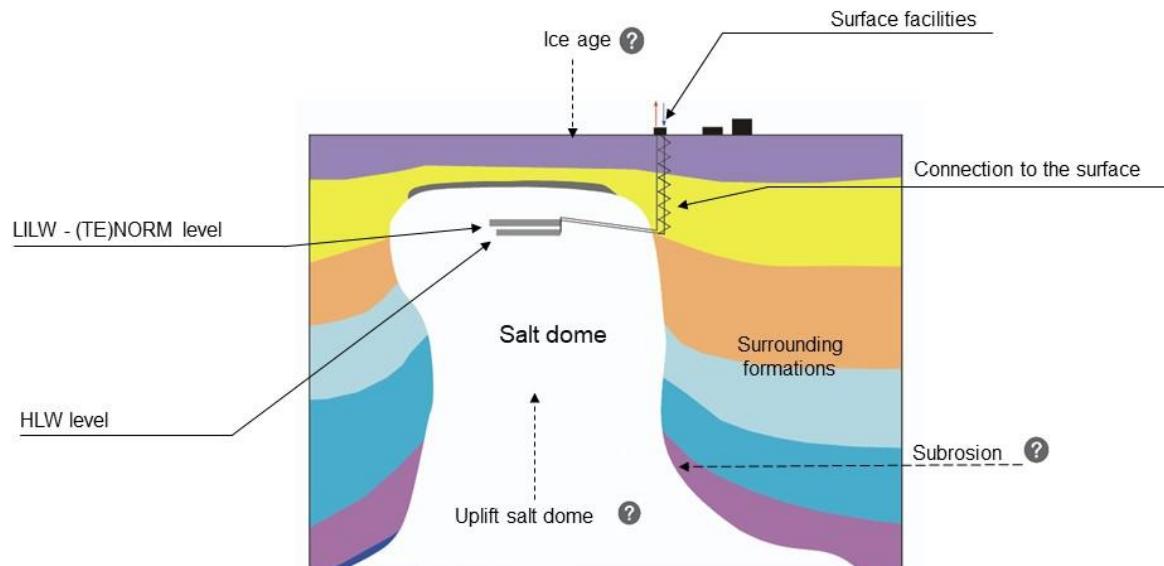
Overall research programme and work programme for 2020-2026  
Date: 6 November 2020

[www.covra.nl](http://www.covra.nl)

More information on the long-term research programme  
can be found on our website [www.covra.nl](http://www.covra.nl)

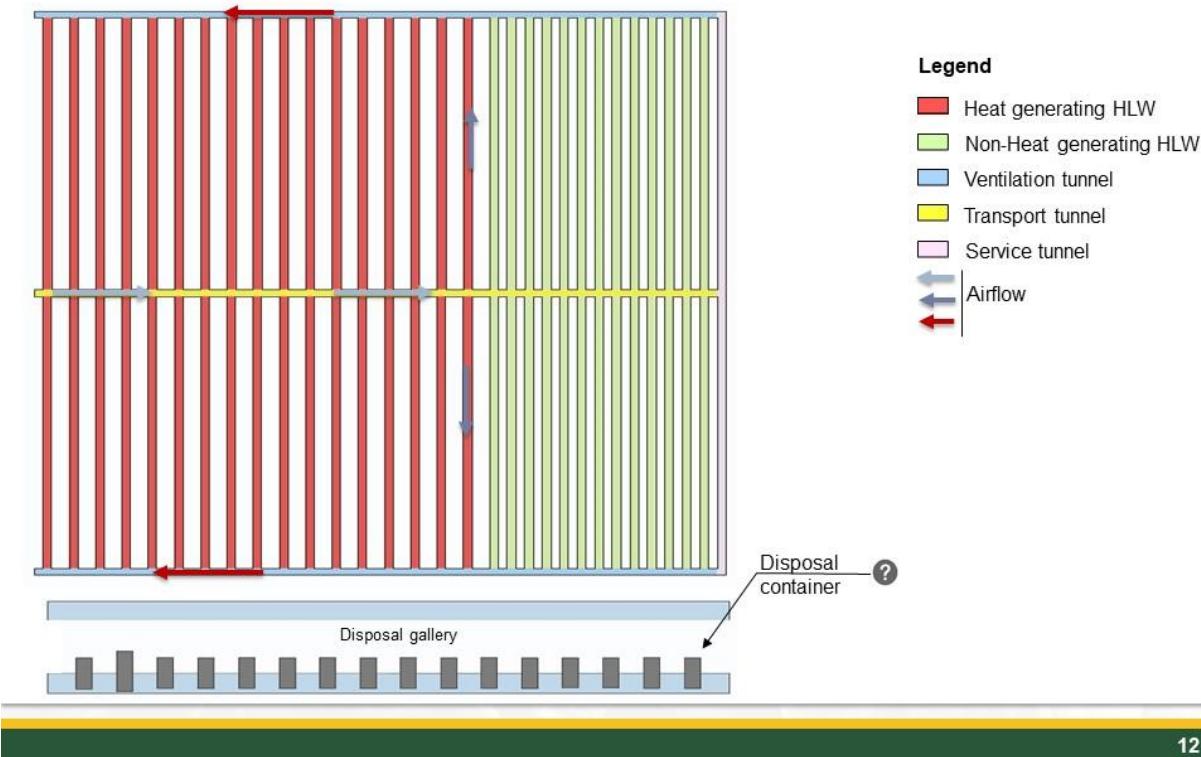
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# Disposal concept

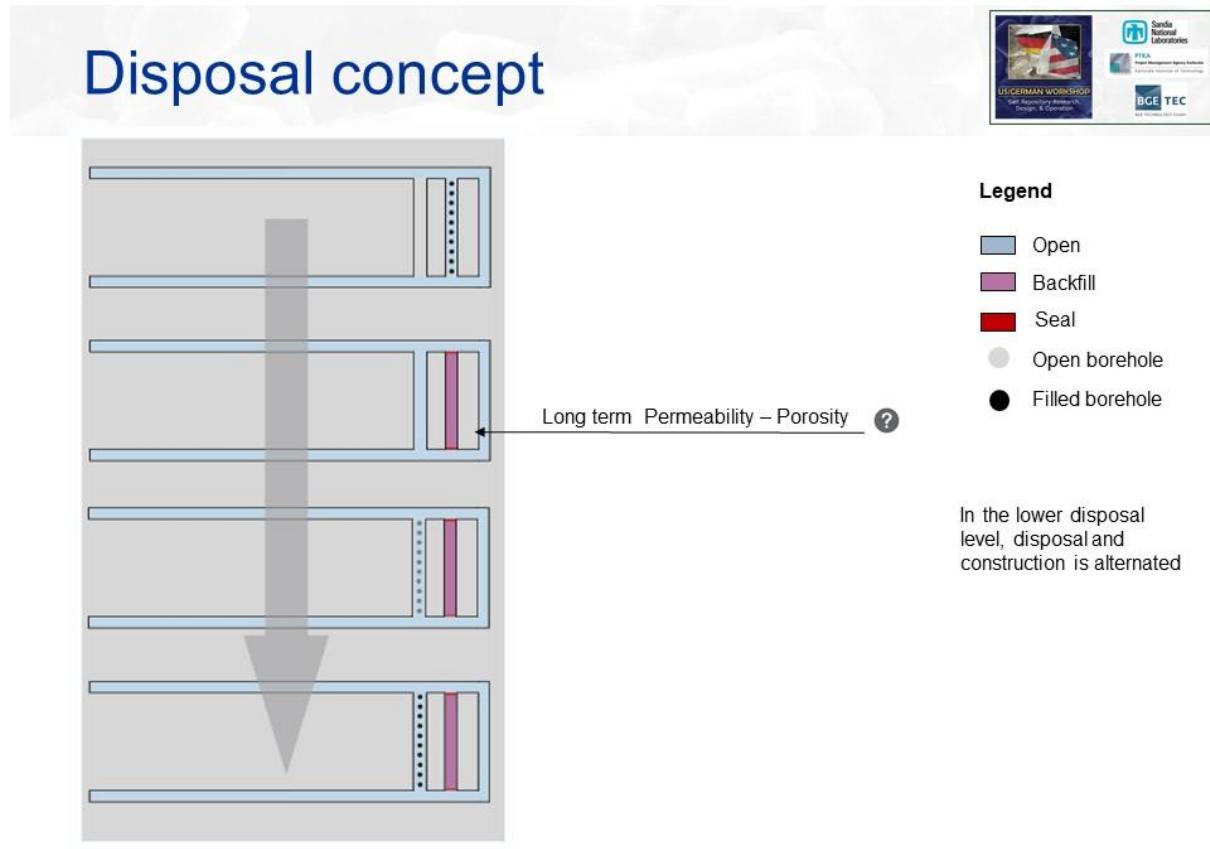


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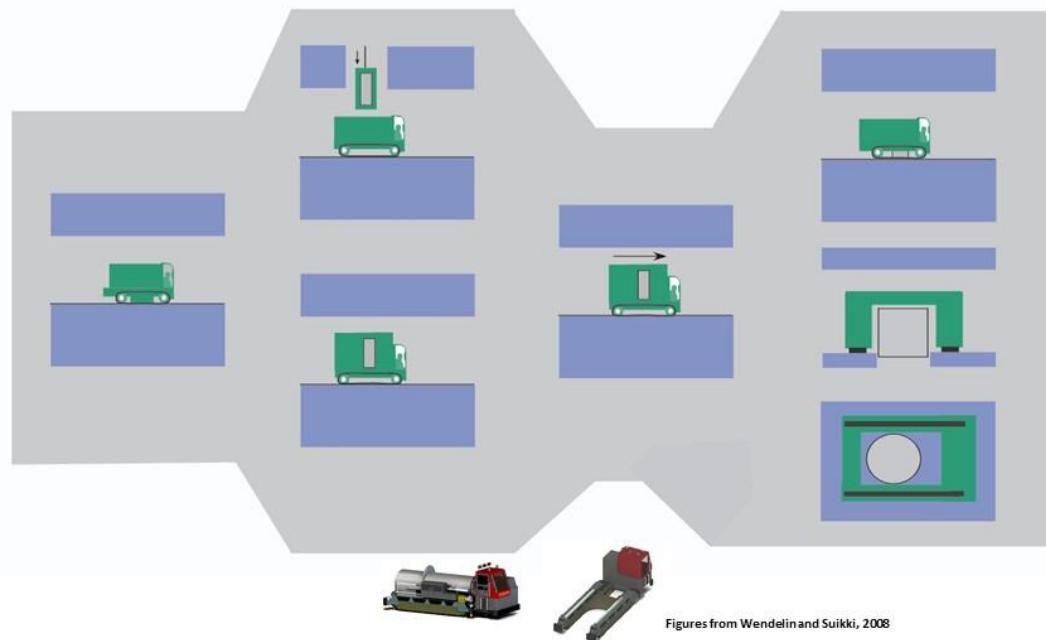
# Disposal concept



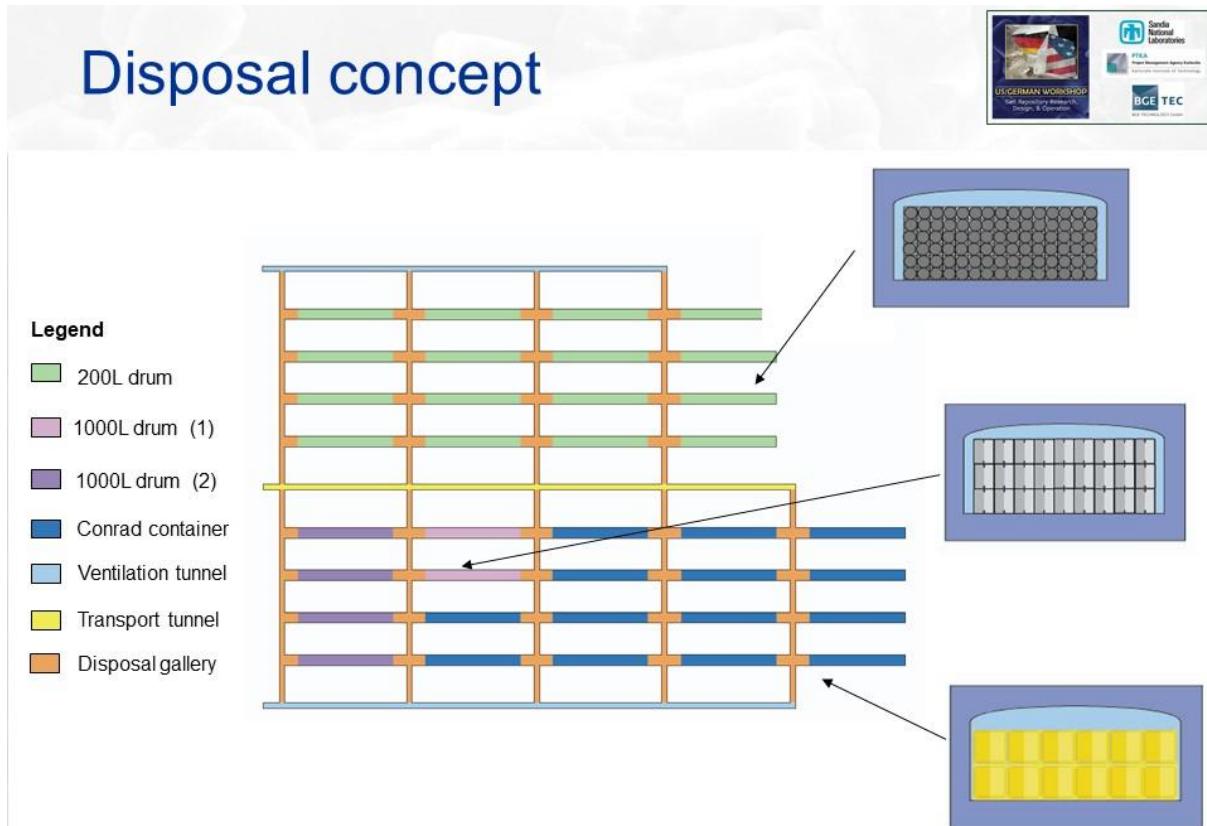
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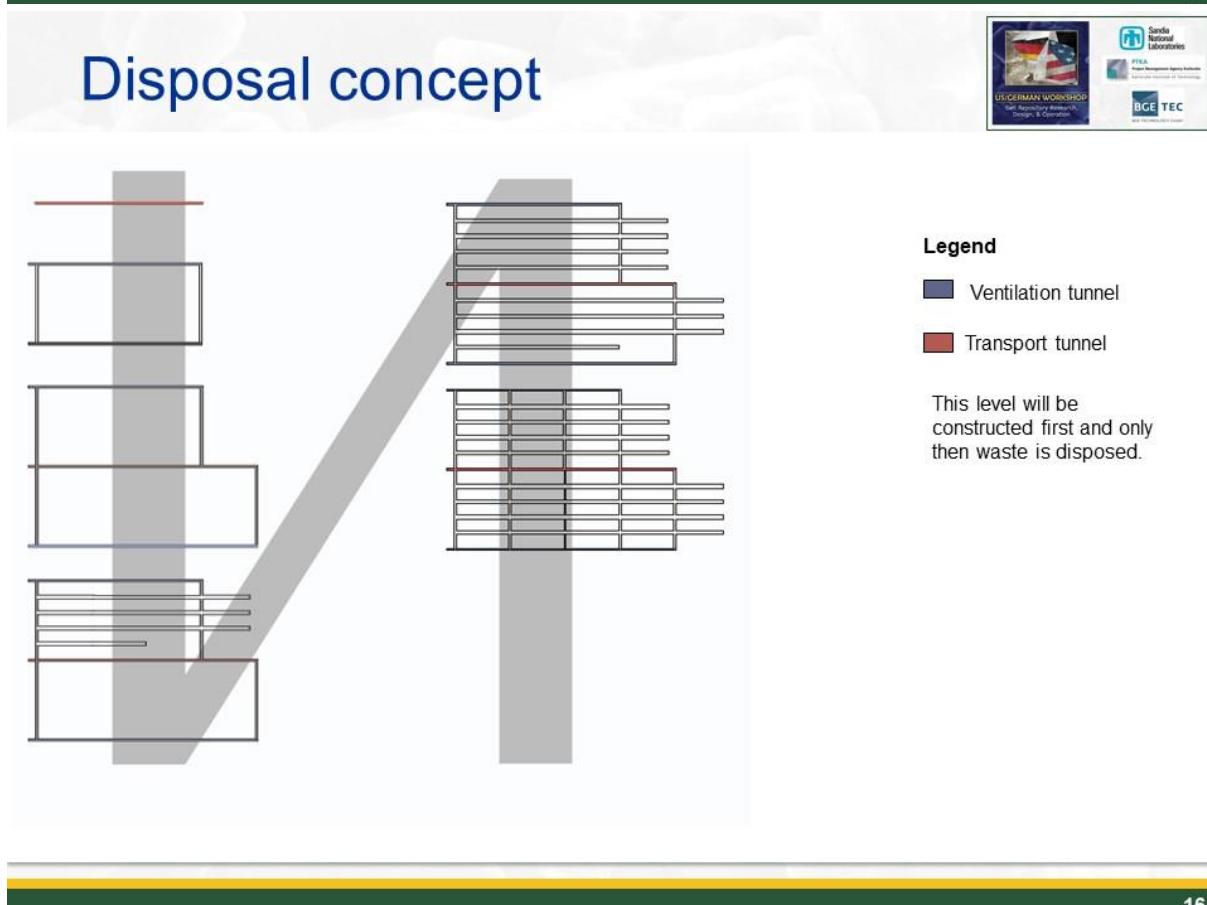
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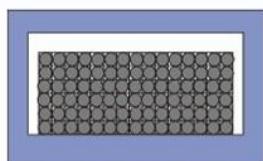
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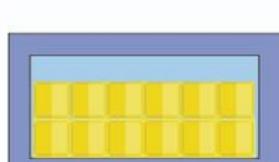
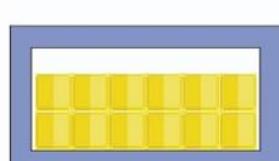
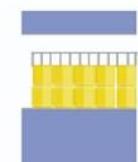
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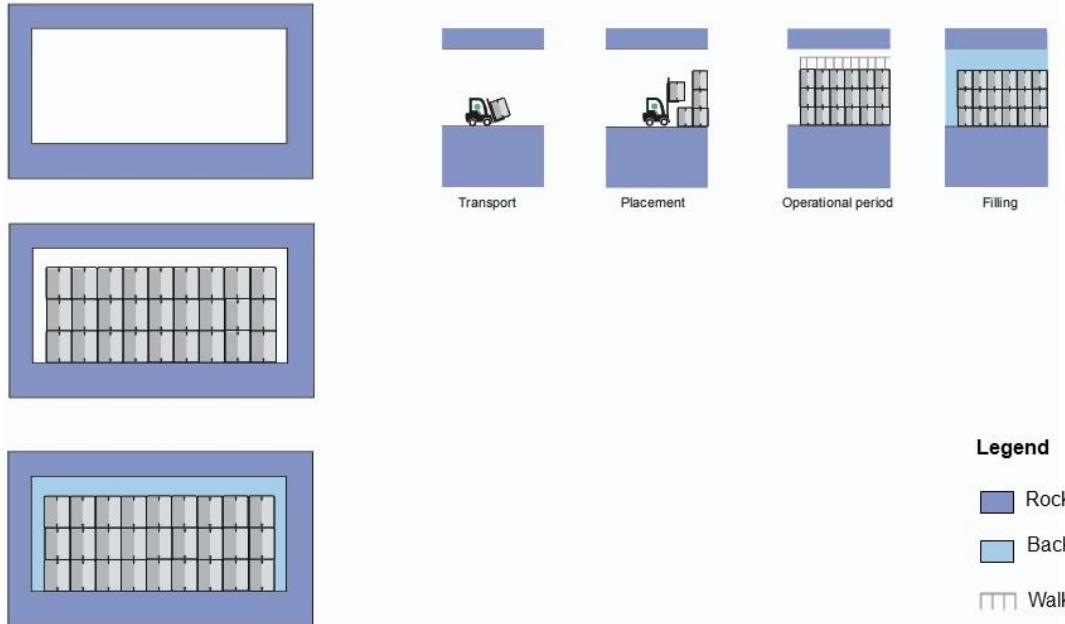


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**Legend**

18

# Disposal concept



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## Finding a willing community and a suitable site



## 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

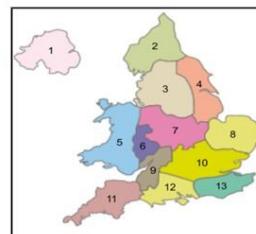
## Range of community benefits



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.



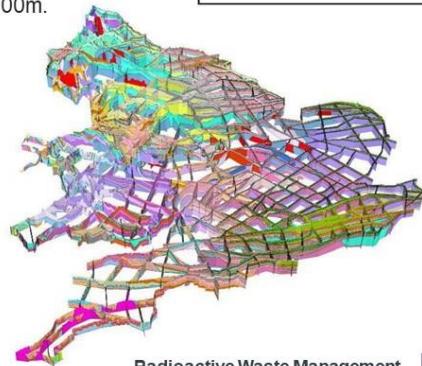
**Higher strength rocks**  
for example  
Granite



**Lower strength sedimentary rocks**  
for example  
Clay



**Evaporite rocks**  
for example  
Rock Salt



Radioactive Waste Management 5

## The Siting Process and Site Evaluation



Radioactive Waste Management 6

## What could a GDF look like?



- Surface facility c1km<sup>2</sup> but could be as small as 0.6km<sup>2</sup>.
- 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.



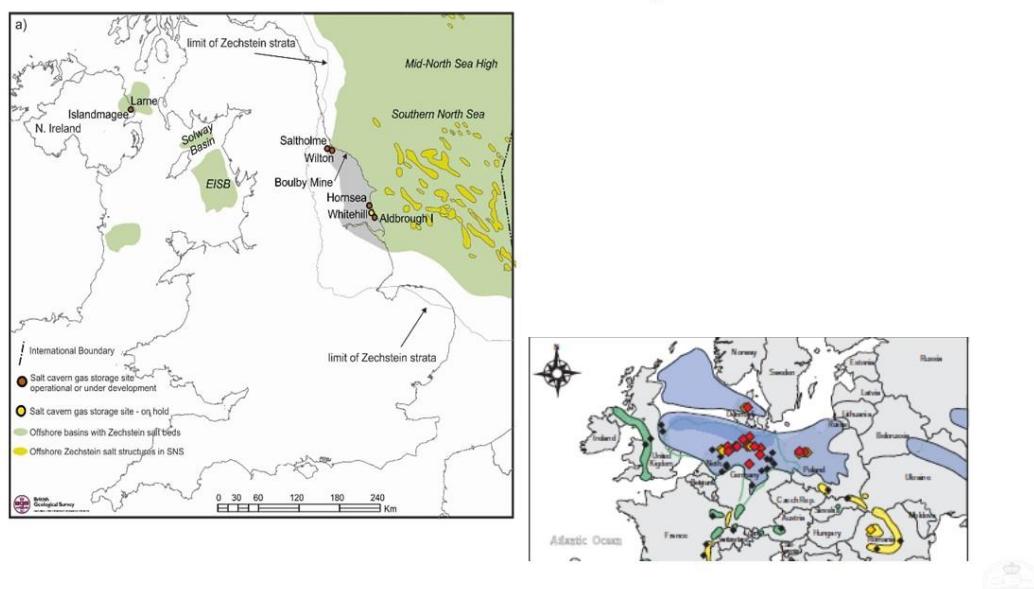
- Surface facilities built onshore.
- Underground vaults can be positioned under the land surface or under the sea in the inshore zone which extends up to 22km from the shoreline.
- Coastal locations open up the possibility to establish sea transport for construction and other materials.
- Spoil from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

## GDF: facts and figures

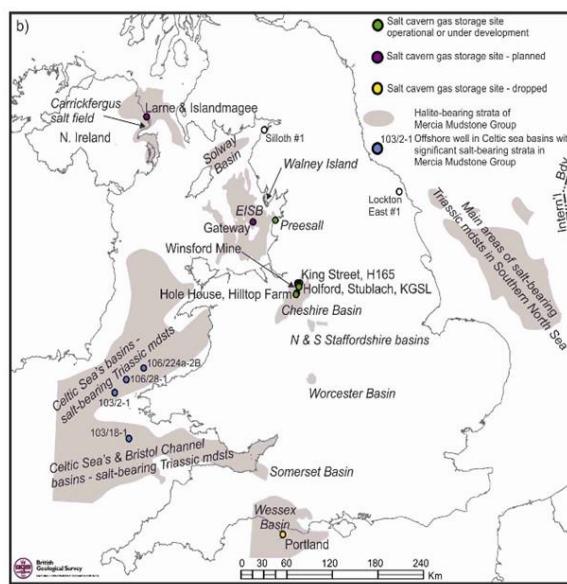
- **Size** – While the underground part of a GDF may cover an area of up to 20km<sup>2</sup>, the surface facilities will occupy around 1 square kilometre of land - typically the size of a small industrial estate.
- **Cost** – A GDF is projected to cost £££ multi-billions. As with any major infrastructure 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.

## 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 800m
Asse II	Permian	LLW 725 m to 750 m
Morsleben	Permian	At least 480 metres below the surface

11

## 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.
- Benefiting from international participation and experience key for RWM.

12



## GDF: roles and responsibilities



HM Government

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



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



Environment Agency



Office for Nuclear Regulation



Cyfoeth Naturiol Cymru  
Natural Resources Wales

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



## Appendix B – Program and Presentations of Part 2 (17<sup>th</sup> June 2021)

Berlin time		17 <sup>th</sup> June 2021	
16:00	16:10	Welcome by the organizers	M. Bühler/PTKA W. Bollingerfehr/BGE TEC
<b>Crushed salt – testing and modelling</b> 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



## 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation

### Role of crushed salt in the repository concept

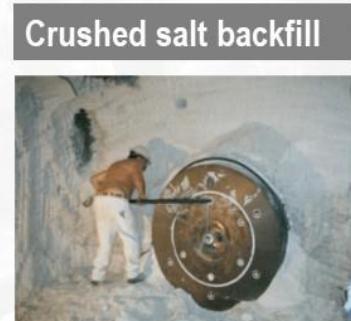
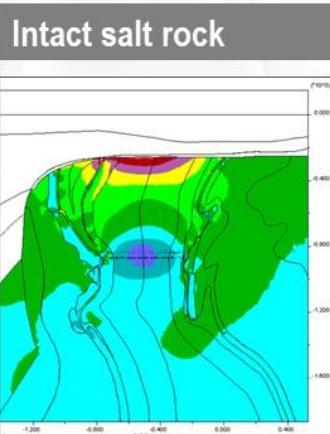


Nina Müller-Hoeppel

Christian Lerch  
BGE TECHNOLOGY GmbH

Part 2 of the online workshop  
June 17, 2021

### Isolation of Radwaste in Salt



# 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  $k \sim 1 \cdot 10^{-14} \text{ m}^2$ )
  - (6) **New: Recovery of the salt barrier's tightness comparable to the host rock in order to achieve isolation of radwaste**

3

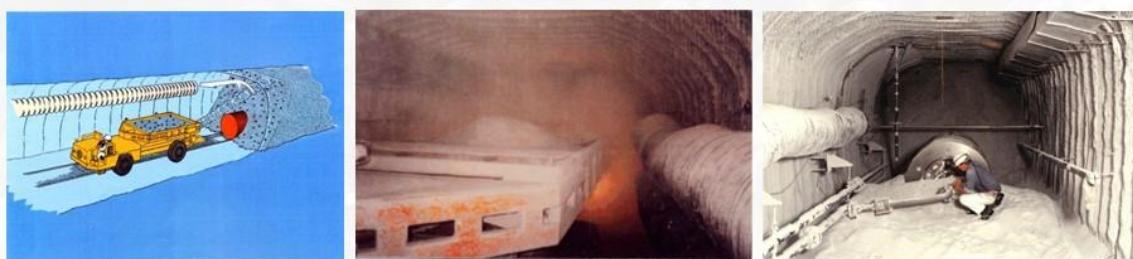
# Functional Requirements



- 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  $\sim 0.02 \text{ M\%}$ )
- Possible emplacement technologies to achieve this goal considering additionally staff's radiation protection (neutrons!)
- Slinger truck technology appeared to be the best option

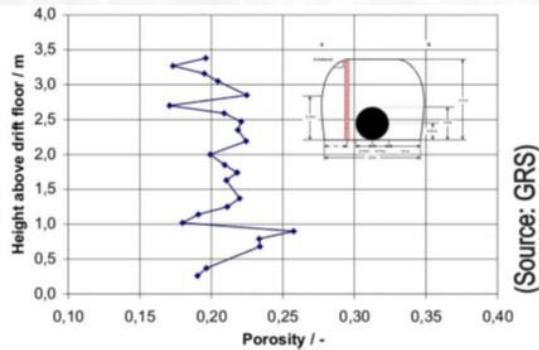
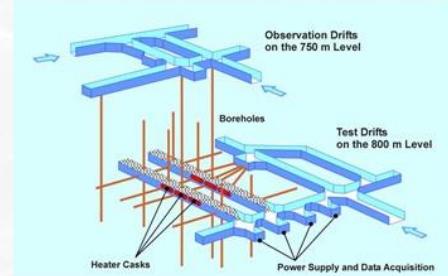


4

# Functional Requirements



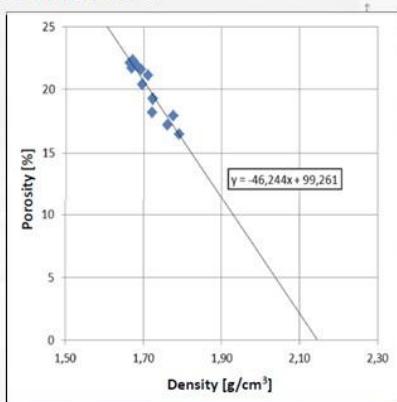
- Compliance with functional requirements (1) – (5) was demonstrated by the TSS/BAMBUS R&D projects
- No gap in the roof (1), (2), (4)



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.



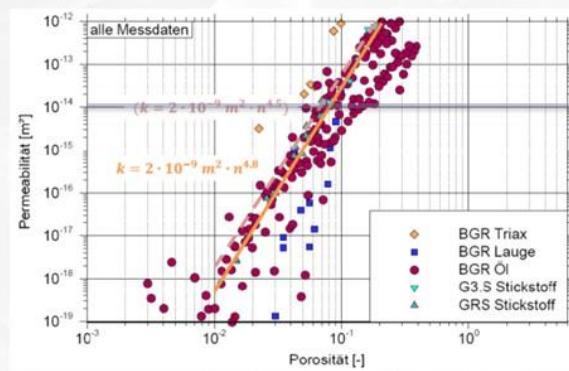
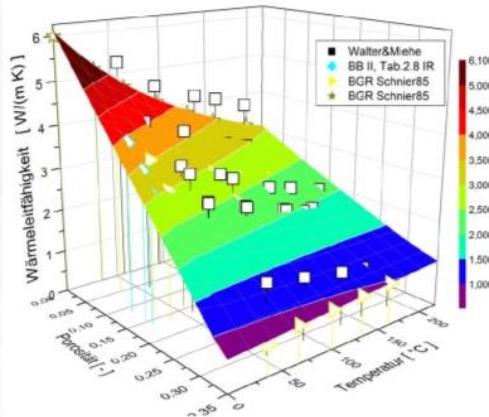
- Porosity: 23 – 17%
- Thermal conductivity: 2.3 W/(m·K)
- Gas permeability: ca.  $5 \cdot 10^{-13} \text{ m}^2$

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

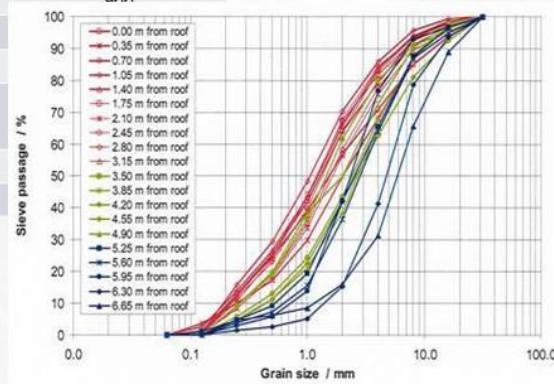
# QA-measures



- 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 [ $m^3$ ]	963	966
Initial bulk density [ $kg/m^3$ ]	1,399	
Specified deviation [%]	+2 ... -2.6	
Range of initial density [ $kg/m^3$ ]	1,363 ... 1,427	
Porosity [-]	0.34 ... (0.35) ... 0.37	
Void ratio [-]	0.52 ... (0.54) ... 0.58	

BAMBUS II project (2004)

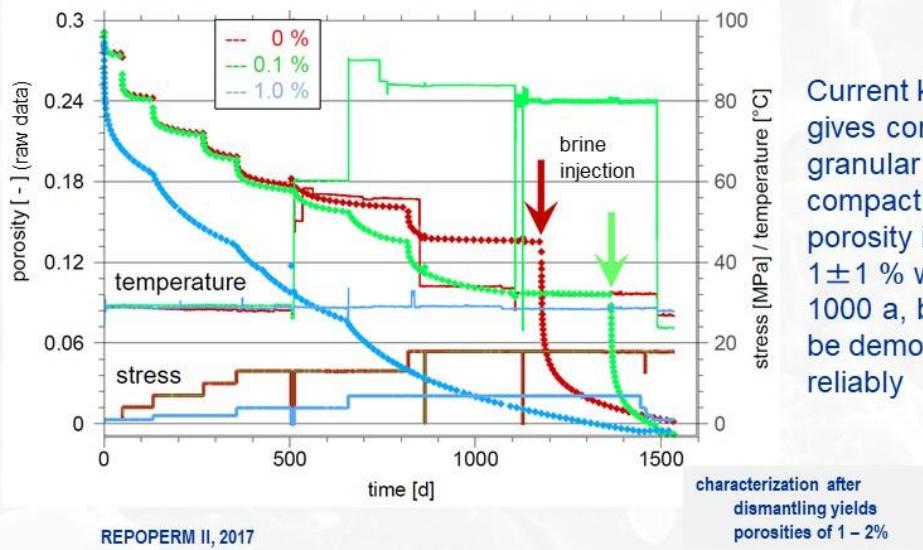


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# Functional Requirement (6)

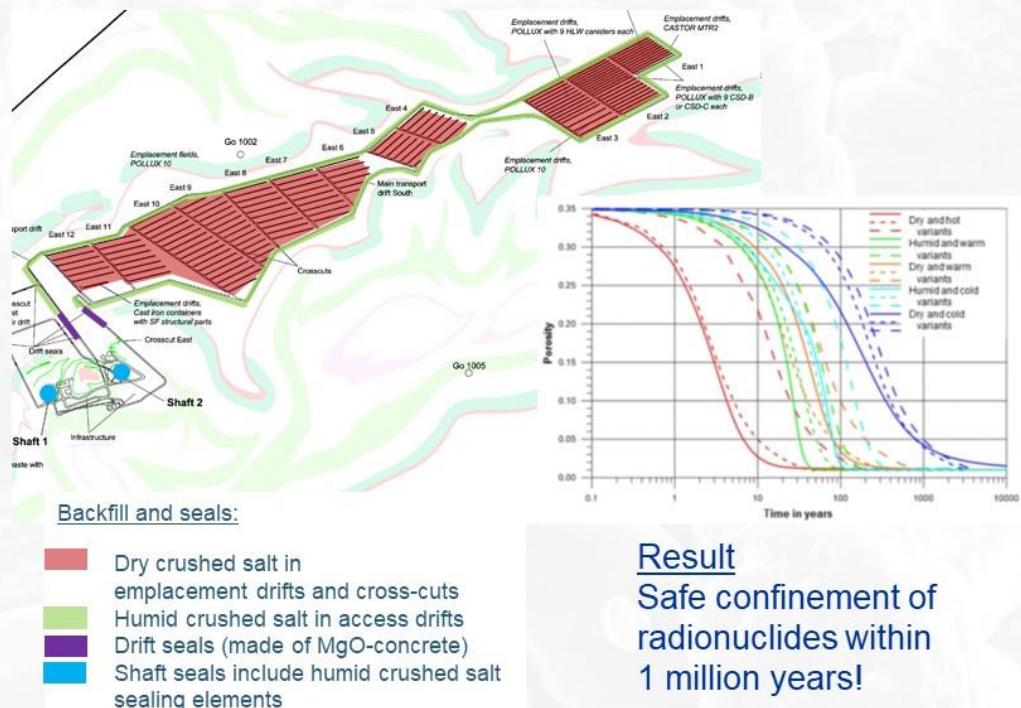
BMU 2010

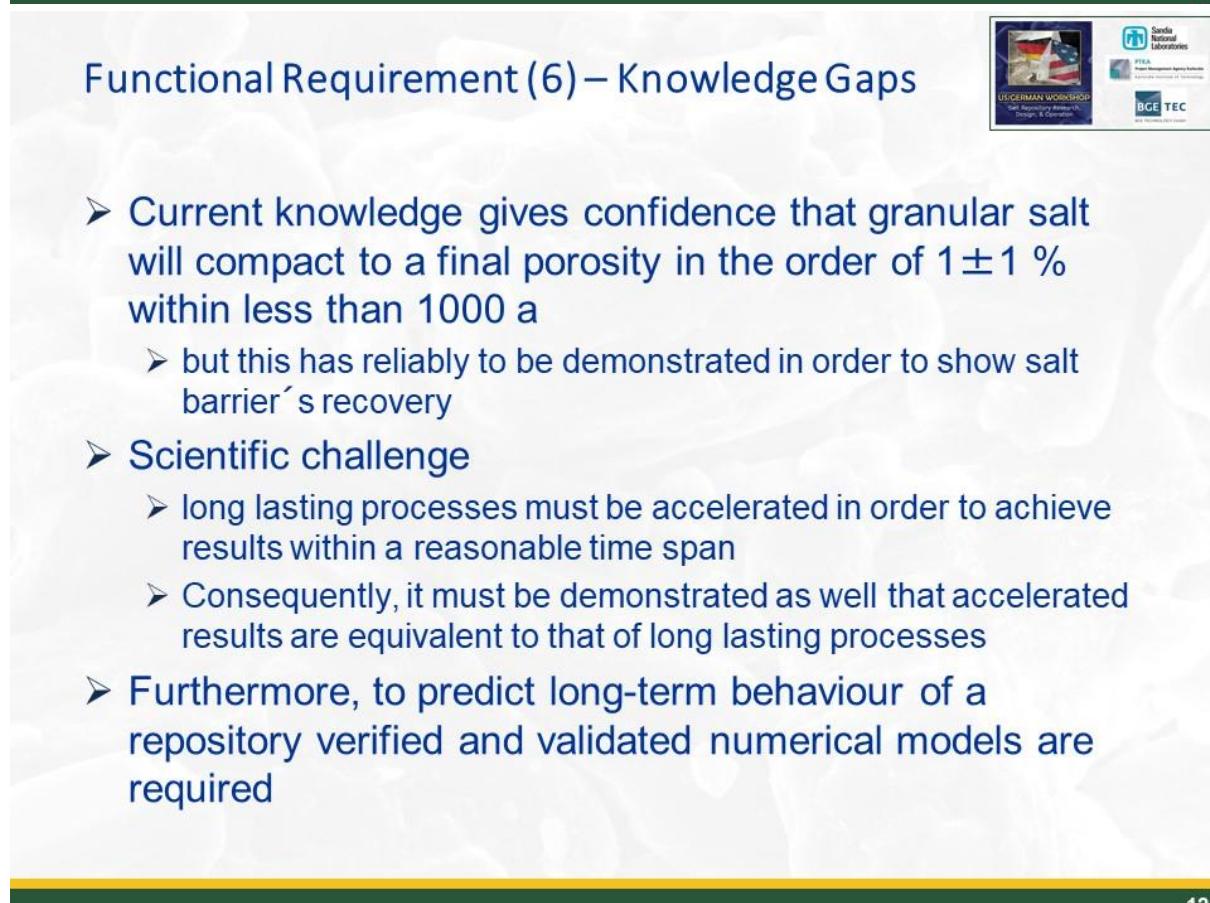
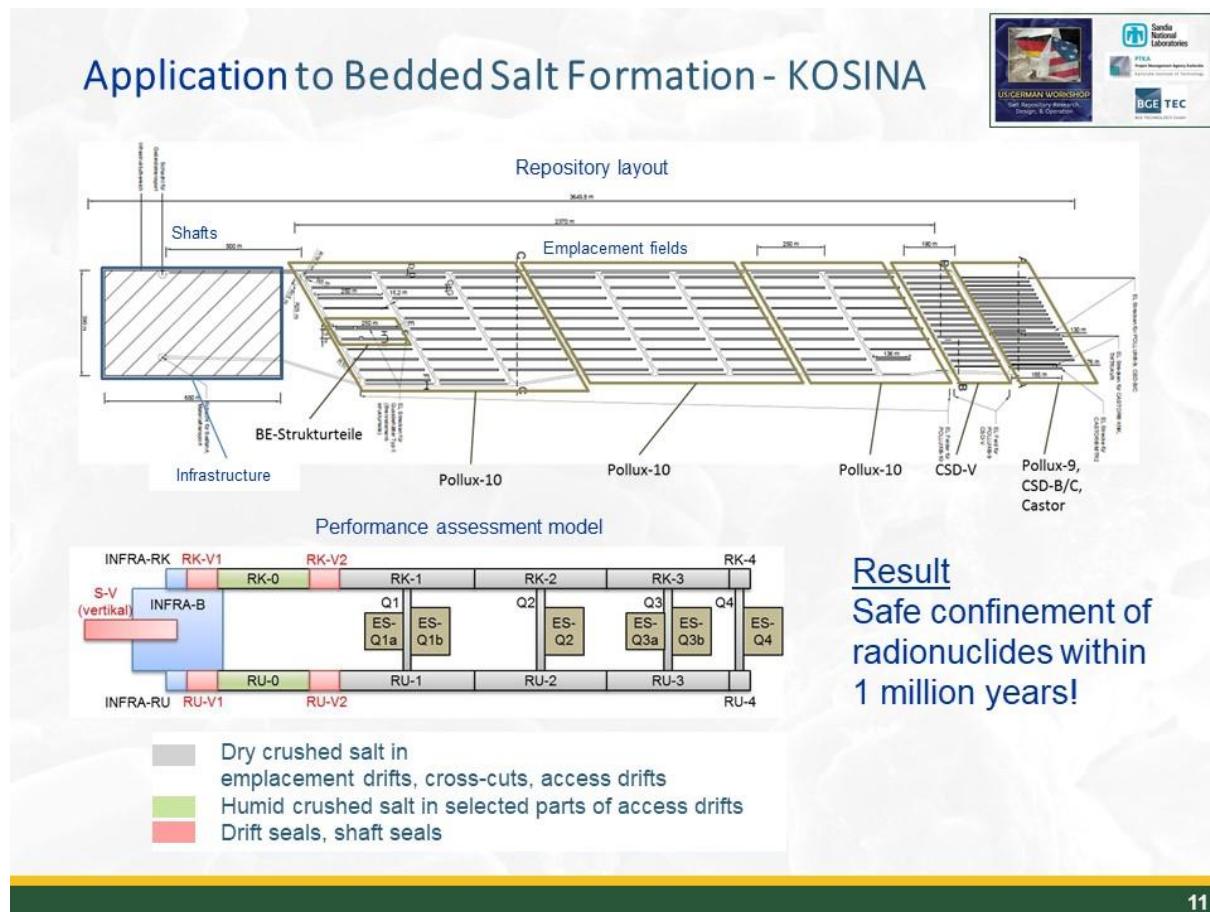
➤ From limited release to isolation of radionuclides



9

## First Application of BMU 2010 Requirements - VSG





## 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-Hoeppke



BGR: Ralf Eickemeier, Ben Laurich, Wenting Liu, Dieter Stührenberg, Kristoff Svensson, Kornelia Zemke

GRS: Larissa Friedenberg, Klaus Wieczorek, Oliver Czaikowski (Coordinator)

Supported by:

IfG: Christoph Lüdeling, Till Popp



TUC: Uwe Düsterloh, Svetlana Lerche, Juan Zhao



Institut für  
Gebirgsmechanik  
GmbH Leipzig



on the basis of a decision  
by the German Bundestag

# The KOMPASS Project – Phase II



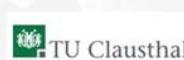
- KOMPASS – Phase II (01.07.2021 – 30.06.2023) is also funded by the Federal Ministry for Economic Affairs and Energy (**BMWi**) under support code 02E11951
- A joint project of BGE TEC, BGR, GRS, IfG, and TUC
- Cooperation with Sandia and Utrecht University as associated partners is planned
- The overall 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



Supported by:



on the basis of a decision by the German Bundestag

Institut für  
Gebirgsmechanik  
GmbH Leipzig

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



## Microstructural Investigations of Pre-Compacted Samples from IfG

Melissa Mills  
Sandia National Laboratories  
Albuquerque, NM, USA

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



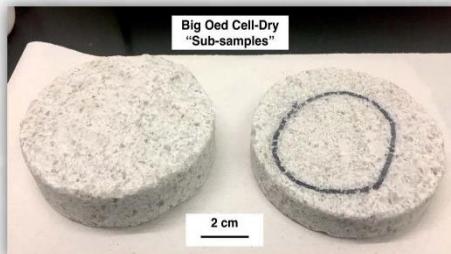
Technique	Resulting sample size	Controlled by strain rate / load	Stress regime	Runtime	Remaining porosity	Material	Number of tests
Plain Strain (TUC)	d = 90 mm h = 180 mm	Radial load ( $\sigma_{max} = 5/10/15$ MPa)	Plain strain (longest axis fixed)	3 d	2 – 11 %	Preliminary tests on not classified crushed salt w = 0.5/1/2/3 %	8
		Radial load ( $\sigma_{max} = 2/4/5/10/15$ 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 ( $\sigma_{max} = 20$ MPa)	Oedometric	1 – 5 d	10 – 20 %	KOMPASS reference material	3
Big Cell (IfG)	d = 500 mm h = 620 mm	Axial load, stepwise ( $\sigma_{max} = 20$ MPa)	Oedometric	< 28 d	10 – 20 %	KOMPASS reference material w = dry/1 %	2
BGR	d = 100 mm h = 200 mm	Strain rate, stepwise ( $\dot{\epsilon}_{max} = 9.1 \cdot 10^{-6}$ 1/s) ( $\sigma_{max} = 20$ 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

## Pre-Compacted Samples (IfG)

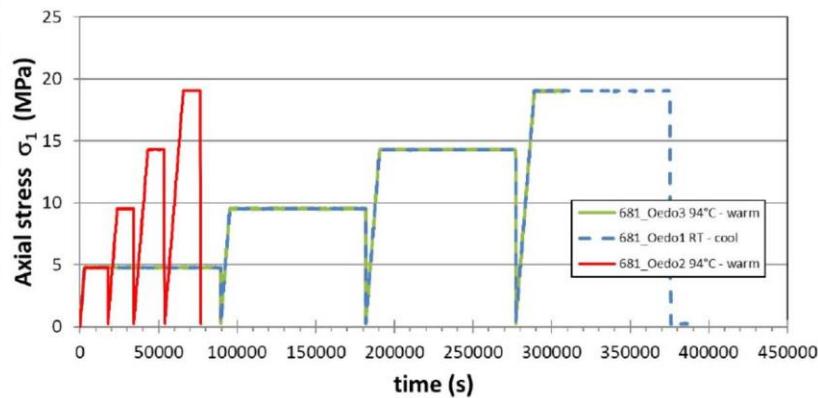


Sample ID	Oedometer Inner Diameter (m)	Temperature (°C)	Axial Stress (MPa)	Duration (days)	Final Relative Porosity (%)
681/Oed 1	0.1	Ambient	20	5	14.8
681/Oed 2	0.1	94	20	1	10.5
681/Oed 3	0.1	94	20	5	10
Big Oed cell Dry (sub-sampled)	0.514	Ambient	20	28	13.6

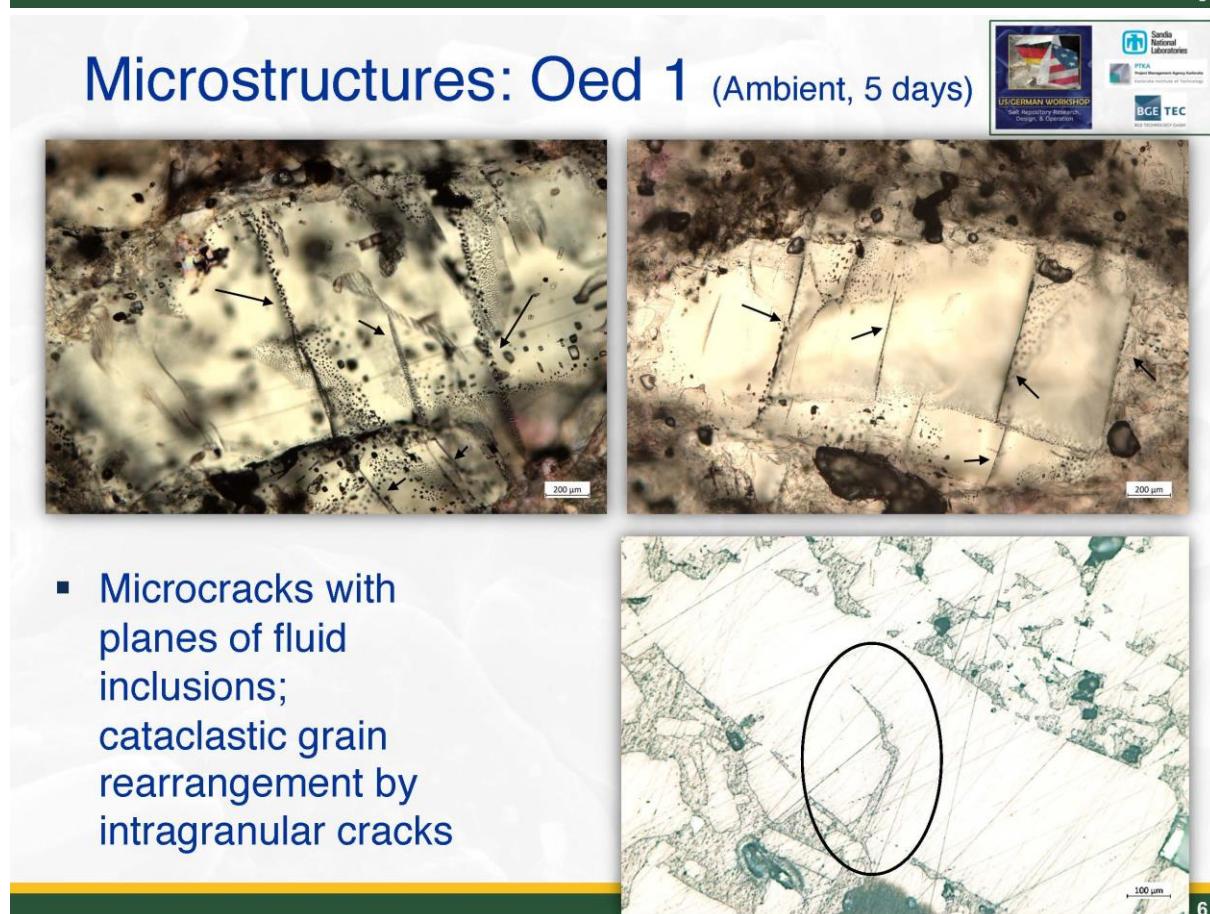
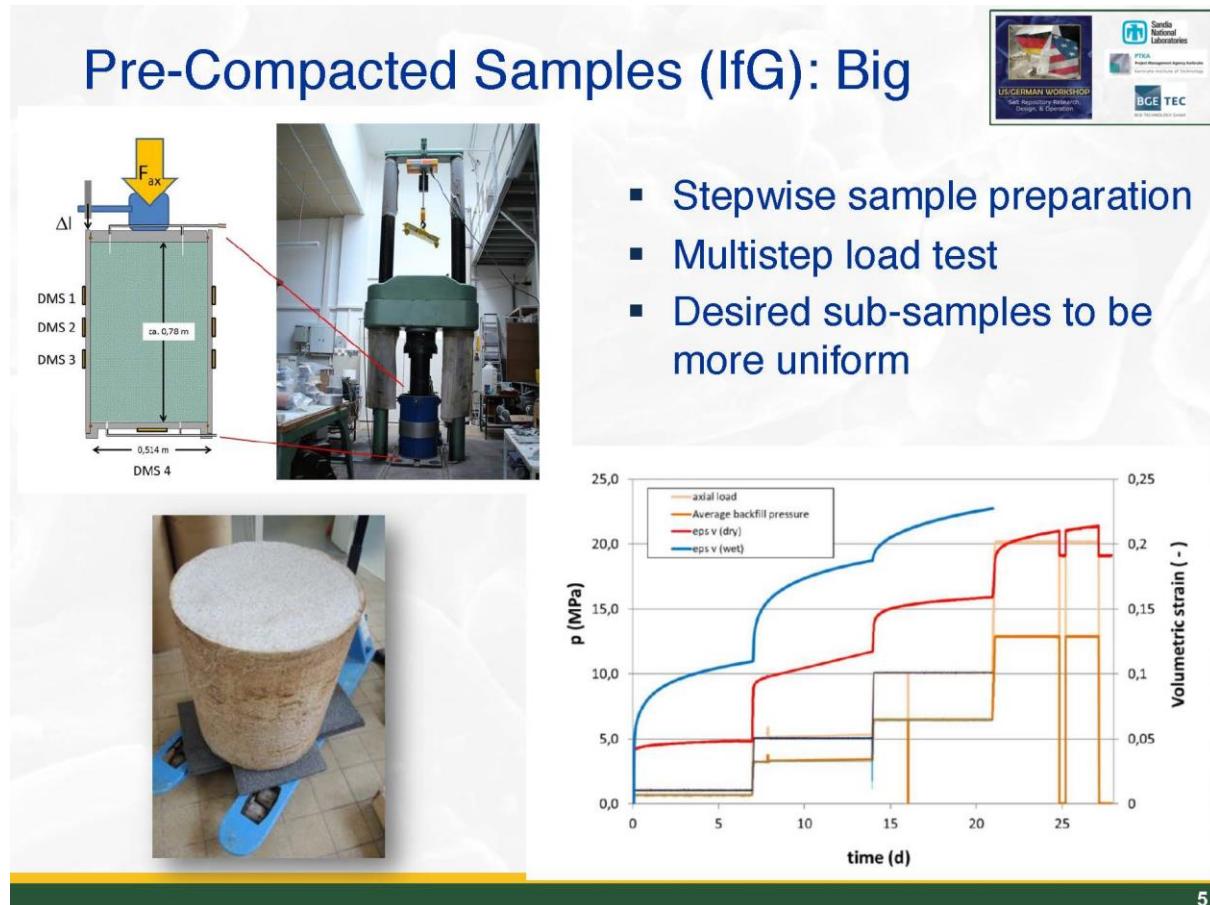


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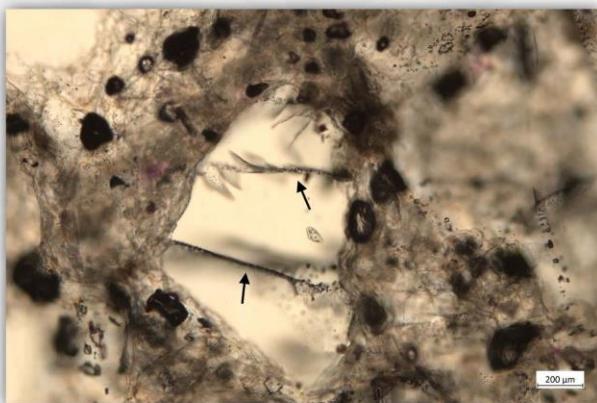
## Pre-Compacted Samples (IfG): Small



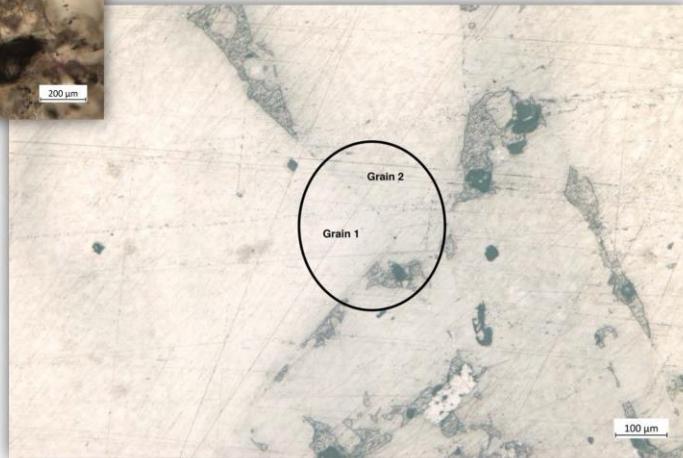
4



## 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)

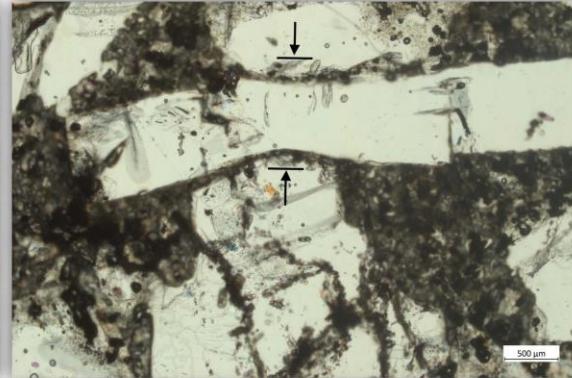
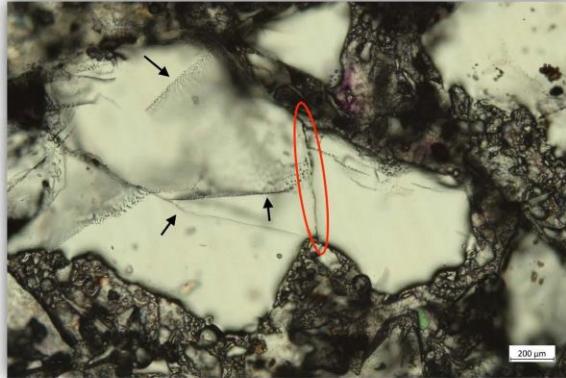


- Fluid inclusion planes; plastic deformation seen at grain contacts; possible pressure solution redisposition and/or dislocation motion



8

# Microstructures: Big Oed (ambient, 28 days)

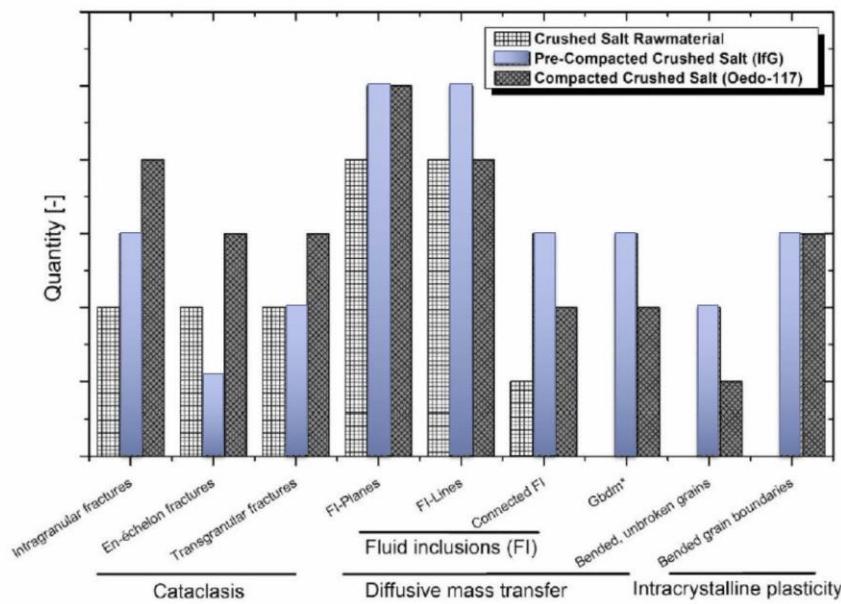


- Microcracks with transgranular crack; cataclastic deformation; mechanically abraded surface between grains



9

## Comparison



10

# Future



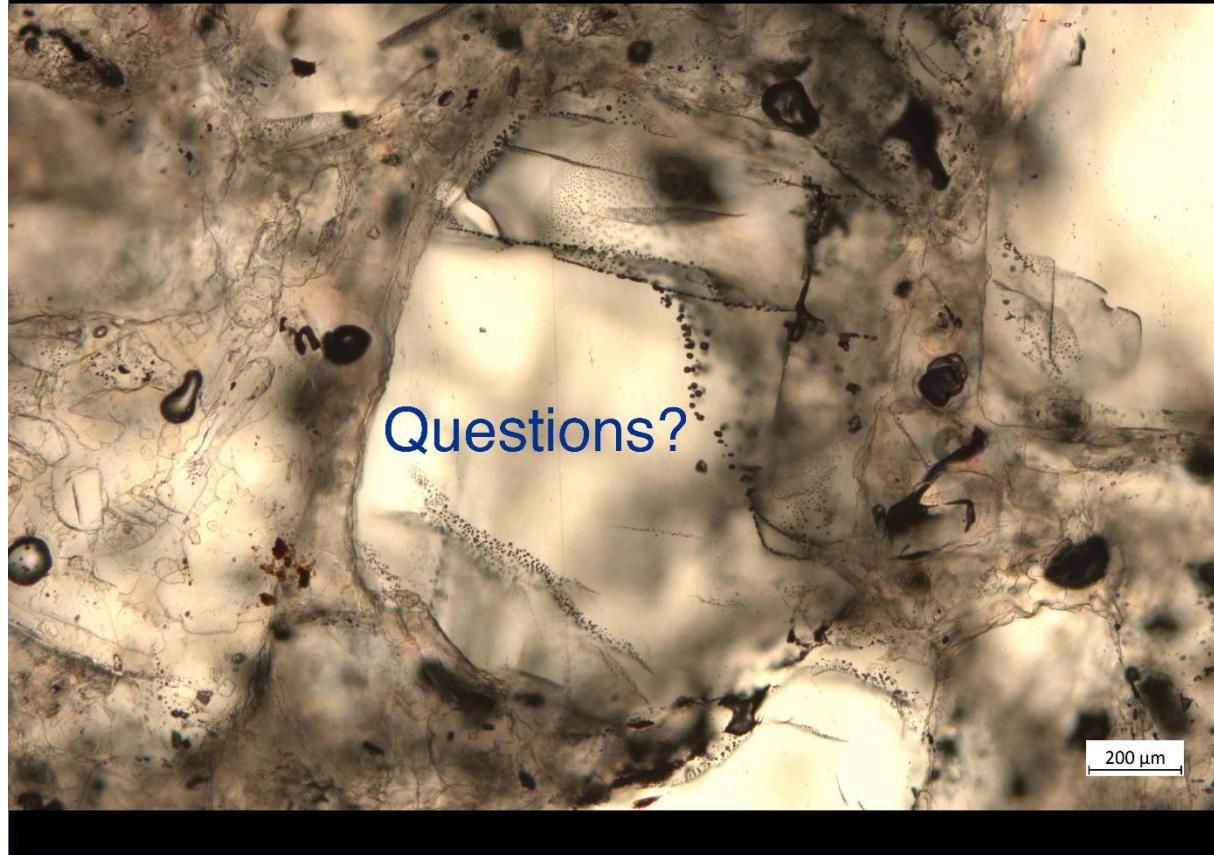
- Subgrain analysis by SEM
- Preparation and analysis of additional pre-compacted samples from TUC, with varying conditions
  - Received samples #14 & #15 (15MPa, 2 days, w=0.5%)
- Examination of fully compacted samples

\*Extra time for any unanticipated shipping delays ☺

11

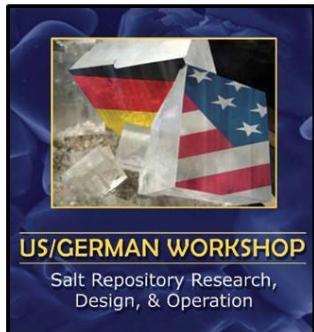
Questions?

A scale bar indicating 200 micrometers.





## 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

**BGR** Bundesanstalt für  
Geowissenschaften  
und Rohstoffe

2

## Microstructures and correlated deformation mechanisms

General	MICROSTRUCTURES		MECHANISMS
	Specific	Specific	
MICROFRACTURES, RIGID PARTICLE DISPLACEMENT AND ROTATION Chapter 2	Microcracks	2.3	CATACLYSIS (2.2)
	Microfaults	2.4	
	Deformation bands	2.5	
	Microfracture cataclasis	2.6	
	Concavo-convex	2.7	
	Microfracture surface features	2.8	
	Crystallologic fabrics	2.9	
	Pro-lithification microstructures	2.10 IPF	
	Psuedotachylite	2.11 Melting	
MATERIAL REMOVAL, TRANSPORT AND DEPOSITION Chapter 3	Grain surface solution textures	3.1	DIFFUSIVE MASS TRANSFER BY SOLUTION (3.2)
	Indirect stretching and interpenetrating grains	3.4	
	Strain caps	3.5	
	Microtectonites	3.6	
	Clavage	3.7	
	Surface deposition textures	3.8	
	Overgrowth, embayments shadows and fringes, micro 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	INTRACRYSTALLINE PLASTICITY (4.2)
	Undulatory extinction	4.4	
	Dislocation annulations bands, kink bands & subgrains	4.5	
	Deformation lamellae	4.6	
	Grain shape fabrics & ribbons	4.7	
	New grains, core and mantle structure	4.8	
	Crystallologic fabrics	4.9	
	Grain shape fabrics & ribbons	5.1	
	Frost texture	5.4	
	Decauve texture	5.5	
MATERIAL REMOVAL, TRANSPORT AND DEPOSITION; PHASE TRANSFORMATIONS Chapter 5	Porphyroblasts	5.6	SOLID STATE DIFFUSIVE MASS TRANSFER, PHASE TRANSFORMATIONS (5.2)
	Reaction rims, reflect minerals, coronas, symplectites	5.7	
	Chemical melting	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



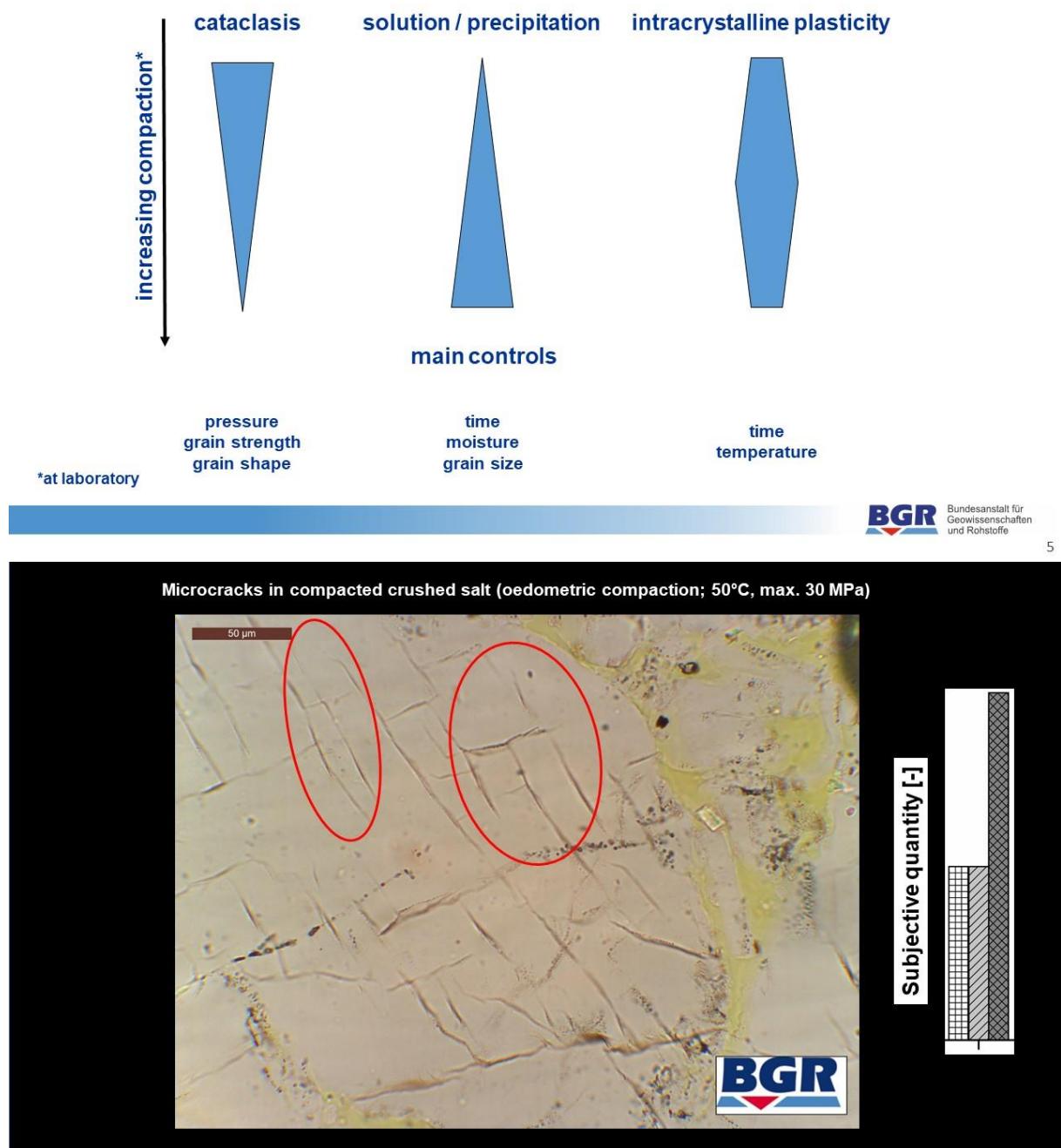
3

## Deformation mechanisms and respective indicators

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



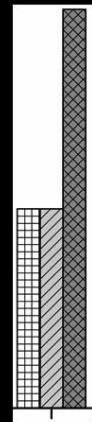
4



Microcracks in crushed salt raw material



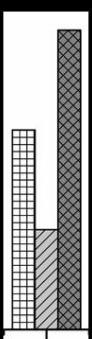
Subjective quantity [-]

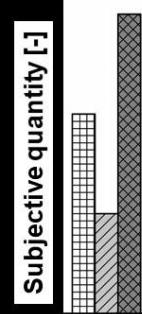


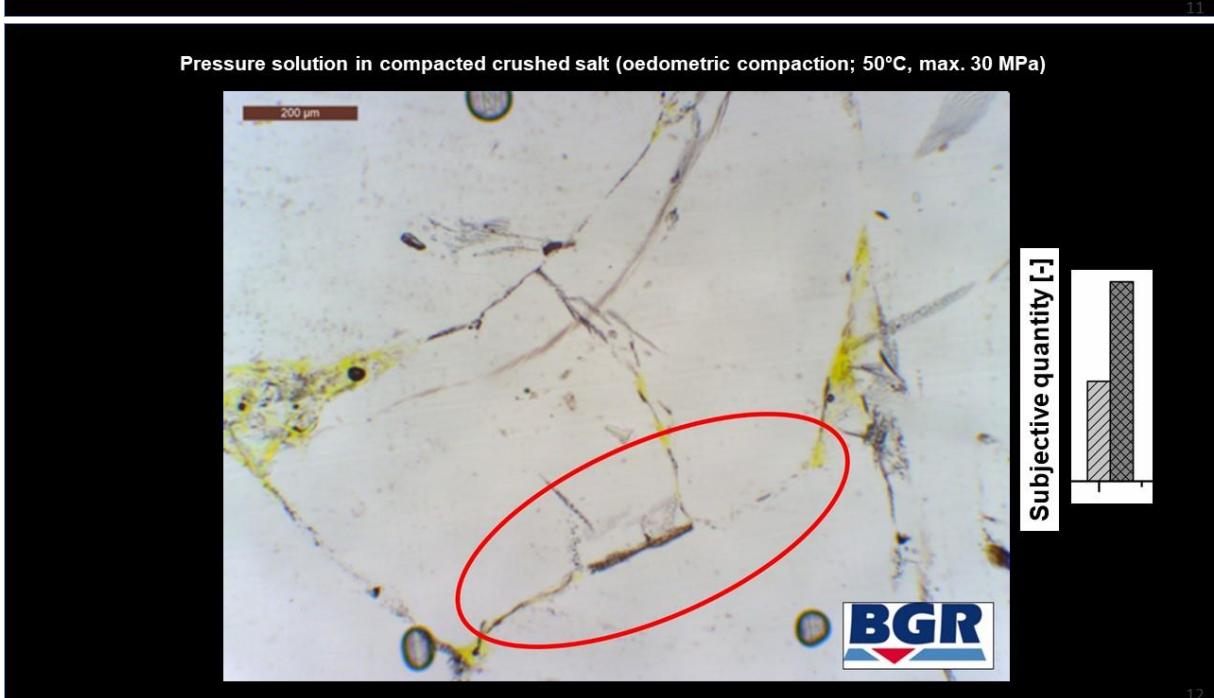
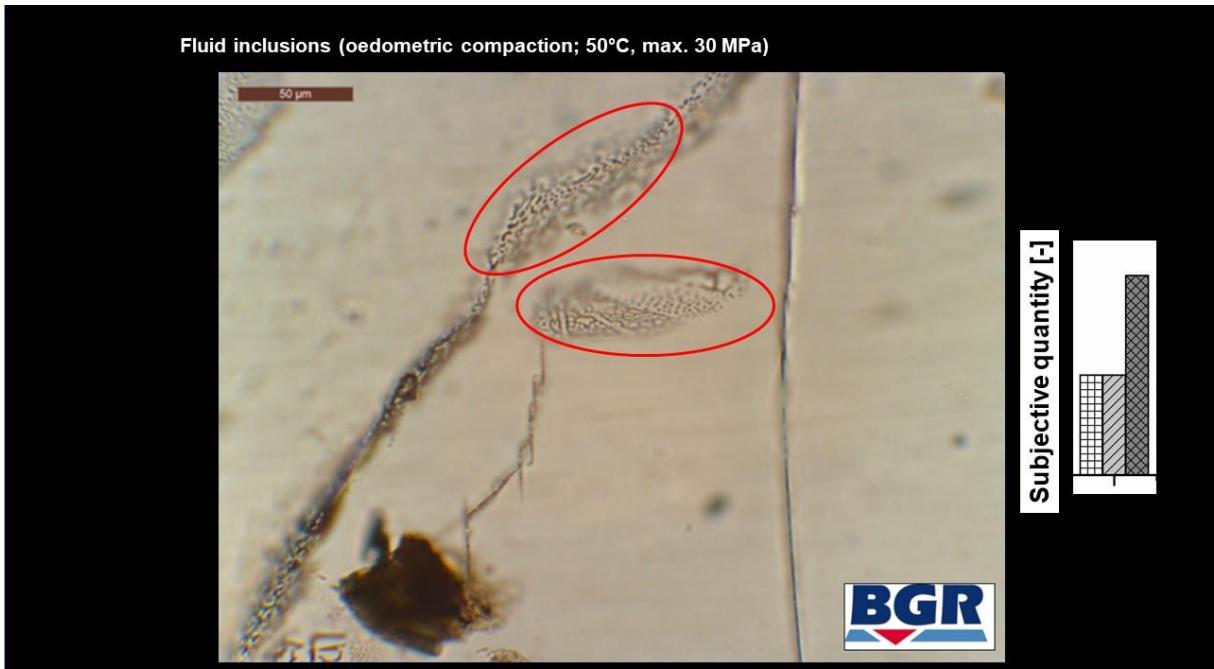
En-échelon structures in crushed salt raw material



Subjective quantity [-]



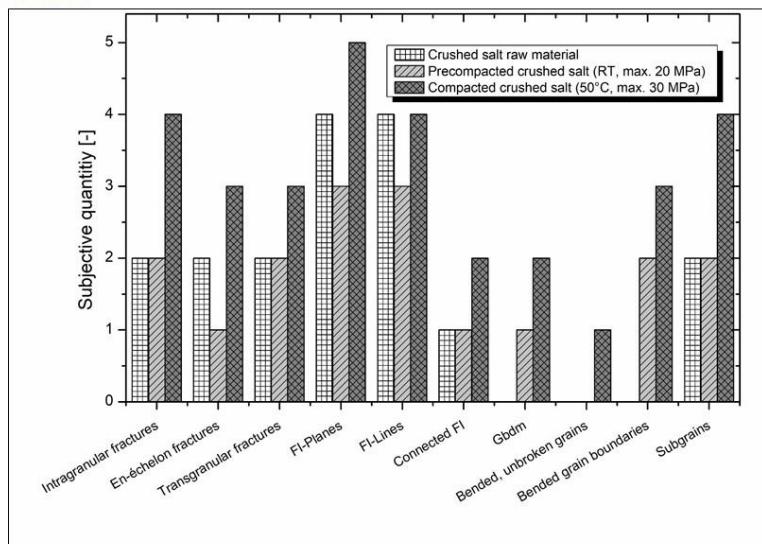






13

### Preliminary results



## 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 abundance of both:**
  - **plastic and cataclastic indicators**

## 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**



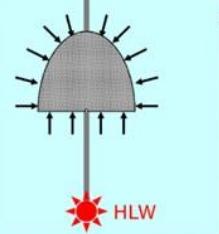




## Granular salt compaction and healing

Natural and Technical analogues

Dirk Naumann / Till Popp (IfG Leipzig)



### Outline

- Background
- Natural and technical analogues
- Fundamental micro-structural processes
- Summary / Open questions

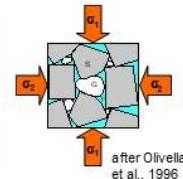


### The problem addressed

- **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.
- **Diluted 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 diluted and re-compacted salt or crushed salt samples → „Mellisa/ BGR“
- **Investigations of analogues** – link between nature and experiments

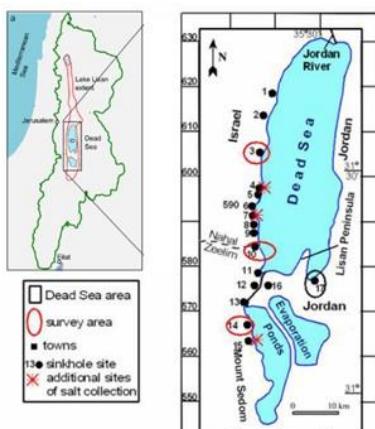


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## Dead Sea salt sediments (crushed salt)



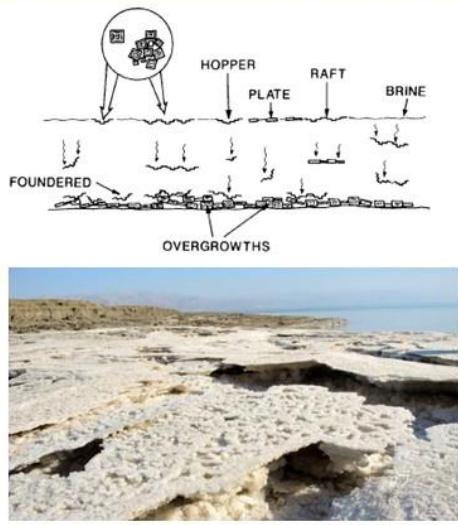
Shallow salt layers buried within the Dead Sea fill during several quaternary time periods:

- 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)

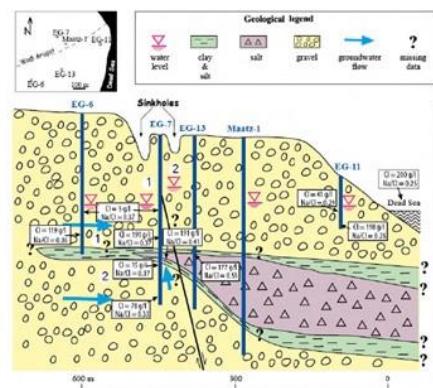


### Presentation of literature findings from boreholes and seismic investigations on core sample

## Syndepositional and postdepositional diagenesis of salt rocks (crushed salt)



**(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 Dead Sea  
(Yechieli et al., 2006).

## Porosity decrease during diagenesis – core investigations

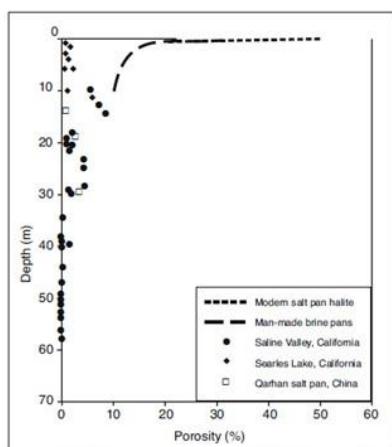


Figure 1.31. Porosity in Quaternary halite beds versus depth (after Casas and Lowenstein, 1989). All effective porosity is lost by 70 m burial.

- 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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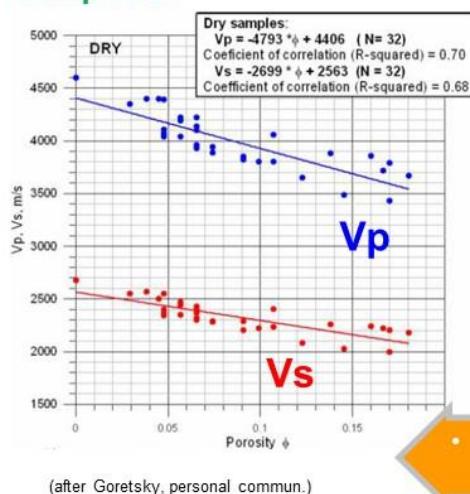
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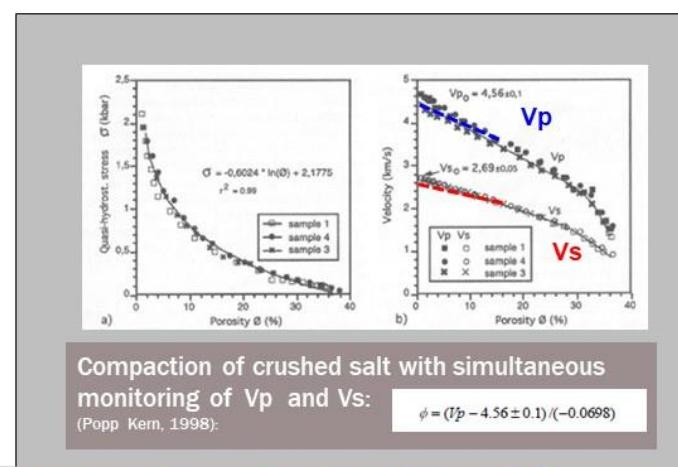
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## Core investigations – ultrasonic velocity measurements

### Deep Sea



(after Goretsky, personal commun.)



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



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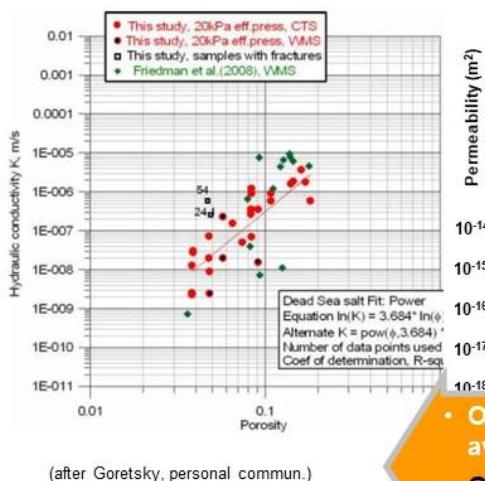
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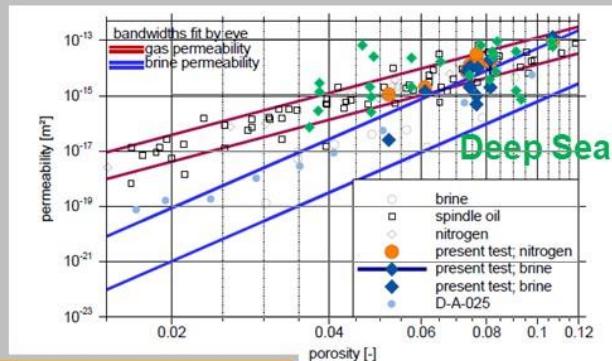
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## Core investigations – permeability measurements

### Deep Sea



### REPOPERM II: permeability testing with various fluids

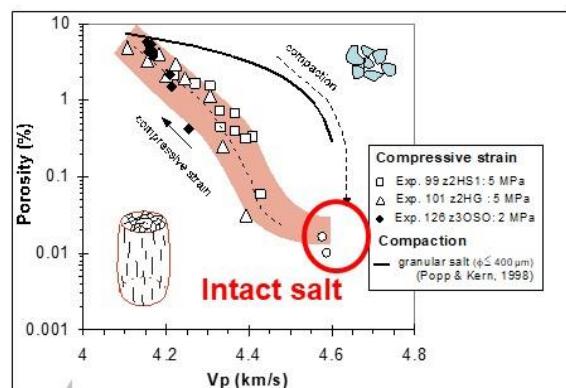
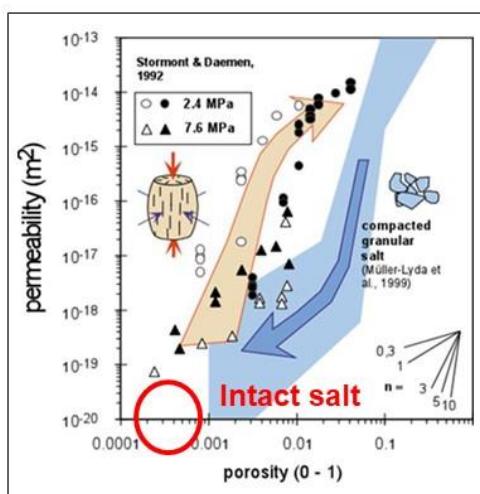


- Only for  $\phi > 4\%$  are data available (sign. Scattering)
- Gas vs. brine: Which permeability trend is true?

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### 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?

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KOMPAS S – Crushed salt analogues

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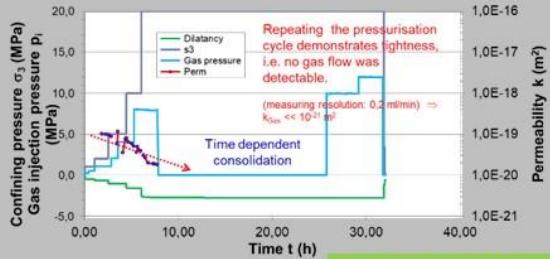
## Re-compaction of dilated salt – Case study Teutschenthal



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

- **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

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



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

**The reconsolidated material behaves like the virgin rock**  
☺ **Low permeability**



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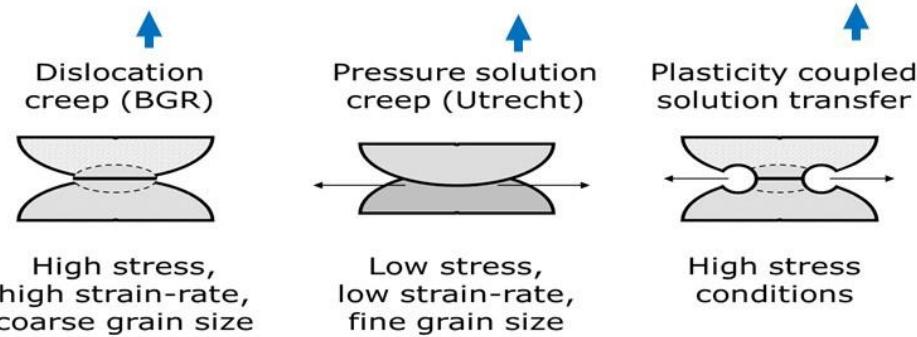
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## Underlying mechanisms: Volumetric creep of salt – Long term

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



(Spiers et al. 2005)



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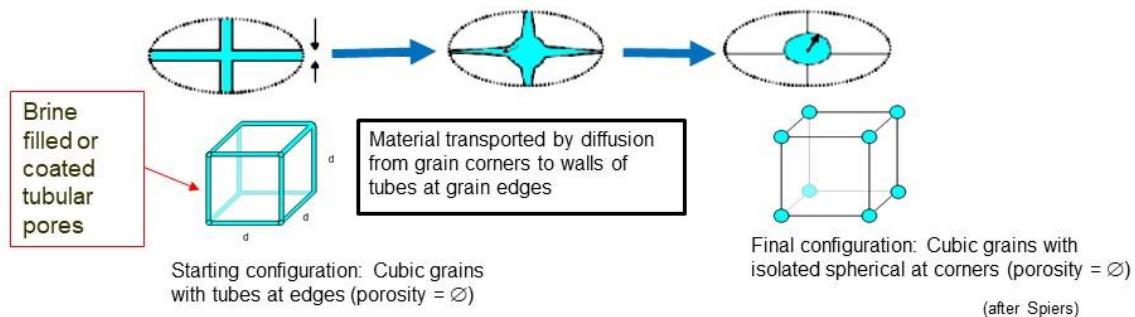
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## Micophysical model for pore disconnection – Fluid transport

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



### Time for pore disconnection:

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

$\phi$  is porosity,  $d$  grain size,  $T$  temperature,  $\gamma = 0.2 \text{ J/m}^2$ ,  
 $D = 5 \times 10^{-9} \text{ m}^2 \text{s}^{-1}$  (70 °C) (diffusion coefficient),  
 $C = 0.2 \text{ m}^3/\text{m}^3$  (solubility of salt),  
 $\Omega = 2.7 \times 10^{-3} \text{ m}^3/\text{mol}$  (molar volume of salt) and  $F(\phi) = \frac{3}{2} \left( \frac{\phi}{3\pi} \right)^{\frac{1}{2}} - \left( \frac{3\phi}{4\pi} \right)^{\frac{2}{3}}$



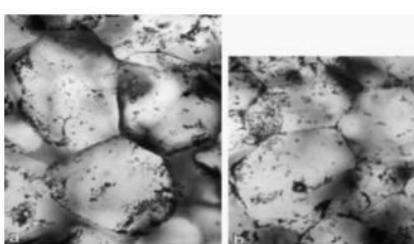
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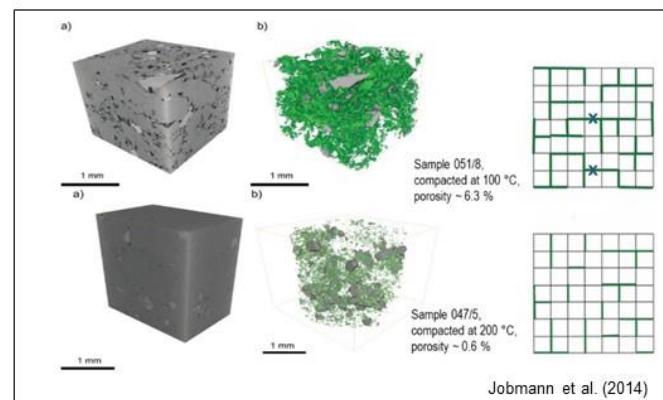
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## Closure of interconnecting pore space – crushed salt



Very intense indentation and grain boundary straightening by pressure solution showing presence of 120° '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



### Percolation network model

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



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## 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“







## 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation

### The KOMPASS project Modelling related experimental aspects



Svetlana Lerche

Uwe Düsterloh

Juan Zhao

TUC

Part 2 of the online workshop

Juni 17, 2021

## Overview

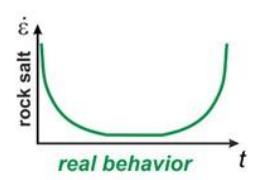


1. General reasons for need in modelling related lab tests
2. Modelling related lab program design for crushed salt
3. Results and next steps: KOMPASS I and KOMPASS II

**General reasons for need in modelling related lab tests**







**real geometry**

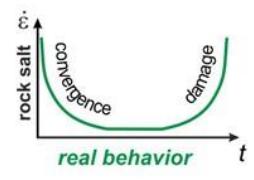
**What?** Basic task in the numerical analyses  
Idealized/simplified reproduction of reality  
**Geomechanics:** underground system with antropogenic construction and geogenic structure

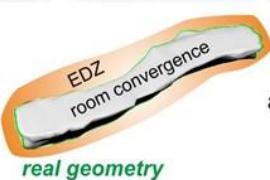
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**General reasons for need in modelling related lab tests**









**real geometry**

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

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

4

**General reasons for need in modelling related lab tests**

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

**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

**real geometry**

**real behavior**

**idealisations for geometry**

**idealisations for behavior**

**State of the art in science and technology**

**State of the art in science and technology**

5

**General reasons for need in modelling related lab tests**

**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*

**idealisations for geometry**

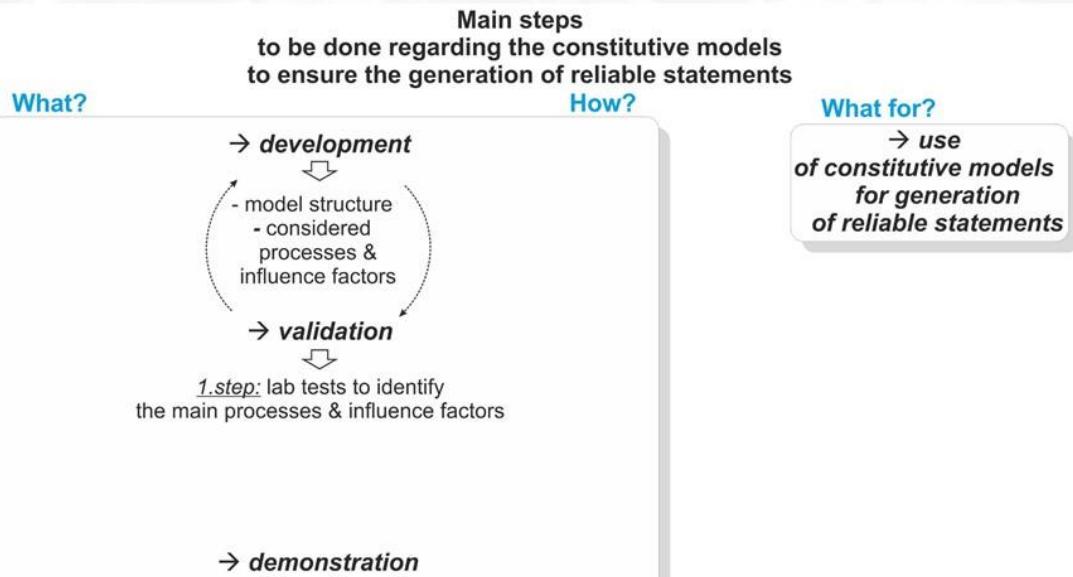
**idealisations for behavior**

**State of the art in science and technology**

**State of the art in science and technology**

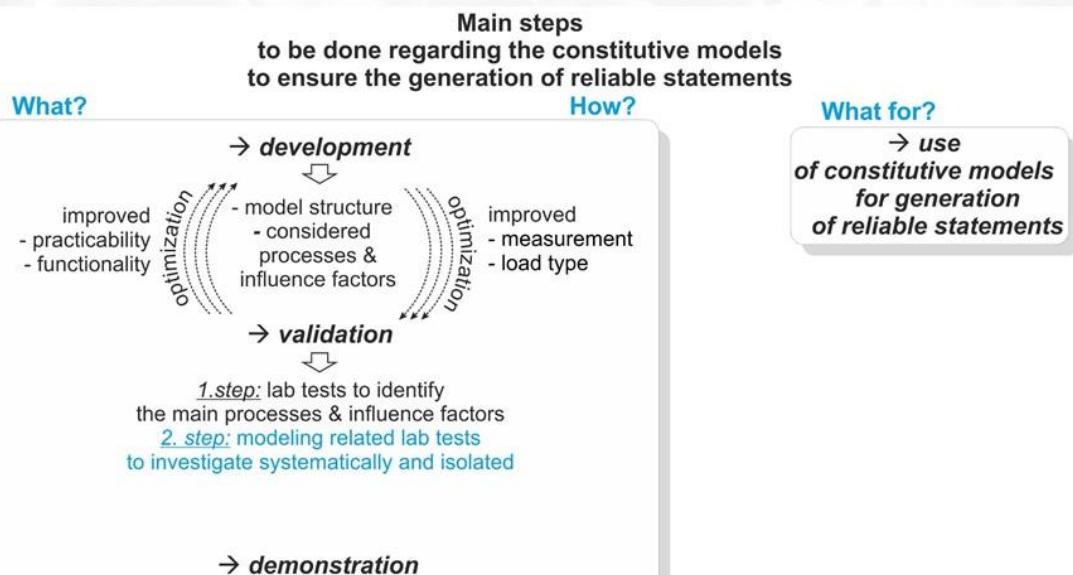
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## General reasons for need in modelling related lab tests

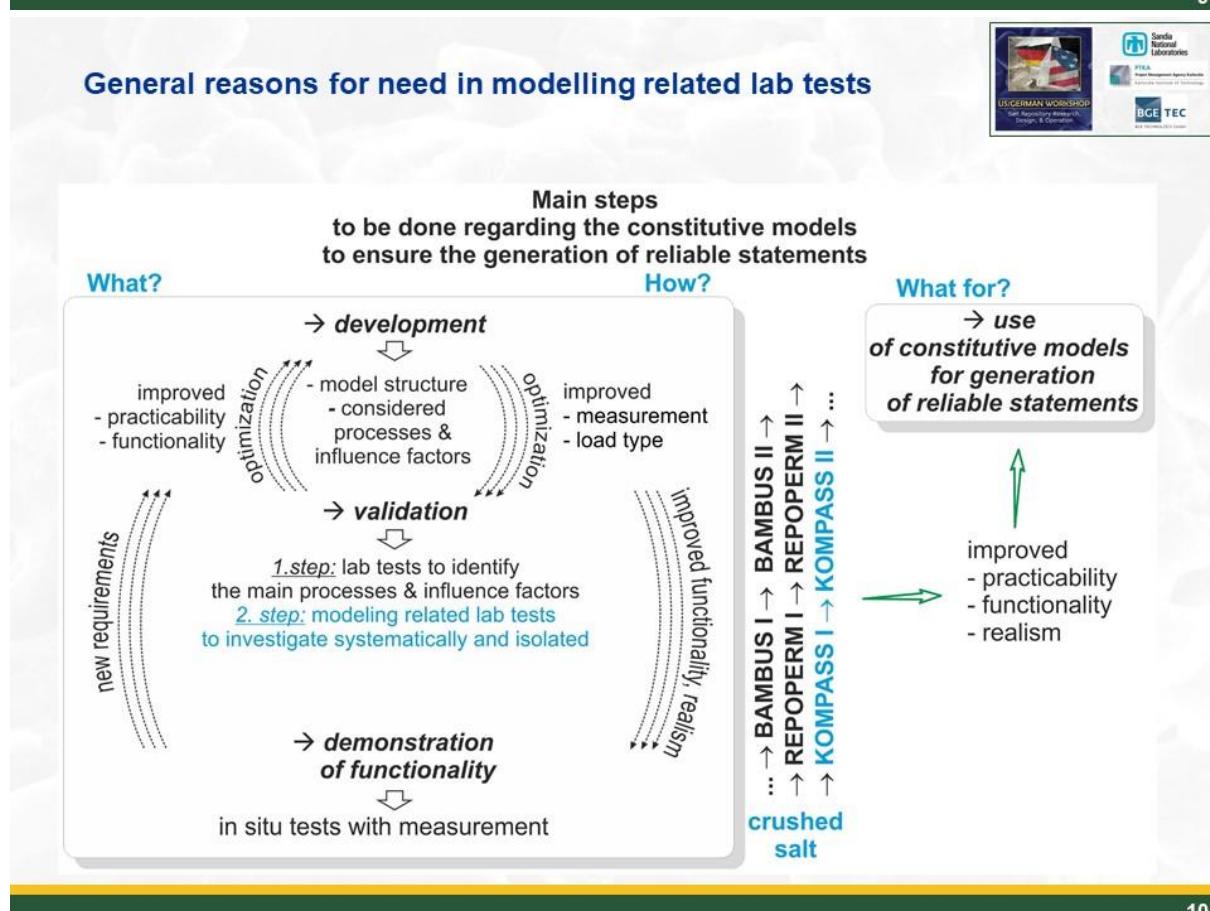
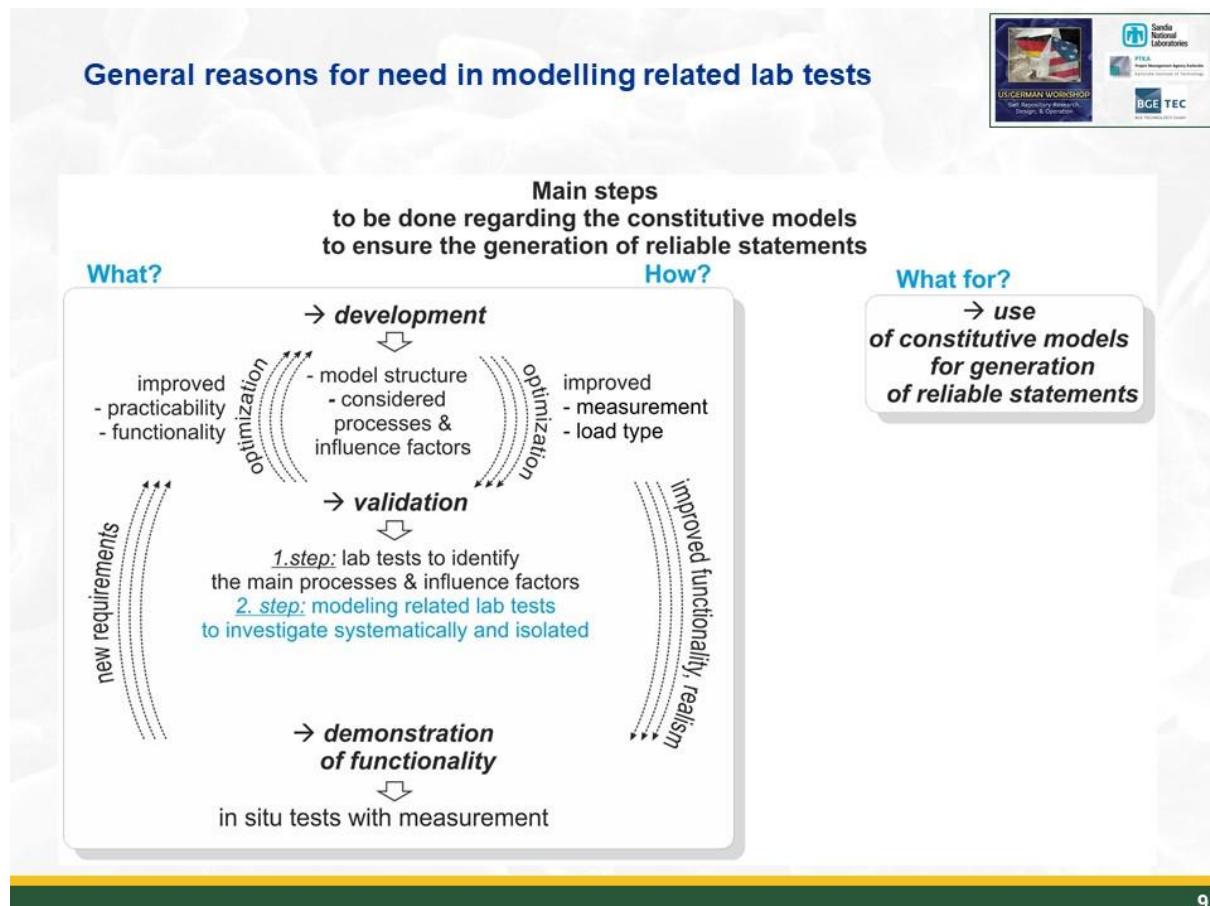


7

## General reasons for need in modelling related lab tests



8



# Overview



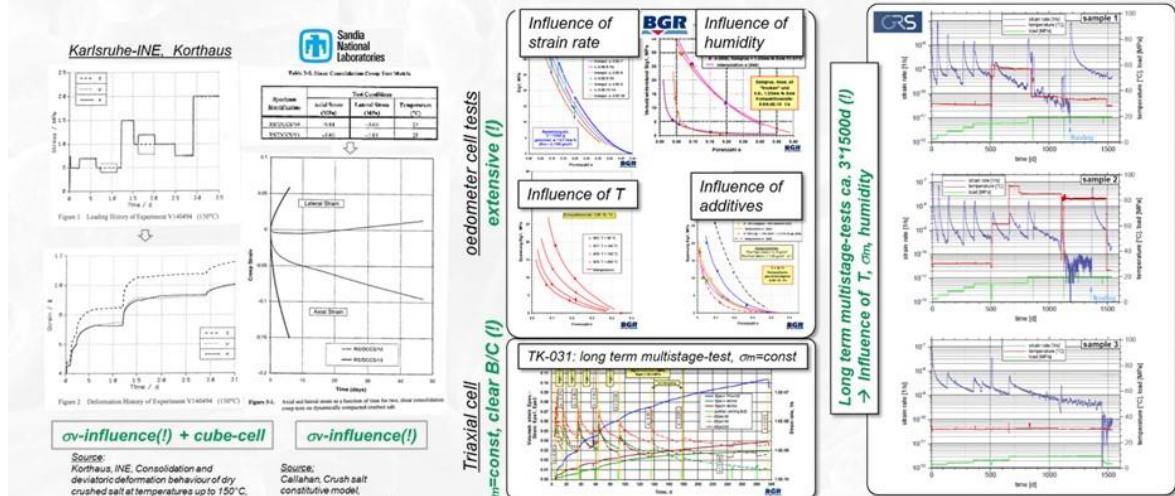
1. General reasons for need in modelling related lab tests
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11

## Modelling related lab program design for crushed salt



### previous investigations



12

**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**  
identification of main processes & influence factors

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modeling related: systematically and isolated investigations

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

**oedometer cell tests extensive (I)**

**Influence of strain rate**

**Influence of humidity**

**Influence of T**

**Influence of additives**

**Triaxial cell (I)**

**TK-031: long term multistage-test,  $cm=const$**

**Long term multistage-tests ca. 3\*1500d (I)**

**Long term multistage-tests ca. 3\*1500d (I) influence of  $T, cm, humidity$**

**ov-influence(!!)**

**Source:** Kilian, Crush salt institute model, ISPEC, Rapid City, 1999

**→ State of the art in science and technology →**

**13**

**Modelling related lab program design for crushed salt**

**concept for modelling related lab program design**

**Principles/Guidelines for planning**

**for the system of tests**

**Completeness** →

**Systematics** →

**Reliability & Effectiveness** →

**for individual tests**

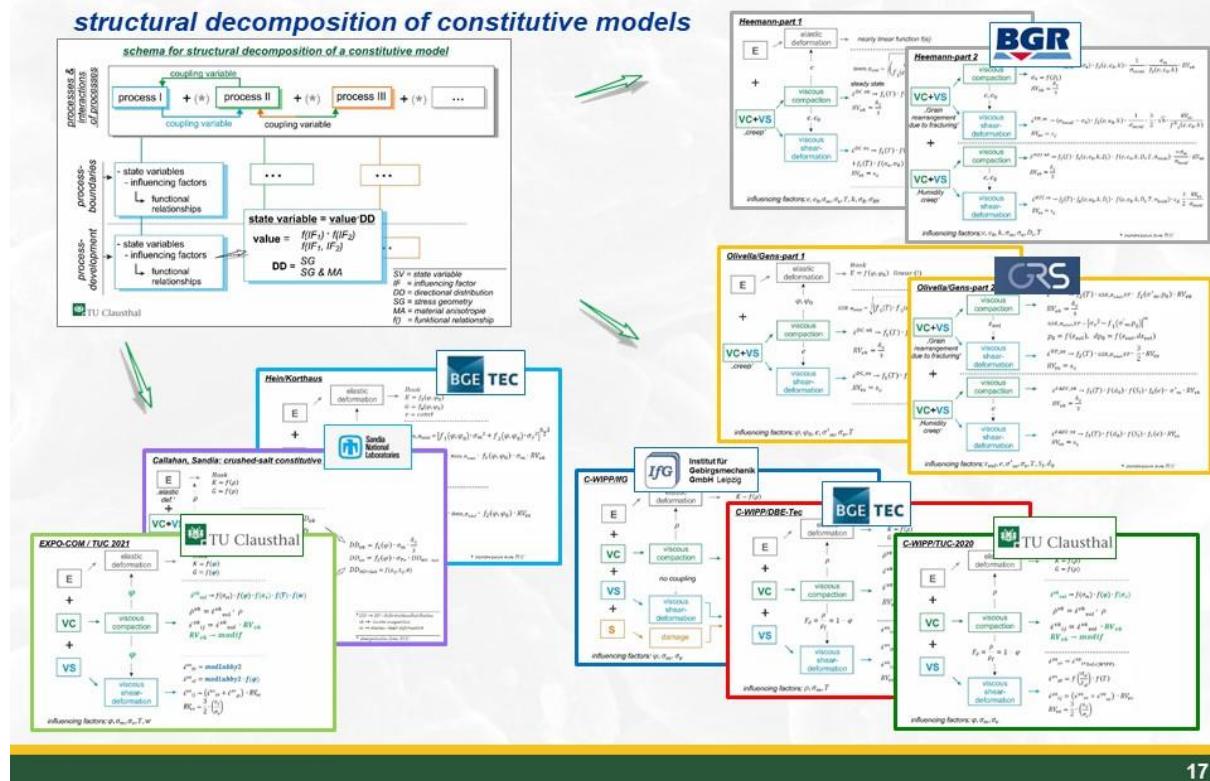
**Clearness/ unambiguity/ clear-cut analysis** →

**How?**

**14**

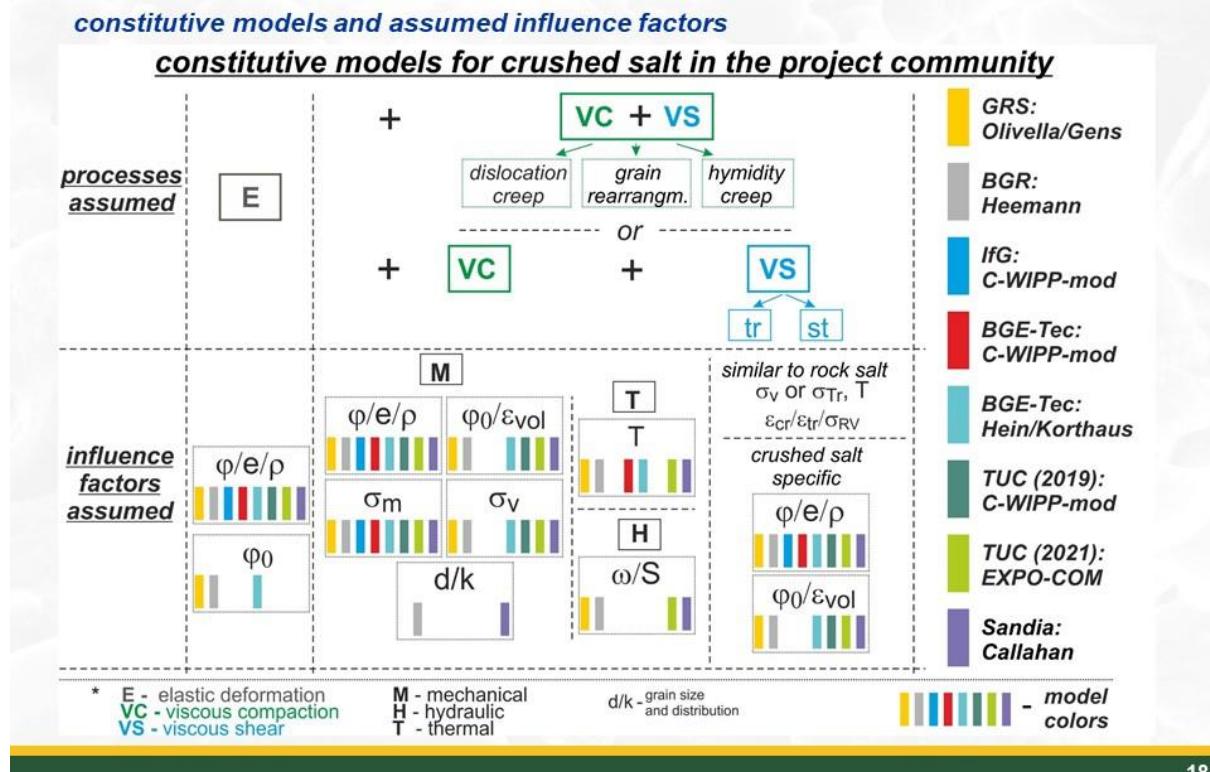


## Modelling related lab program design for crushed salt

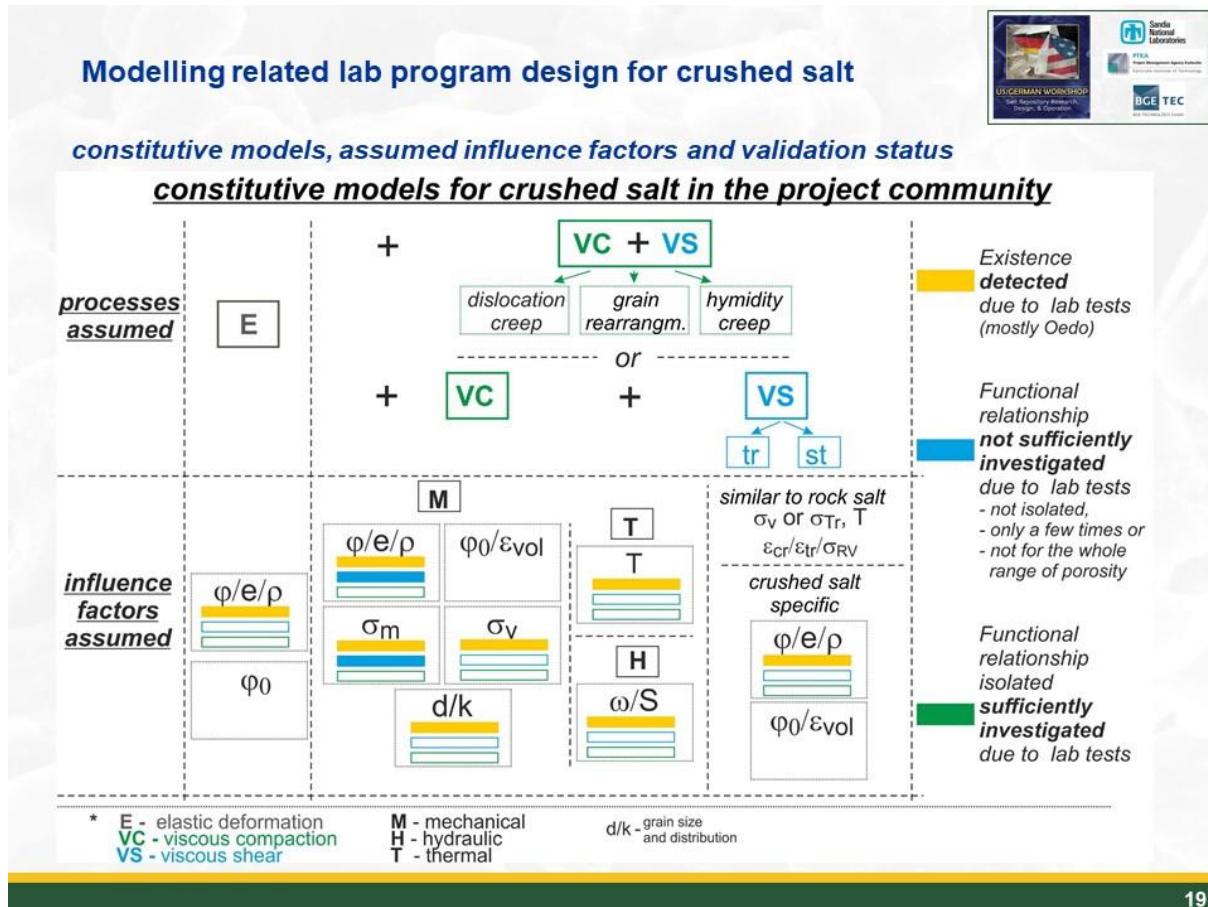


17

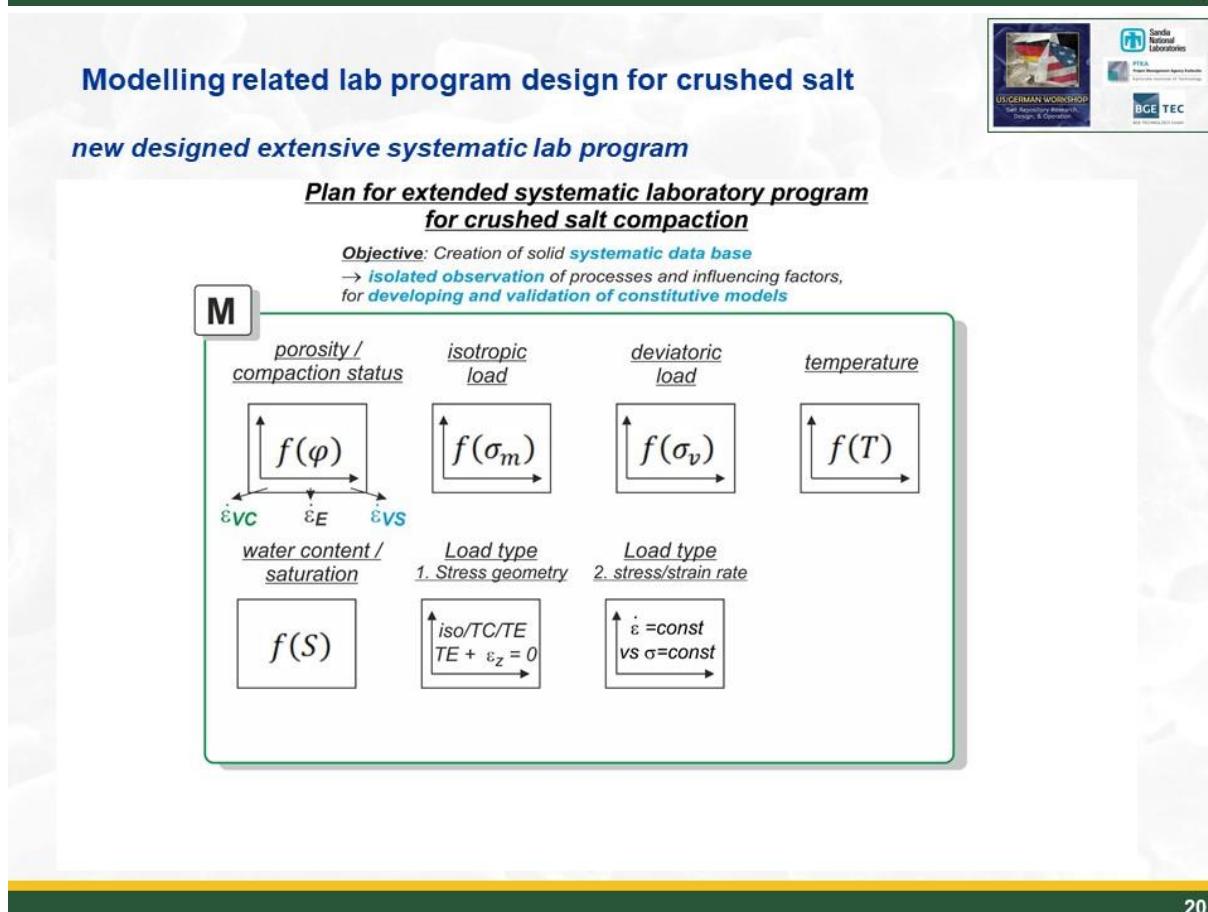
## Modelling related lab program design for crushed salt



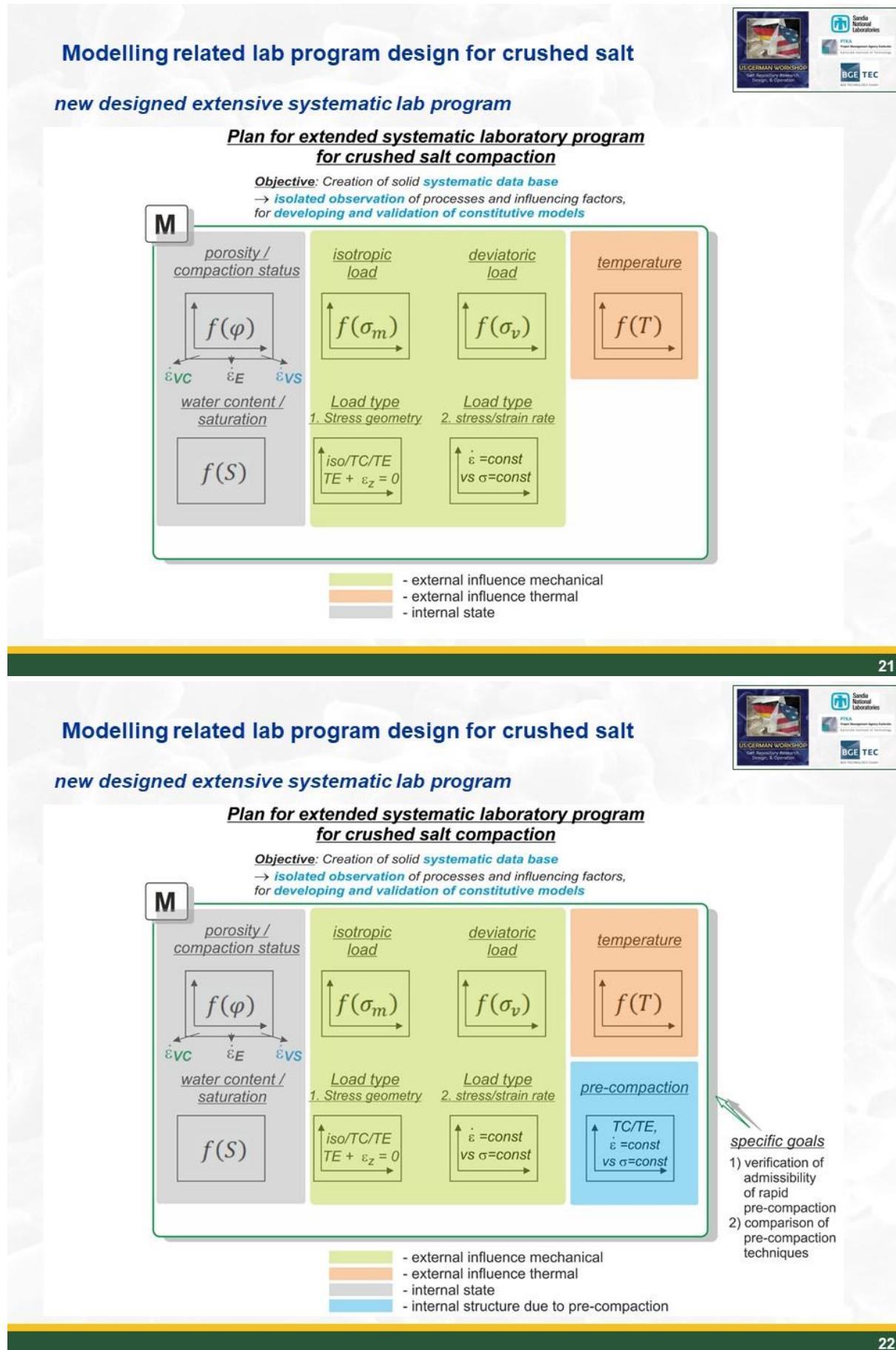
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19



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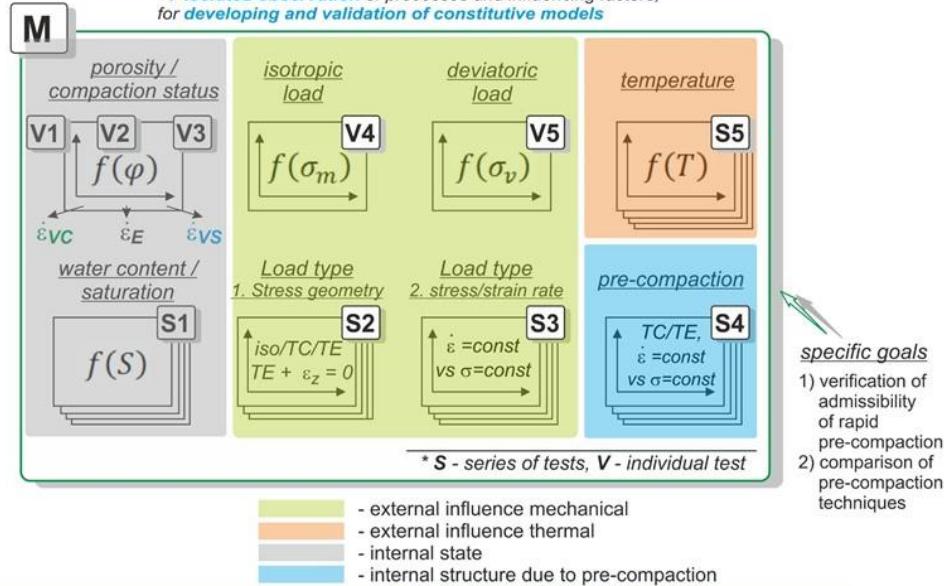


## Modelling related lab program design for crushed salt

### 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**

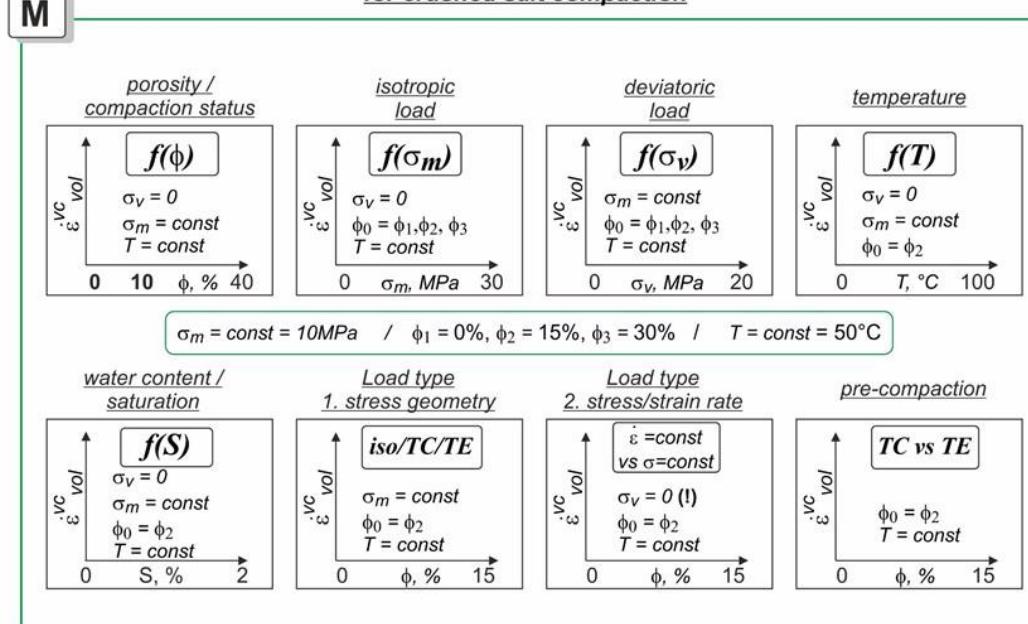


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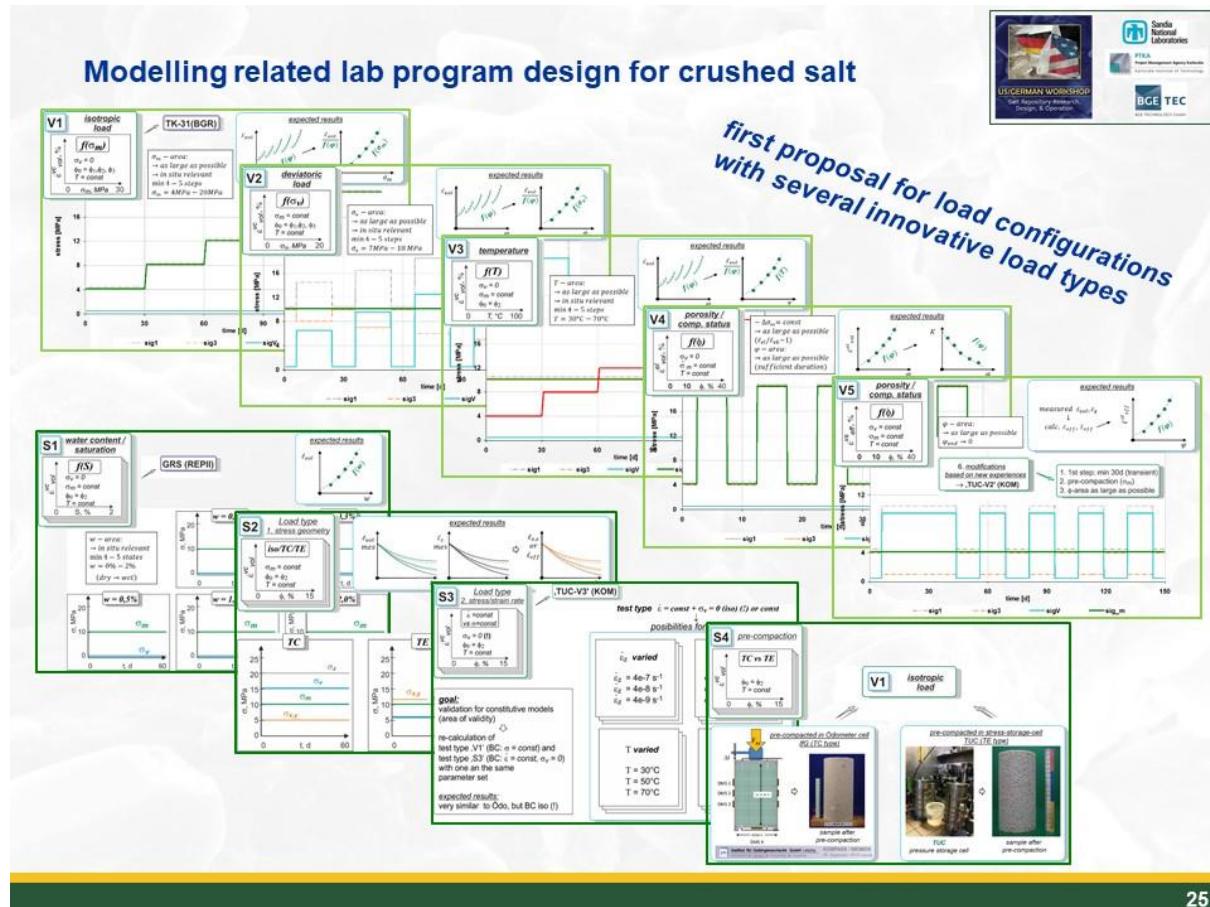
## Modelling related lab program design for crushed salt

### new designed extensive systematic lab program

#### Plan for extended systematic laboratory program for crushed salt compaction



24



25

## 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

26

## Results and next steps: KOMPASS I and KOMPASS II

### pre-compaction techniques

Oedometric conditions



Institut für  
Gebirgsmechanik  
GmbH Leipzig



BGR

**Plain Strain**



TU Clausthal

**KOMPASS I**

**technical realization & first experience**

- technical realization
- first experience for guide values  $\sigma_c / t$
- sample preparation for further investigations

$w=0.5\%$ : 6 samples prepared  
 $w=0.1\%$ : 1 sample prepared  
 $w=1.0\%$ : 1 sample prepared  
 $(\delta_{end}) = 14\%-19\%$

Total: ca. 25 tests

**KOMPASS II**

**pre-compaction tests**  
 procedure with using of storage cell  
 in situ similar B/C:  $TE + \epsilon_2 = 0$

**Series 1 - TUC**  
 → systematic research  
 suitable values for control parameter  
 $\sigma_c$  - variation  
 $w$  - variation  
 Total: ca. 10 tests

**Series 2 - TUC**  
 → systematic research  
 suitable values for control parameter  
 $\sigma_c$  - variation  
 $t$  - variation  
 Total: ca. 20 tests

**Series 3 - TUC**  
 → systematic research  
 suitable values for control parameter  
 $t$  - variation  
 Total: ca. 24 tests

**Series 4 - TUC**  
 → increasing the database  
 during the pre-compaction  
 Total: 1-2 tests, triax cell (I)

**Series 5 - TUC**  
 → long term behavior  
 → in situ similar low stress value  
 → reaching of 0.51%  
 Total: 1-2 tests, long term (I)



27

## 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**

$\epsilon_{VC}$

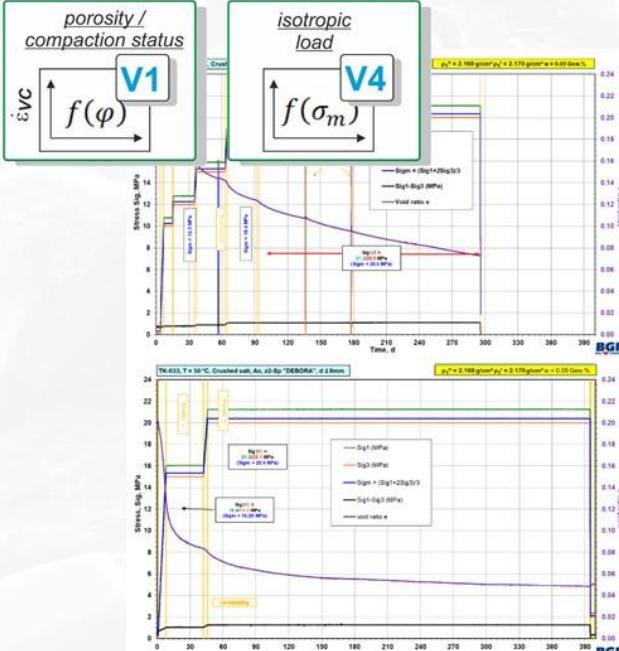
$f(\varphi)$

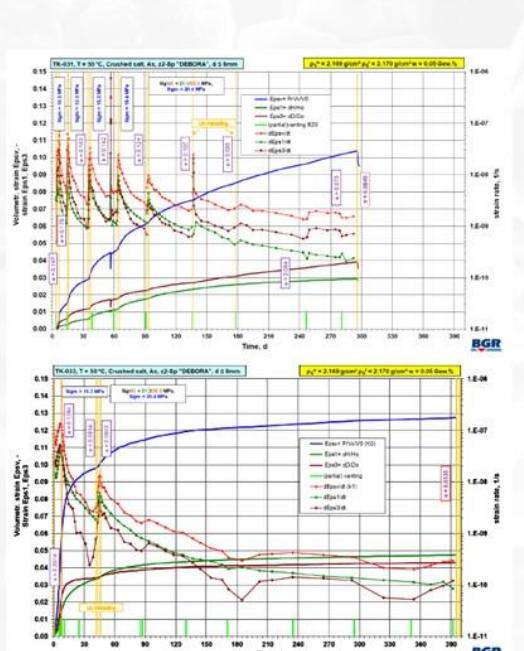
**isotropic load**

**V4**

$\sigma_m$

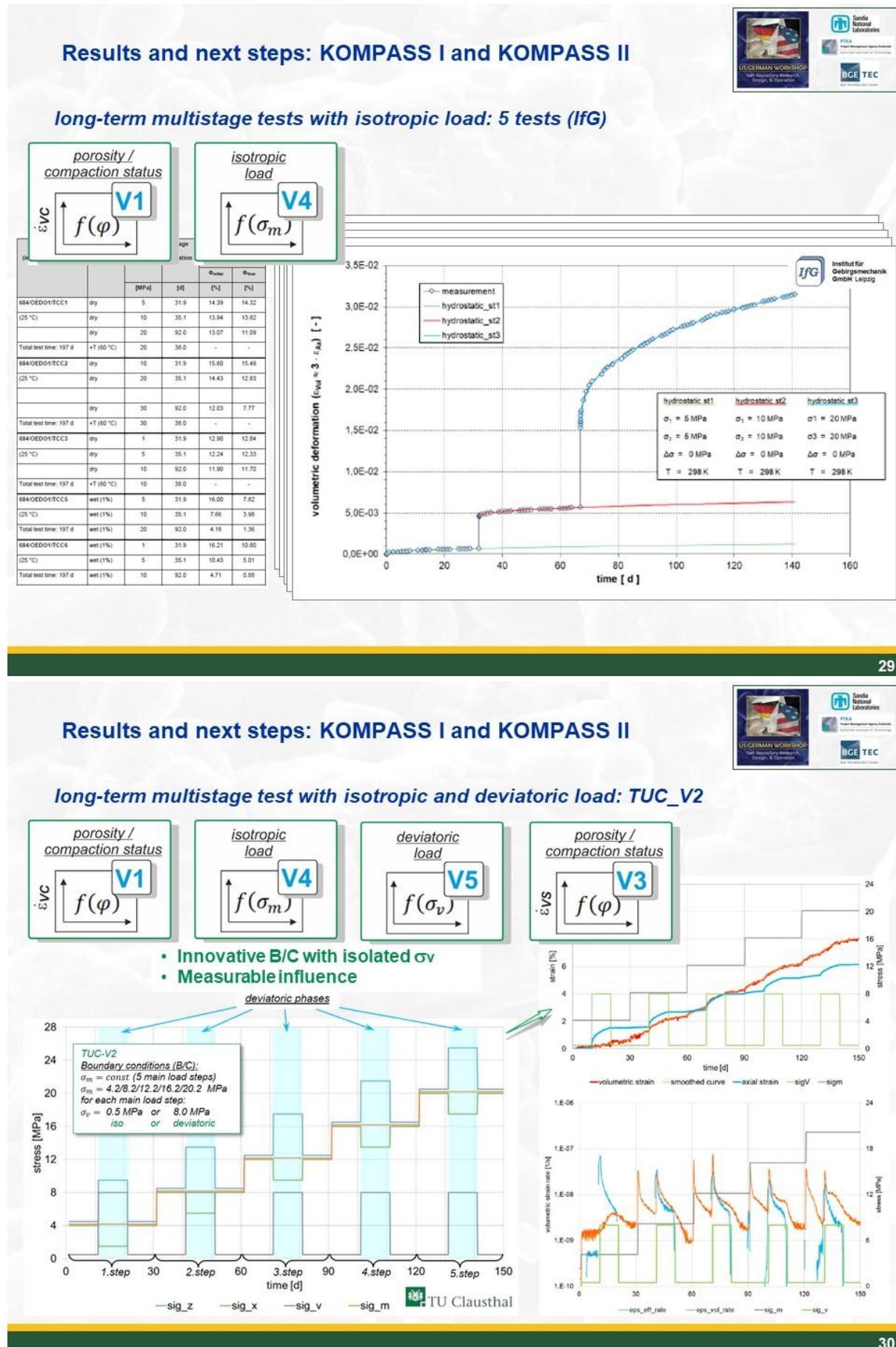
$f(\sigma_m)$







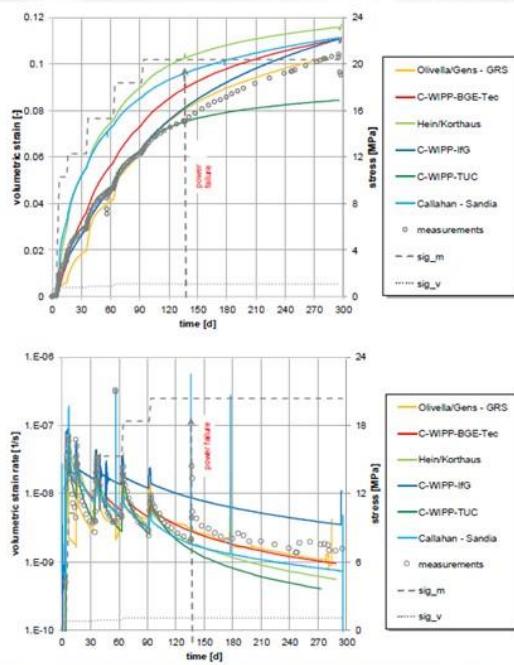
28



## Results and next steps: KOMPASS I and KOMPASS II



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



#### Modelling

##### Basic functionality/ Qualitative agreement:

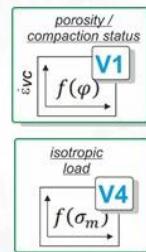
All models used here are capable of reproducing  
 → reduction of compaction with decrease of porosity  
 → increase of compaction with increase of main stress

##### 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  
 $\sigma_m = [0 \rightarrow [10 \div 20] \rightarrow 25] \text{ MPa}$   
 $\varphi = [1 \rightarrow [17 \div 7] \rightarrow 30] \%$

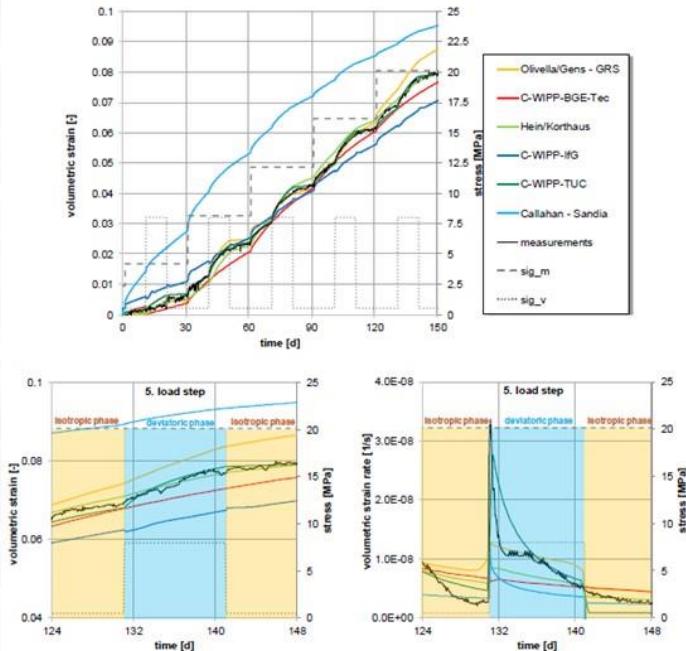


31

## Results and next steps: KOMPASS I and KOMPASS II



### recalculation results for the multistage isotropic and deviatoric test: TUC\_V2



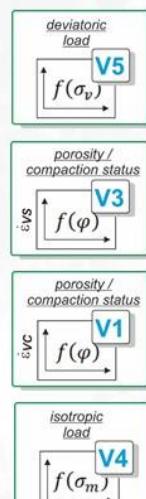
#### Modelling

##### Basic functionality/ Qualitative agreement:

Most models used here are capable of reproducing increase of compaction by activation of deviatoric stress

#### Lab

- Innovative B/C with isolated  $\sigma_v$
- Measurable influence



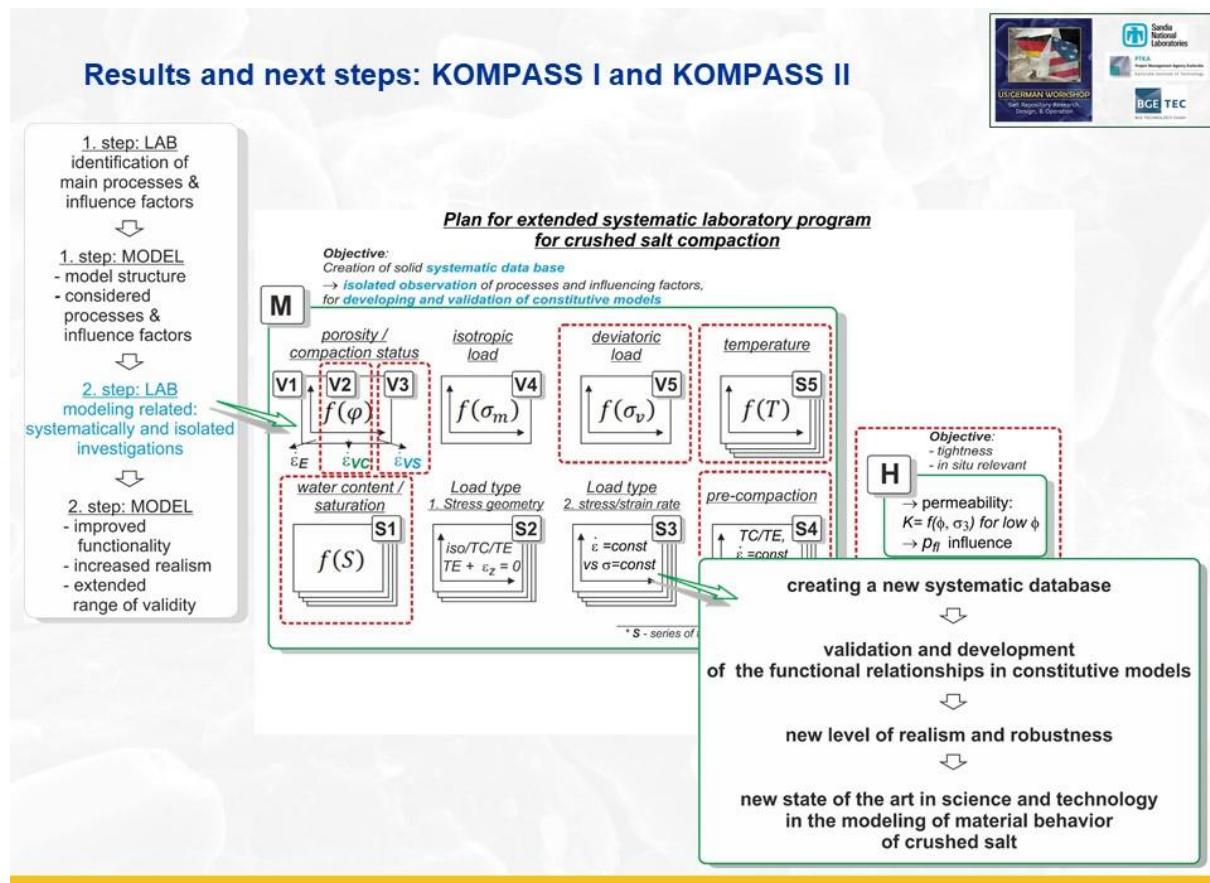
##### Realism/ Quantitative Agreement:

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  
 $\sigma_m = [0 \rightarrow [4 \div 20] \rightarrow 25] \text{ MPa}$   
 $\varphi = [1 \rightarrow [17 \div 9] \rightarrow 30] \%$   
 $\sigma_v = [0 \rightarrow [8] \rightarrow 20] \text{ MPa}$

32







## 11<sup>th</sup> 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



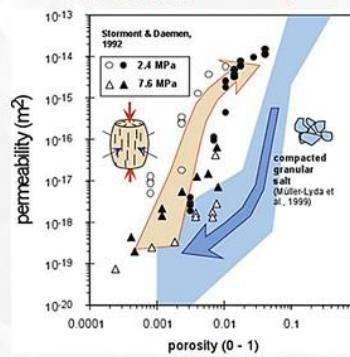
1. KOMPASS objectives
2. Requirements for long-term safety
3. KOMPASS future

# 1. KOMPASS objectives



3

# 1. KOMPASS objectives



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

5

## 3. KOMPASS future



6

### 3. KOMPASS future

**GRS**  
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH

**TU Clausthal**

**Prognosis quality improvement**

**BGR** Bundesanstalt für Geowissenschaften und Rohstoffe

**IfG** Institut für Gebirgsmechanik GmbH  
Untersuchung-Prüfung-Beratung-Begutachtung

**COVRA**<sub>NV</sub>

**BGE TEC**  
BGE TECHNOLOGY GmbH

**Sandia National Laboratories**

**U.S.-GERMAN WORKSHOP**  
Salt Repository Research, Design & Operation

**PTKA** Projektträger Karlsruhe  
Karlsruher Institut für Technologie

**BGE TEC**  
BGE TECHNOLOGY GmbH

7

### Thank you

**BGE TEC**  
BGE TECHNOLOGY GmbH

**BGR** Bundesanstalt für Geowissenschaften und Rohstoffe

**IfG** Institut für Gebirgsmechanik GmbH  
Untersuchung-Prüfung-Beratung-Begutachtung

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**U.S. DEPARTMENT OF ENERGY**

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Attended by:

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 –



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

11<sup>th</sup> 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

# 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

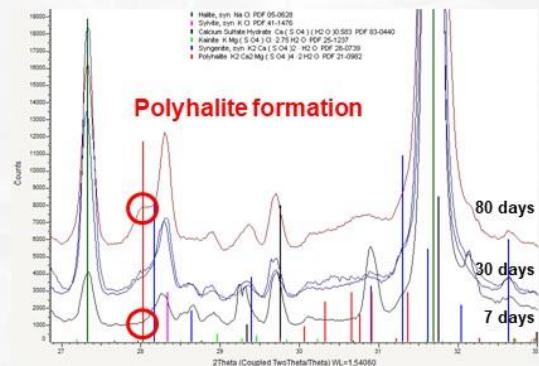


**Rock salt – NaCl:** 85 %

**Salt binder:** 15 %

- $\text{CaSO}_4 \cdot 0,5 \text{ H}_2\text{O}$
- Kieserite –  $\text{MgSO}_4 \cdot \text{H}_2\text{O}$
- $\text{K}_2\text{SO}_4$
- $\text{MgCl}_2\text{-H}_2\text{O}$  brine

Formation of **Polyhalite**  $\text{K}_2\text{Ca}_2\text{Mg}(\text{SO}_4)_4 \cdot 2 \text{ H}_2\text{O}$  (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

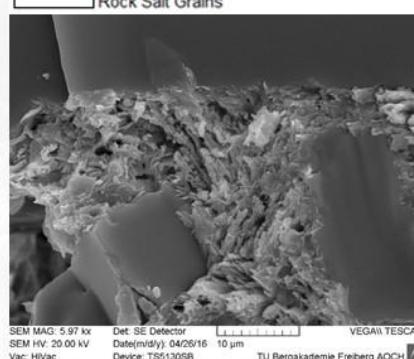
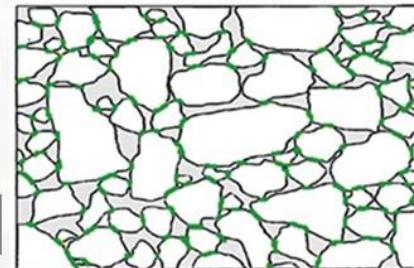


- Optimized crushed rock salt fractions (85 %)
- Max. grain size of 14 mm
- Moisture content 3,75 %

## ➤ Moistened bulk material

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

## ➤ Matrix-stabilization, no gap filling



Review of the GESAV II Project

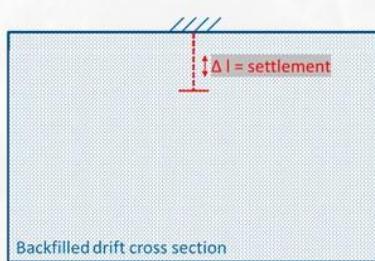
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# Experimental Approach

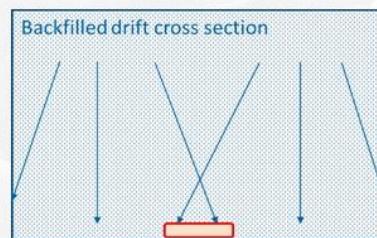
## Relevant Material Parameters



### Time dependent settlement



### Load bearing capacity



### Integral permeability



Review of the GESAV II Project

6



## In situ Measurement Systems



## Filling Technologies in Salt Mining

Pneumatic Stowing

Hydraulic fill

Paste fill

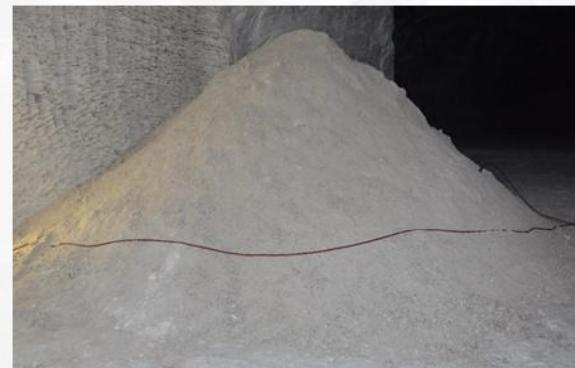
Dump fill

Slinger fill

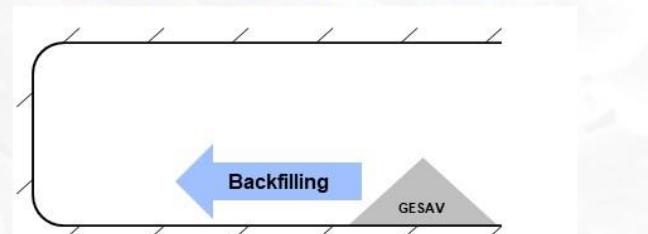
Push fill

Stack fill

➤ 4 Mock-Up tests:  
salt mine Sondershausen

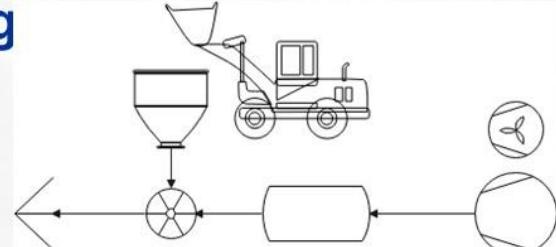


GESAV-Material before backfilling



**(1) Pneumatic Stowing**

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





<https://www.wemermader.de/cms/de/betonsanierung/trockenspritzen>

**(2) Slinger Fill**

- Adapted slinger machine
- Load-Haul-Dump machine




[https://www.swisstruck.ch/surl\\_detail.php?occasoin=SPKA/89\\_10/78333](https://www.swisstruck.ch/surl_detail.php?occasoin=SPKA/89_10/78333)



**10**



## (3a) Push Fill

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



<https://www.lmbv.de/index.php/verwaltungsmanagement.html>



11

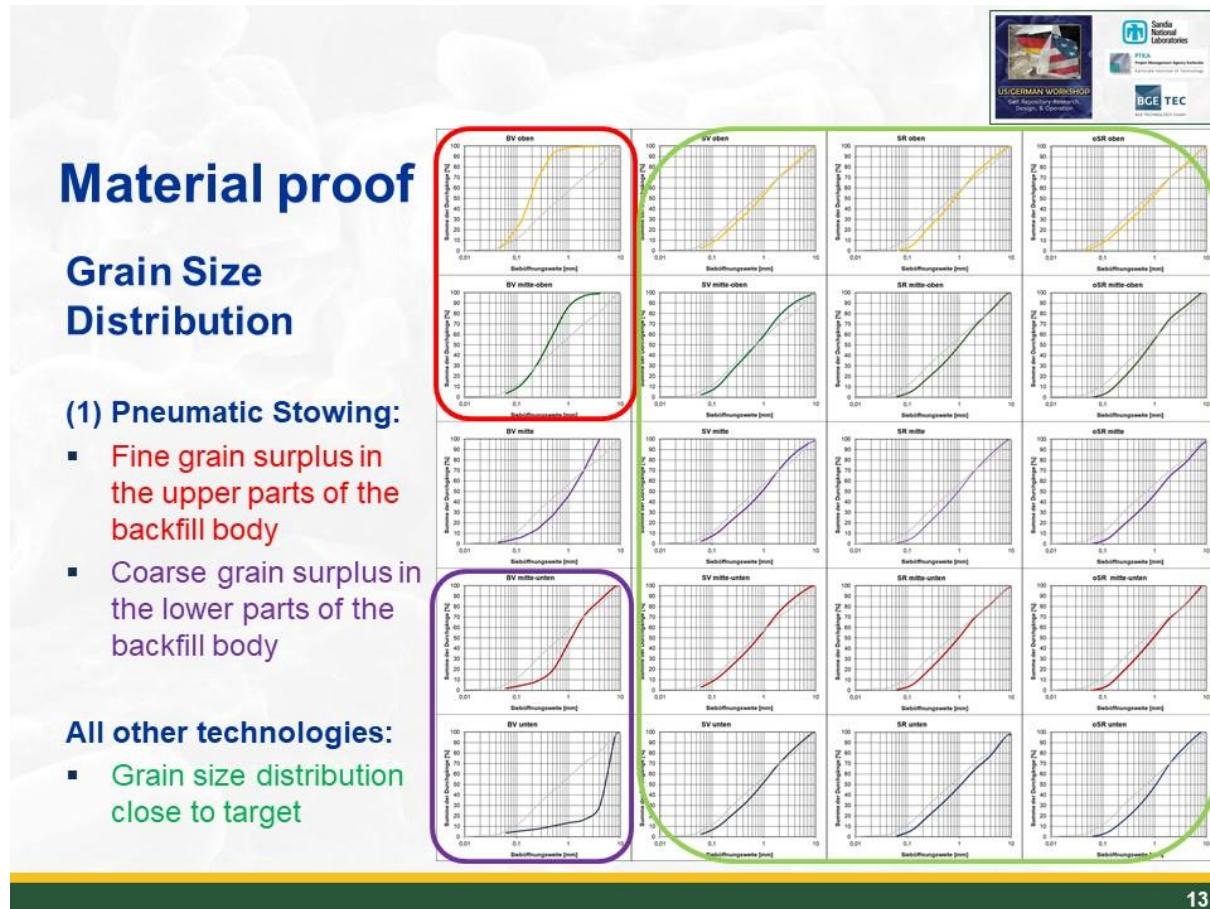


## (3b) Push Fill & Vibratory Compaction

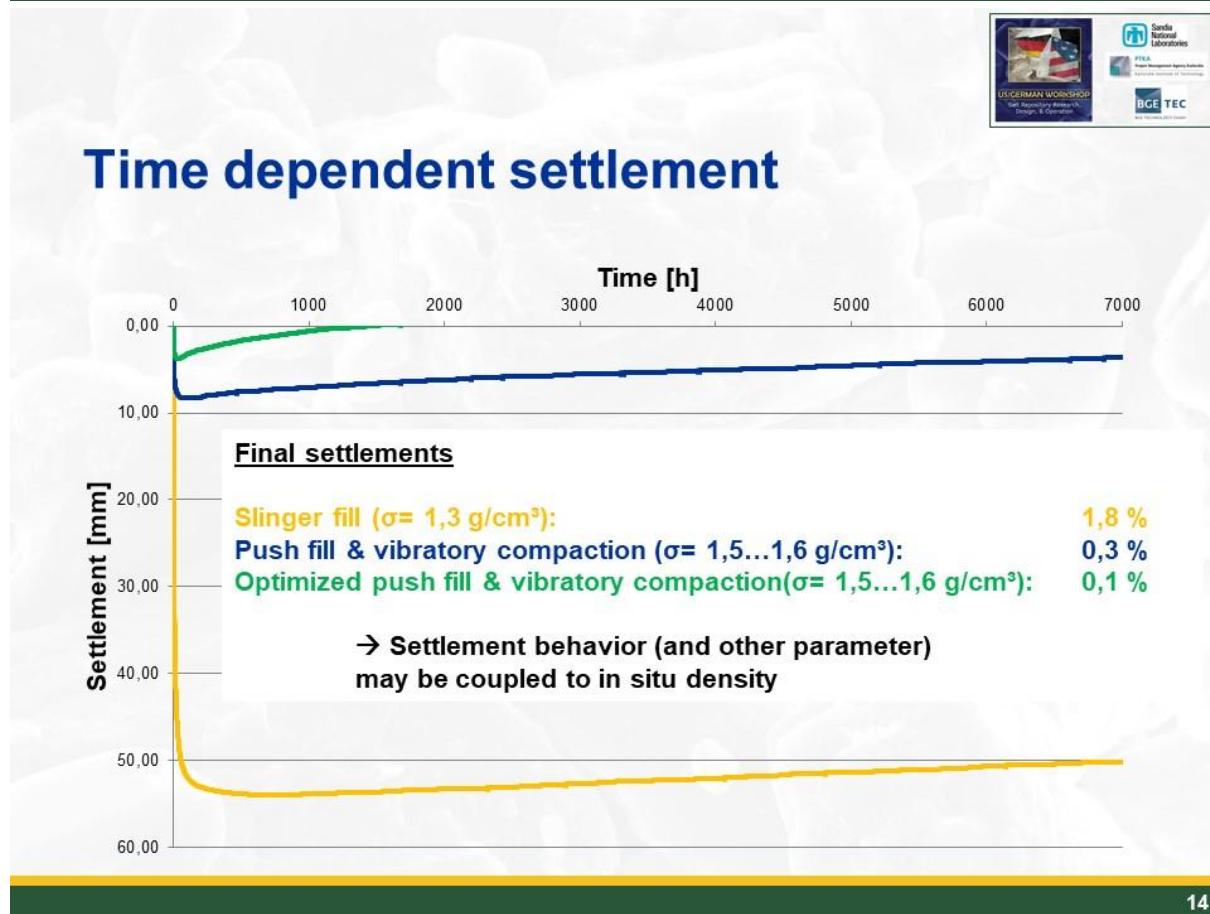
- Small loader
- Attachment vibratory plate



12



13



14

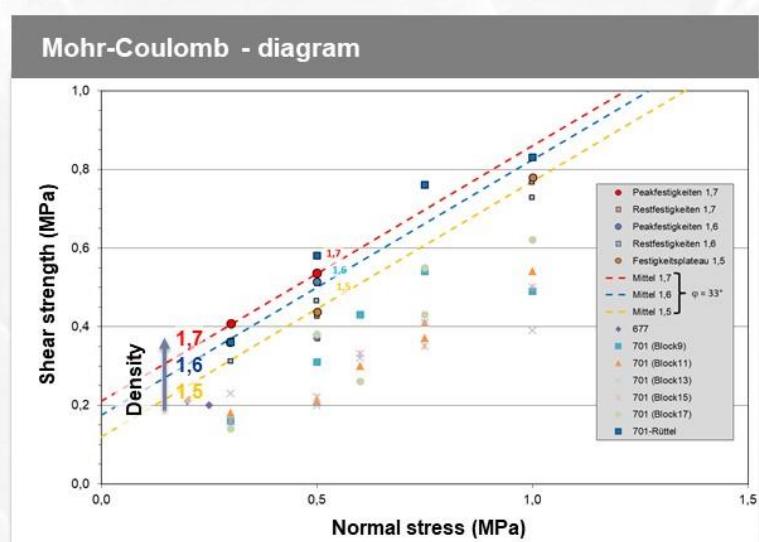


15

## Shear strength

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

Push fill & vibratory compaction:  
 $c = 0,21 \text{ MPa}$   
 $\phi = 34^\circ$

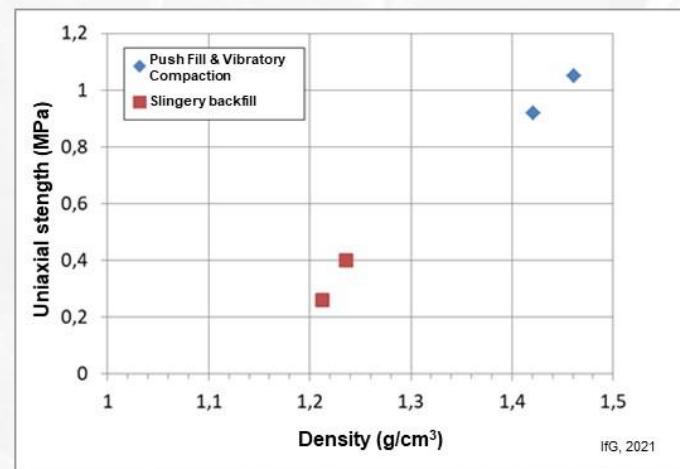


IfG, 2021

16

## Uniaxial compressive strength

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

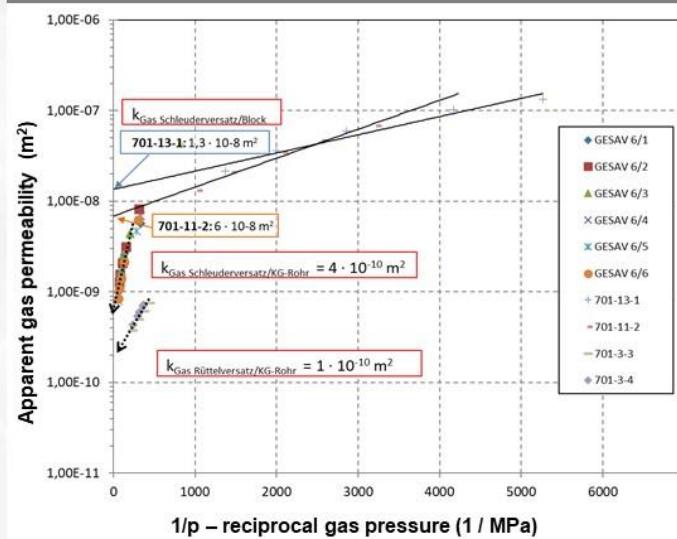


17

## Gas-Permeability

- Slinger fill:  
 $k_{\text{Gas}}: 4 \cdot 10^{-10} \text{ m}^2$
- Push fill & vibratory compaction  
 $k_{\text{Gas}}: 1 \cdot 10^{-10} \text{ m}^2$

Klinkenberg – diagram (lab-samples)



IfG, 2021

18

## 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

19

## 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

20



## THANKS TO THE GESAV II PROJECT TEAM!



### 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

21



THANK YOU FOR YOUR ATTENTION.



GLÜCKAUF!

22



**Appendix C – Program and Presentations of Part 3 (8<sup>th</sup> September 2021)**

Berlin time		<b>8<sup>th</sup> September 2021 – Part 3</b>	
16:00	16:10	Welcome by the organizers	K. Kuhlman/SNL P. Herold/BGE TEC
<b>EBS, Materials and Backfilling</b> 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 closing 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



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

Part 3 of the online workshop  
September 8, 2021

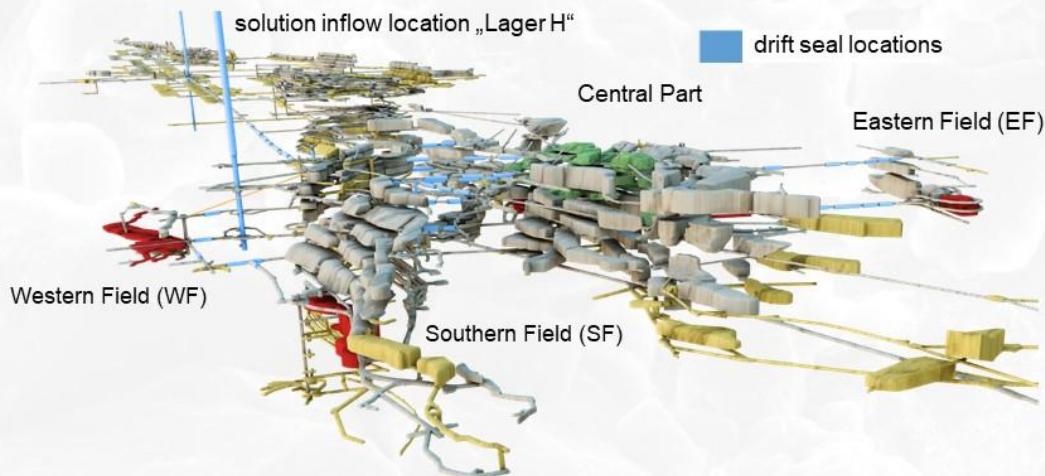
## Content

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



# Morsleben Repository (ERAM)

## Closure Concept and Sealing Measures



- **Extensive backfilling of excavations ~5 million m<sup>3</sup> 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**

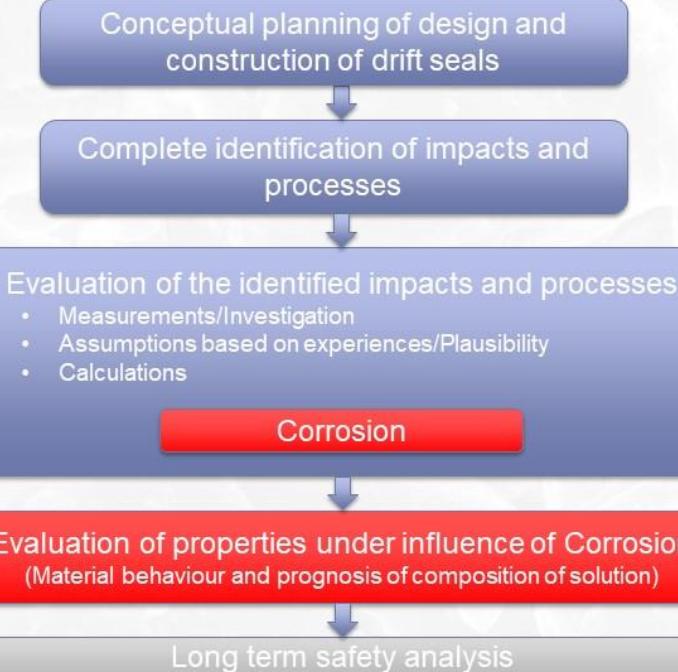
**Mass concrete**

**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

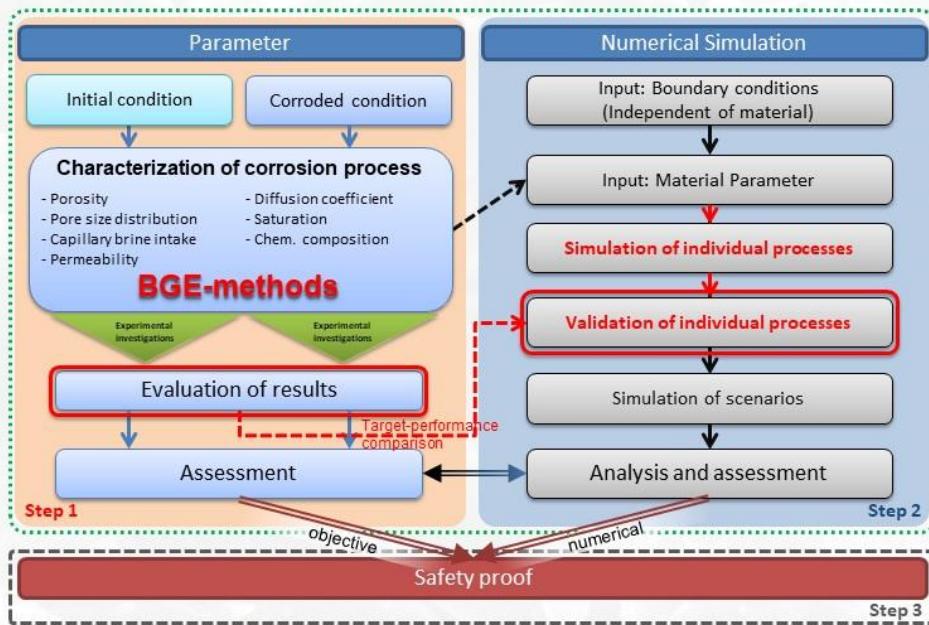
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# Long term safety analysis



5

## Evaluation of drift seal materials taking into account corrosion



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# Why can corrosion be important?

## 1. Homogenous corrosion

- No preferred flow path

- Plane corrosion

⇒ Slow, no issue

## 2. Local corrosion

- Preferred flow path (EDZ)

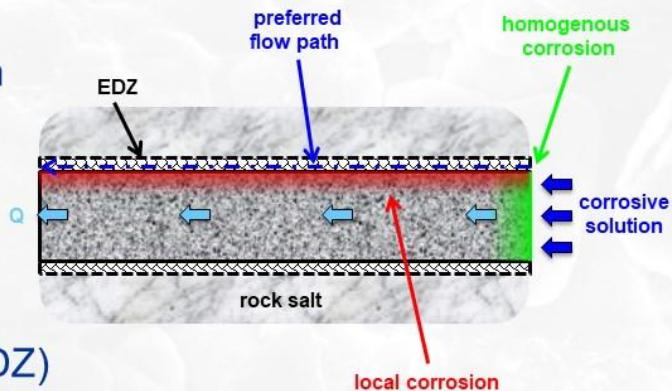
- Mass transport is deciding, not flow rate

- Higher permeability + lower porosity

- Much higher flow velocity

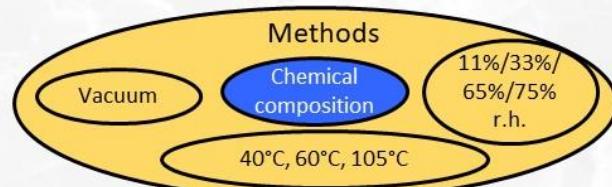
- Process can be exponential

⇒ Reality: Mixture of both concepts

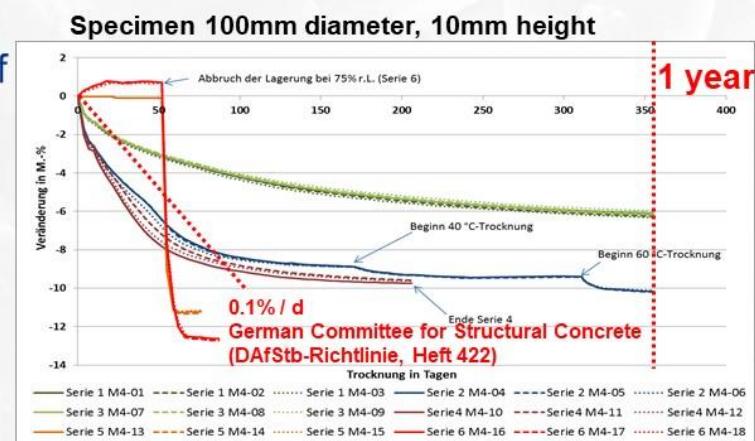


7

# Sample preparation: Drying



⇒ Development of methods  
⇒ Additional measurements



8

# 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

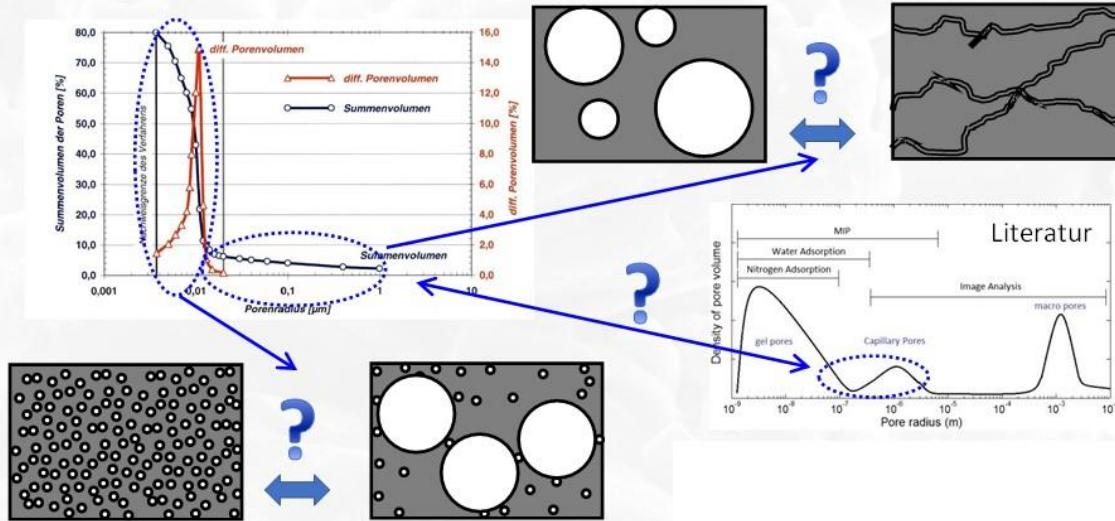
⇒ Plausibility check

⇒ Validation/cross check

⇒ Measurements are really substantial and complex

9

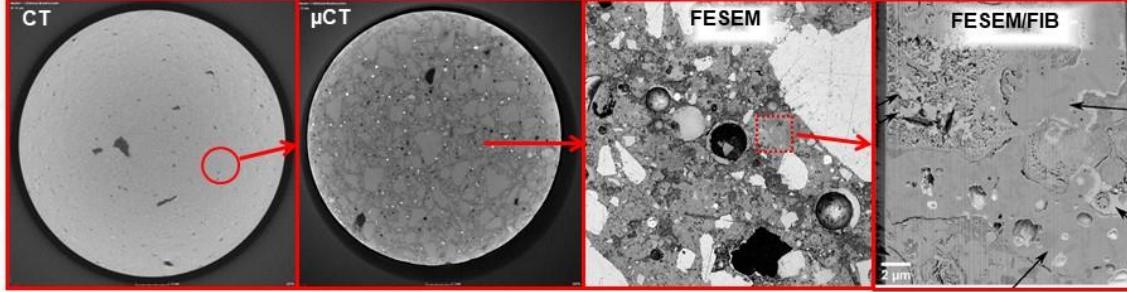
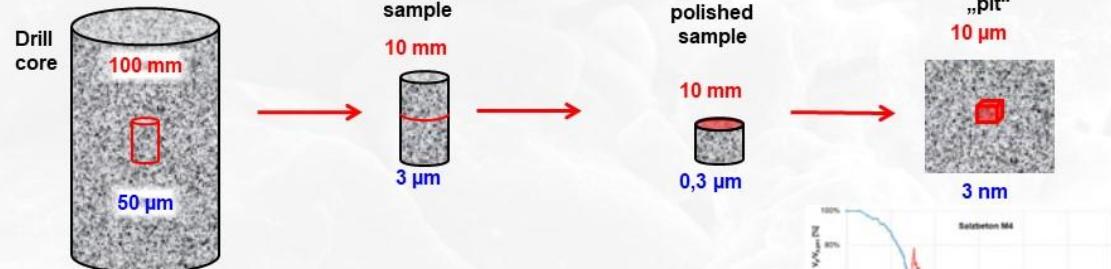
## Structure analysis - Background



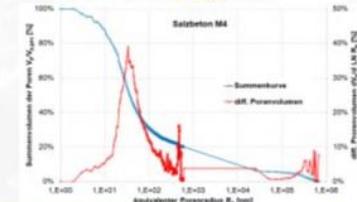
- Goal: Visualization of structure from nm to mm
- Not possible with one method

10

## Structure analysis - Procedure

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



11

## 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 ✓

12

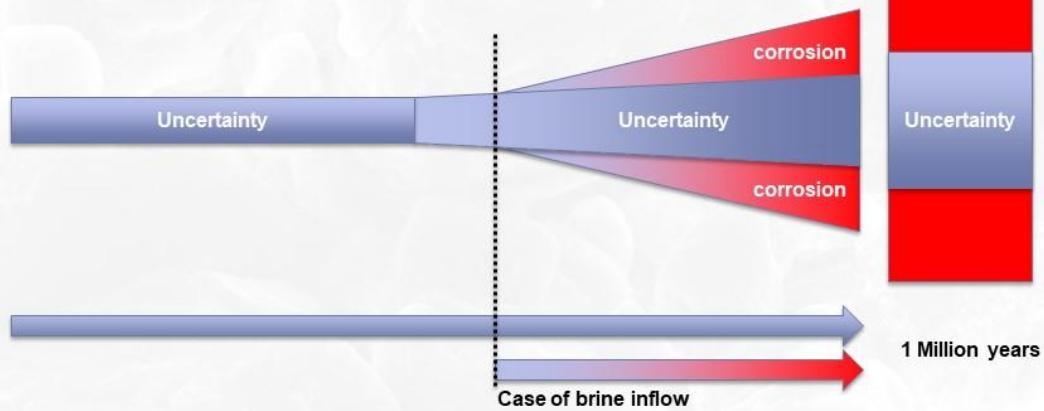
# Long term safety analysis with corrosion effects



Construction stages

Structural integrity and functionality

Long term safety analysis ERAM



⇒ Corrosion increases uncertainty of prognosis

13

# Long term safety analysis without corrosion effects



Construction stages

Structural integrity and functionality

Long term safety analysis ERAM



⇒ 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

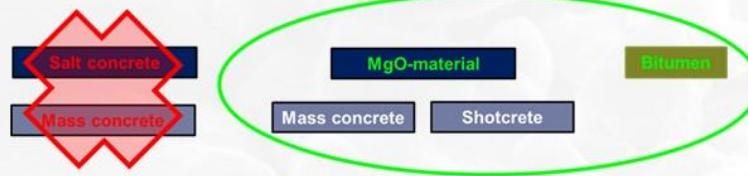
14

# Selected materials for drift seals



Current knowledge:

- Solution composition at sealing sites:  
⇒ MgCl<sub>2</sub>-concentration content at all sites
- Stability of MgO-Phases  
⇒ Stable even at low concentration of Mg<sup>2+</sup> ( $\geq 0.5 \pm 0.6$  molal)  
⇒ 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")

15



Thank you for listening

16





## 11<sup>th</sup> 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 8<sup>th</sup>, 2021

### ELSA - a joint project of:



- Prof. Wolfram Kudla
- Jan Aurich



TU Bergakademie Freiberg

Institute of Mining and Special Civil Engineering

- Philipp Herold



BGE TECHNOLOGY GmbH

Department Research and Development

- Coordination



Karlsruhe Institute of Technology (KIT)

Project Management Agency Karlsruhe (PTKA)

- Funding



Bundesministerium  
für Wirtschaft  
und Energie

Federal Ministry for Economic Affairs  
and Energy (BMWi)



# 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

## 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

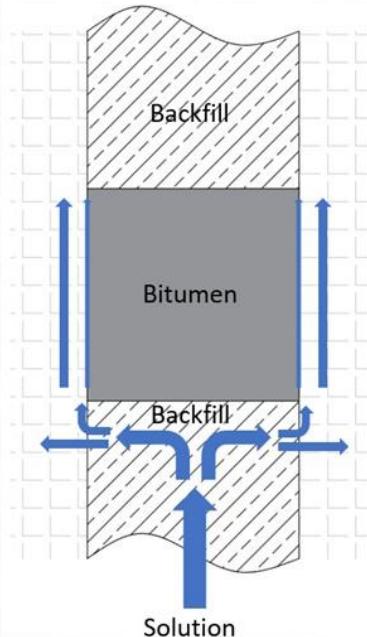
# Experimental objectives



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.

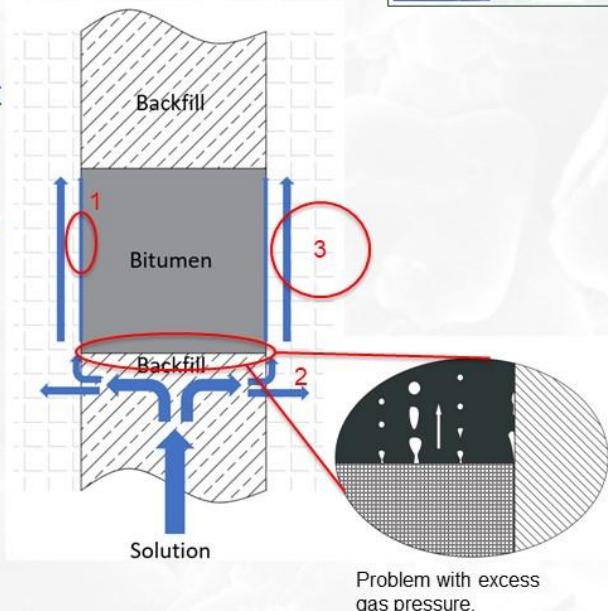


# Experimental objectives



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

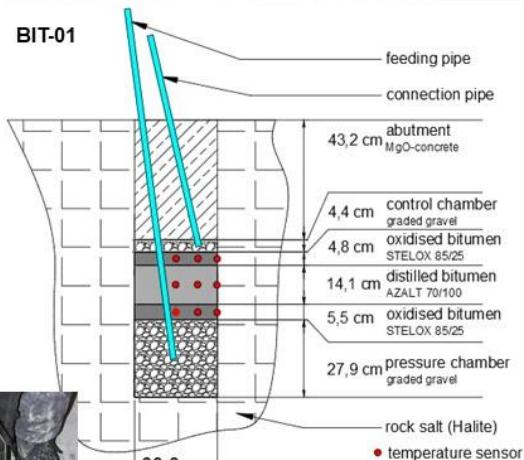


# Experimental setup



## 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

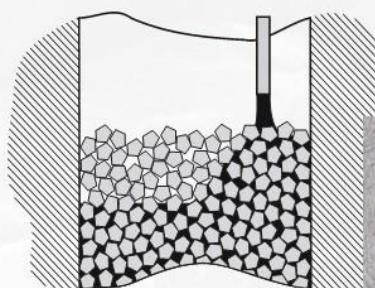
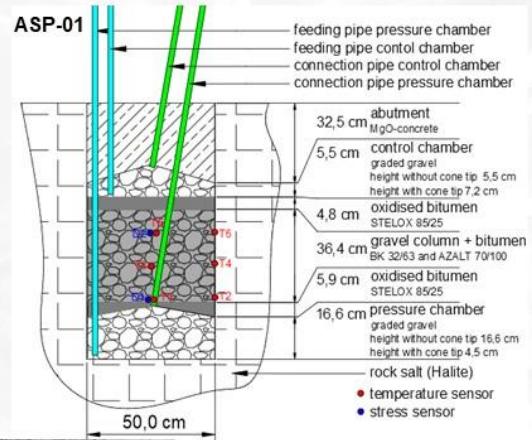


# Experimental setup



## Basic concept gravel column filled with bitumen

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

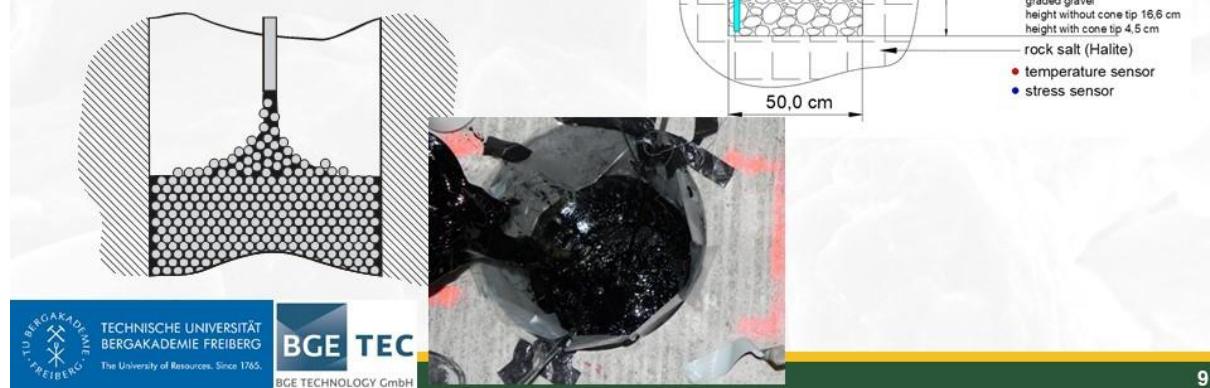


# Experimental setup



## 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)



# Overview of in-situ trials

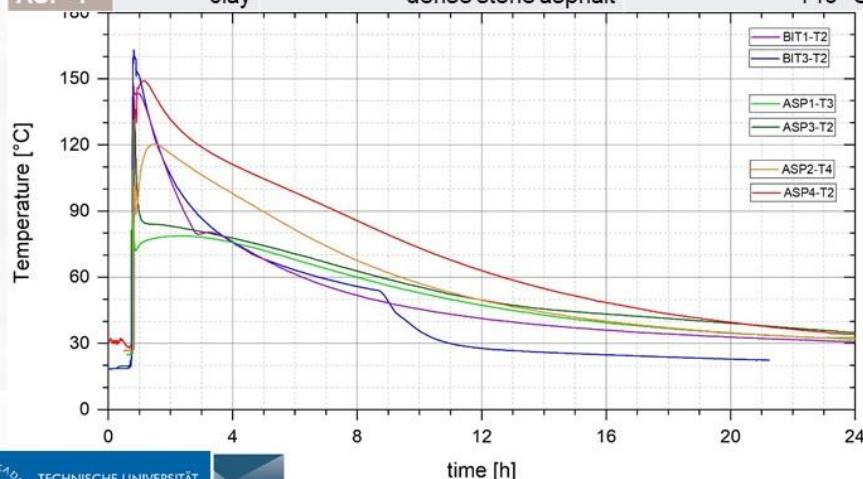


Name	Material	Test site	Investigations
<b>BIT-01</b>	core: AZALT 70/100 shell: STELOX 85/25		<ul style="list-style-type: none"> <li>• temperature</li> <li>• gas permeability</li> <li>• dismantling</li> </ul>
<b>BIT-02</b>	core: AZALT 70/100 shell: STELOX 85/25		<ul style="list-style-type: none"> <li>• gas permeability</li> <li>• fluid permeability</li> <li>• dismantling</li> </ul>
<b>ASP-01</b>	core: gravel column filled with AZALT 70/100 shell: STELOX 85/25	Test site rock salt (Sondershausen mine)	<ul style="list-style-type: none"> <li>• temperature</li> <li>• pressure</li> <li>• gas permeability</li> </ul>
<b>ASP-02</b>	core: dense stone asphalt with AZALT 70/100 and rounded basalt gravel "Saxorund 20/40" shell: STELOX 85/25	Test site rock salt (Sondershausen mine)	<ul style="list-style-type: none"> <li>• temperature</li> <li>• pressure</li> <li>• gas permeability</li> </ul>
<b>BIT-03</b>	core: AZALT 70/100 shell: STELOX 85/25		<ul style="list-style-type: none"> <li>• temperature</li> <li>• gas permeability</li> <li>• dismantling</li> </ul>
<b>ASP-03</b>	core: gravel column filled with AZALT 70/100 shell: STELOX 85/25	Test site clay (open pit Wiesa)	<ul style="list-style-type: none"> <li>• temperature</li> <li>• gas permeability</li> <li>• dismantling</li> </ul>
<b>ASP-04</b>	core: dense stone asphalt with AZALT 70/100 and rounded basalt gravel "Saxorund 20/40" shell: STELOX 85/25	Test site clay (open pit Wiesa)	<ul style="list-style-type: none"> <li>• temperature</li> <li>• gas permeability</li> <li>• dismantling</li> </ul>

## 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

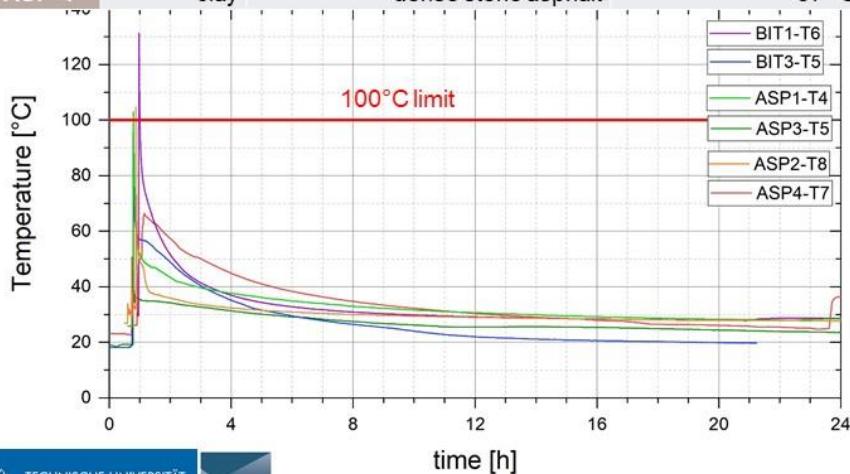


- high temperatures decrease viscosity of bitumen  $\Rightarrow$  enhanced permeation into gaps and voids between gravel grains

## 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



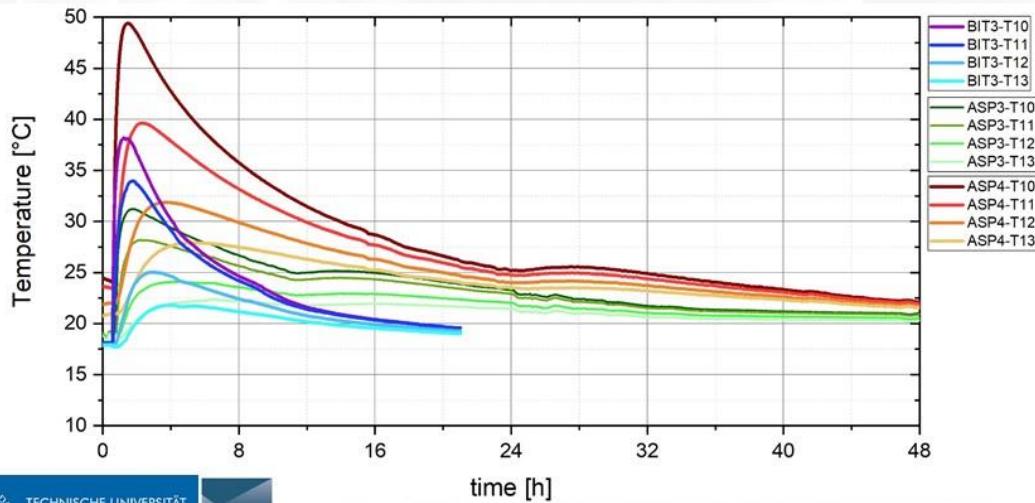
- Max. temperature for a very short time interval
- Experience from first trials led to adjustments on the later trials

# 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



# Results of thermal investigations



Comparison of heat balance:

- Considerably differences of total thermal energy amount  $\Delta Q$  between pure bitumen, bitumen filled gravel column and dense stone asphalt
- Approx. same relative thermal energy input ( $\Delta Q$  / lateral surface) into host rock resp. contour by comparison of pure bitumen and bitumen filled gravel column
- Higher relative thermal energy input ( $\Delta Q$  / 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 $\Delta Q$	$\Delta Q$ / lateral surface
	[kg]	[kg]	[°C]	[°C]	[kJ]	[kJ/m <sup>2</sup> ]
<b>BIT-1</b>	10.2	-	143	27	2,130	16,148
<b>BIT-3</b>	15.5	-	163	18	4,046	20,942
<b>ASP-1</b>	24.1	96.0	170	25	6,290	13,953
<b>ASP-2</b>	26.3	138.8	140	27	15,732	27,820
<b>ASP-3</b>	28.6	94.9	171	20	7,773	16,440
<b>ASP-4</b>	24.9	112.5	168	23	16,357	36,666

# Results of pressurization



- Pressurization with compressed air (dotted with FREON) and saline solution (NaCl saturated)
- No detection of FREON gas on test sides within control chambers  $\Rightarrow$  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	$3 \cdot 10^{-21} \text{ m}^2$	
		doped compressed air	1.05 MPa	$2 \cdot 10^{-20} \text{ m}^2$	
BIT-02	rock salt	doped compressed air	1.05 MPa	$6 \cdot 10^{-20} \text{ m}^2$	
		saline solution	1.20 MPa	$1 \cdot 10^{-20} \text{ m}^2$	
BIT-03	clay		-	-	not performed
ASP-01	rock salt	doped compressed air	0.20 MPa	$4 \cdot 10^{-20} \text{ m}^2$	
ASP-02	rock salt	doped compressed air	0.23 MPa	$3 \cdot 10^{-19} \text{ m}^2$	
ASP-03	clay	doped compressed air	0.15 MPa	$1.5 \cdot 10^{-14} \text{ m}^2$	
ASP-04	clay	doped compressed air	0.15 MPa	-	pressure buildup not possible
Natural gas permeability at test side – rock salt				$1 \cdot 10^{-21} \text{ m}^2$	
Natural gas permeability at test side – clay				ca. $1 \cdot 10^{-17} \text{ m}^2$	

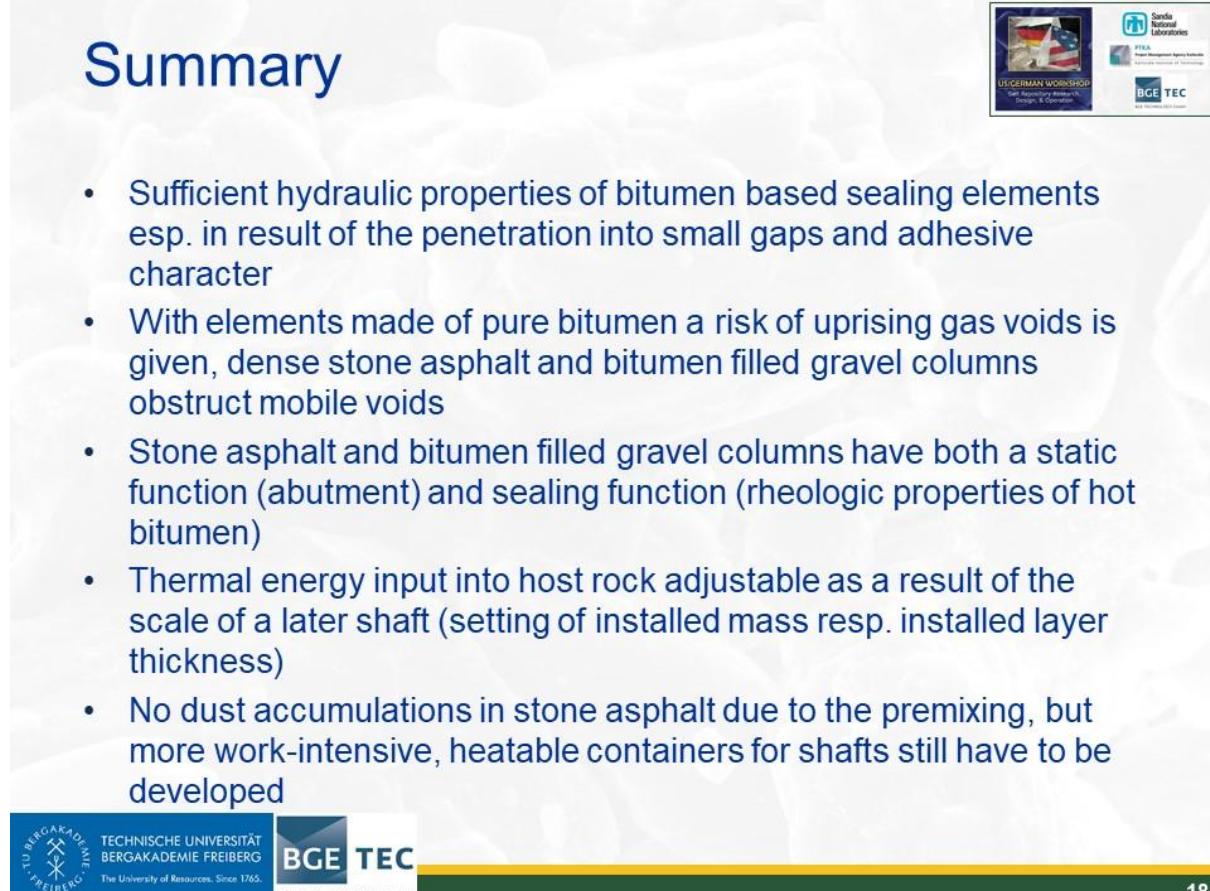
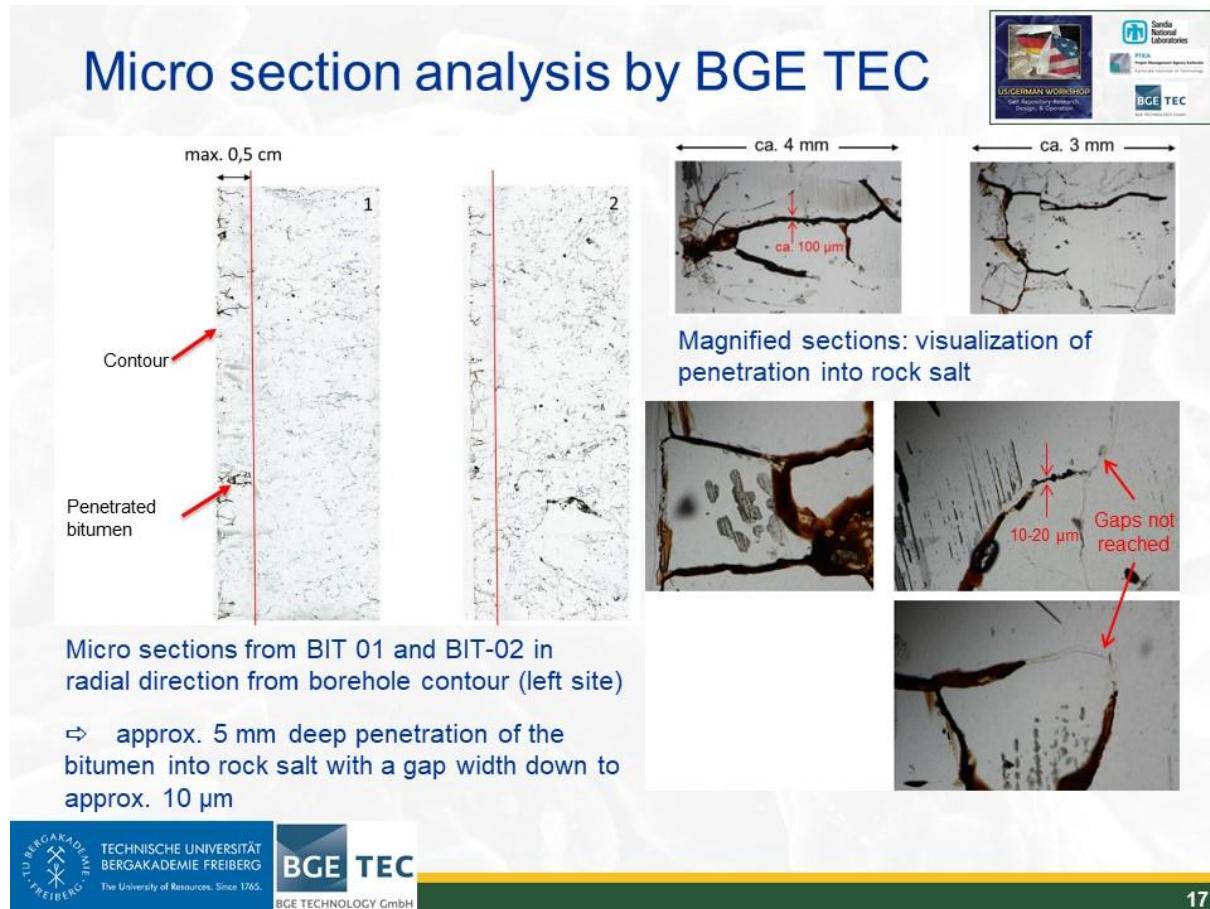
# Dismantling of trials



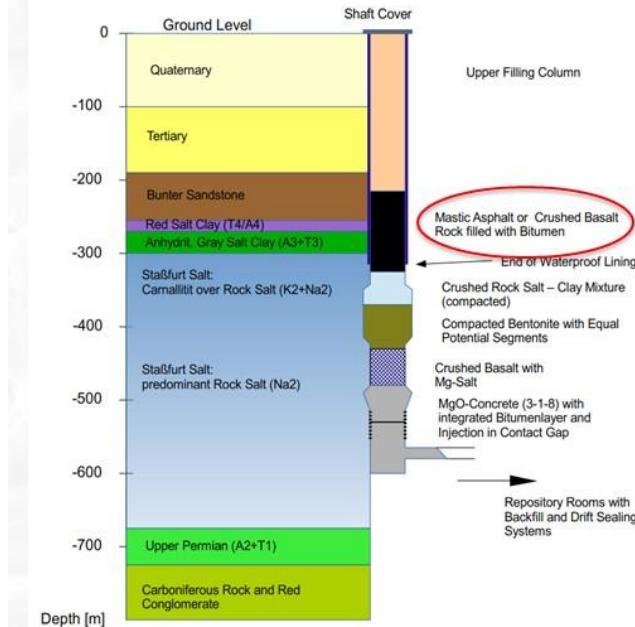
## Results and observations:

- 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)  
 $\Rightarrow$  Obstruction of transport through EDZ and contact gap between sealing element and host rock





# 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



19

Many thanks and Glückauf!



20



## Investigation of T-H-M-C processes on sealing systems in rock salt



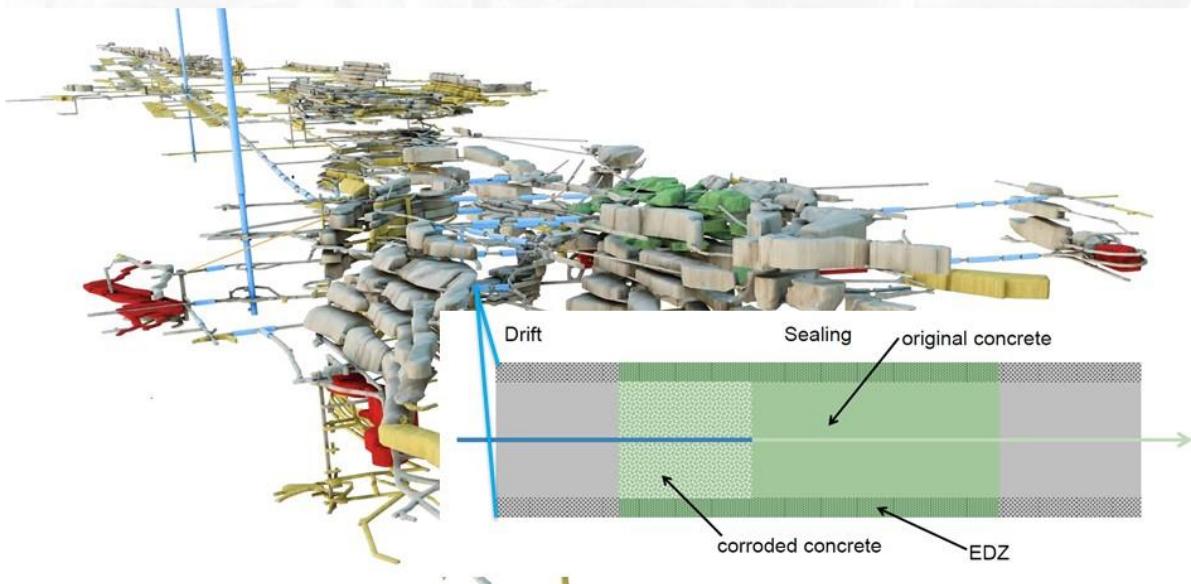
Thorsten Meyer  
GRS

EBS, Materials and Backfilling  
8th September, 2021

### Morsleben



#### ▪ ERAM – Sealing locations (BfS 2015)

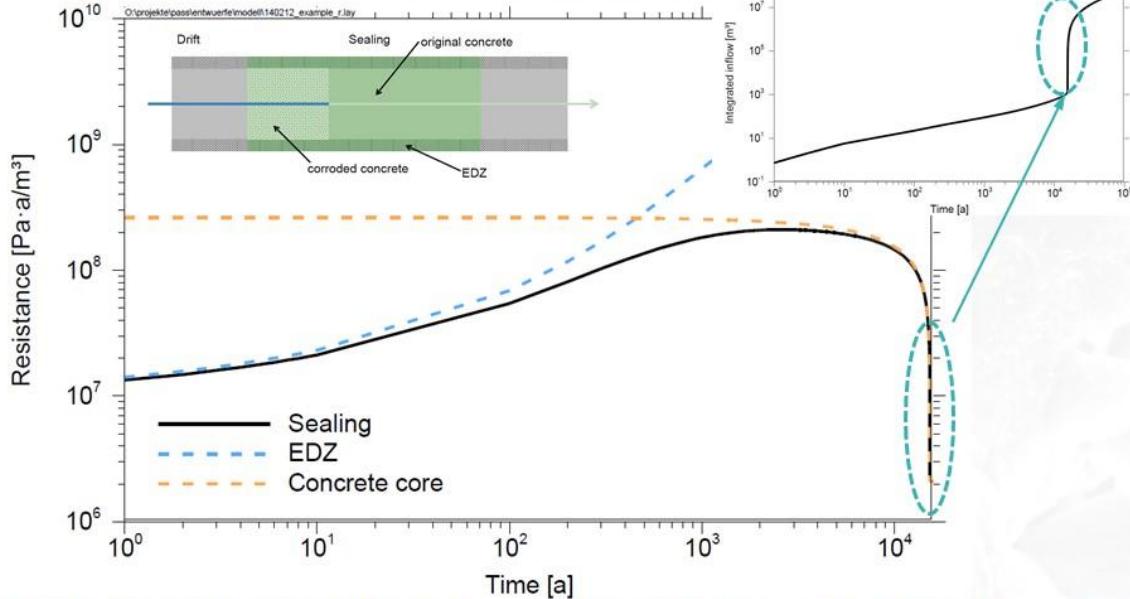


2

# 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

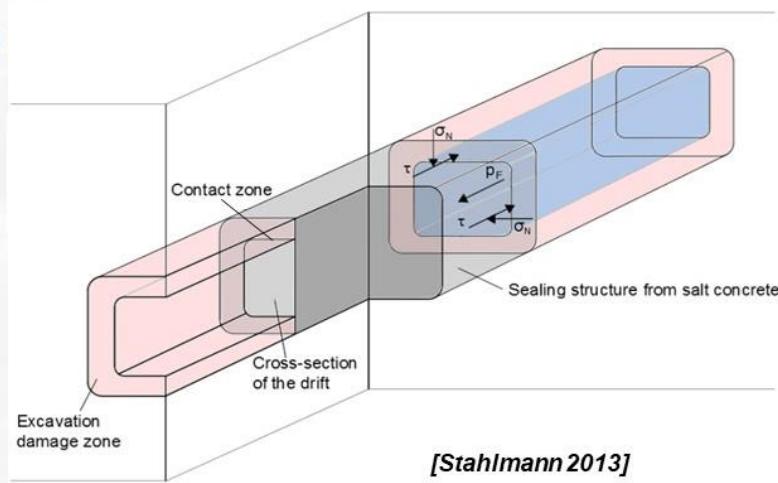
3

## Motivation / Objectives



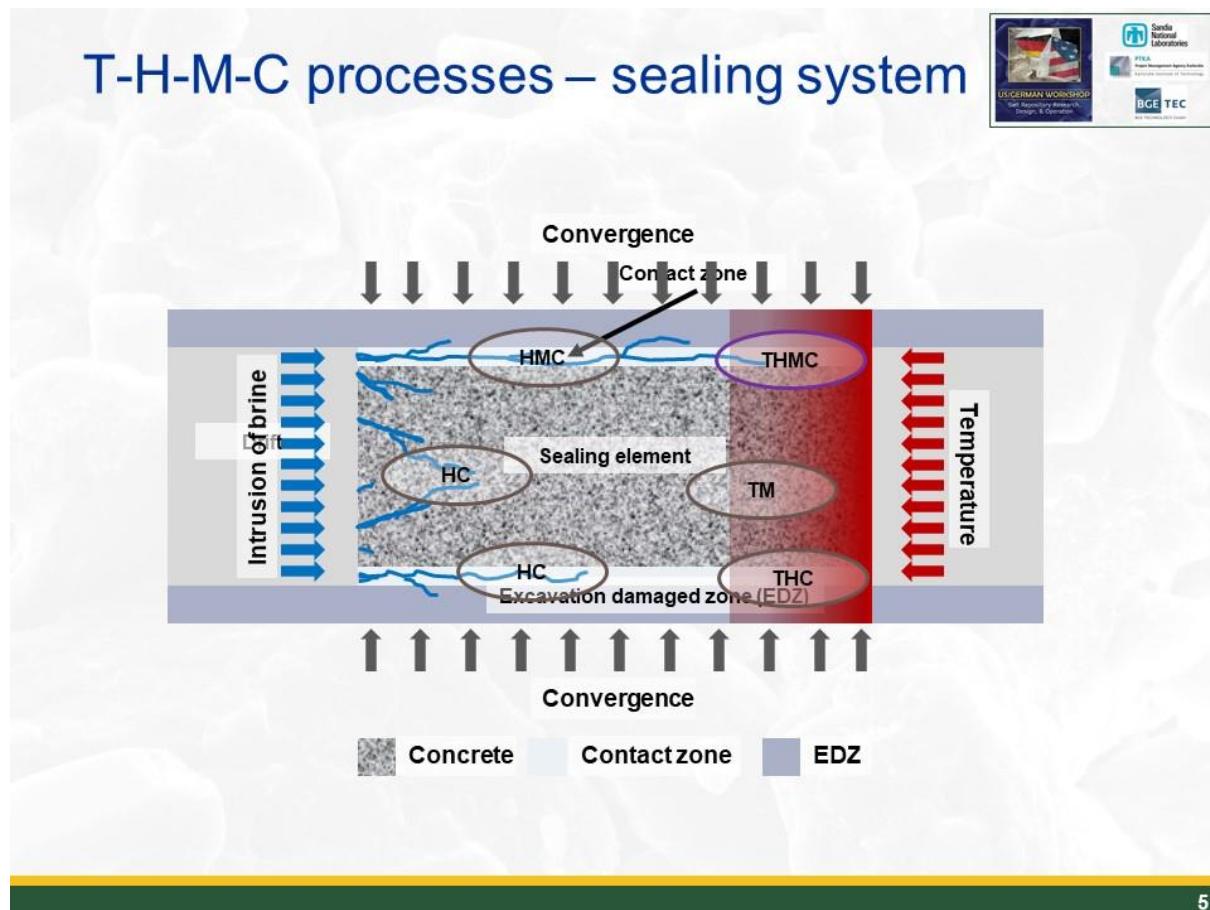
### Assessment of the sealing system

- excavation damage zone
- sealing material
- contact seam

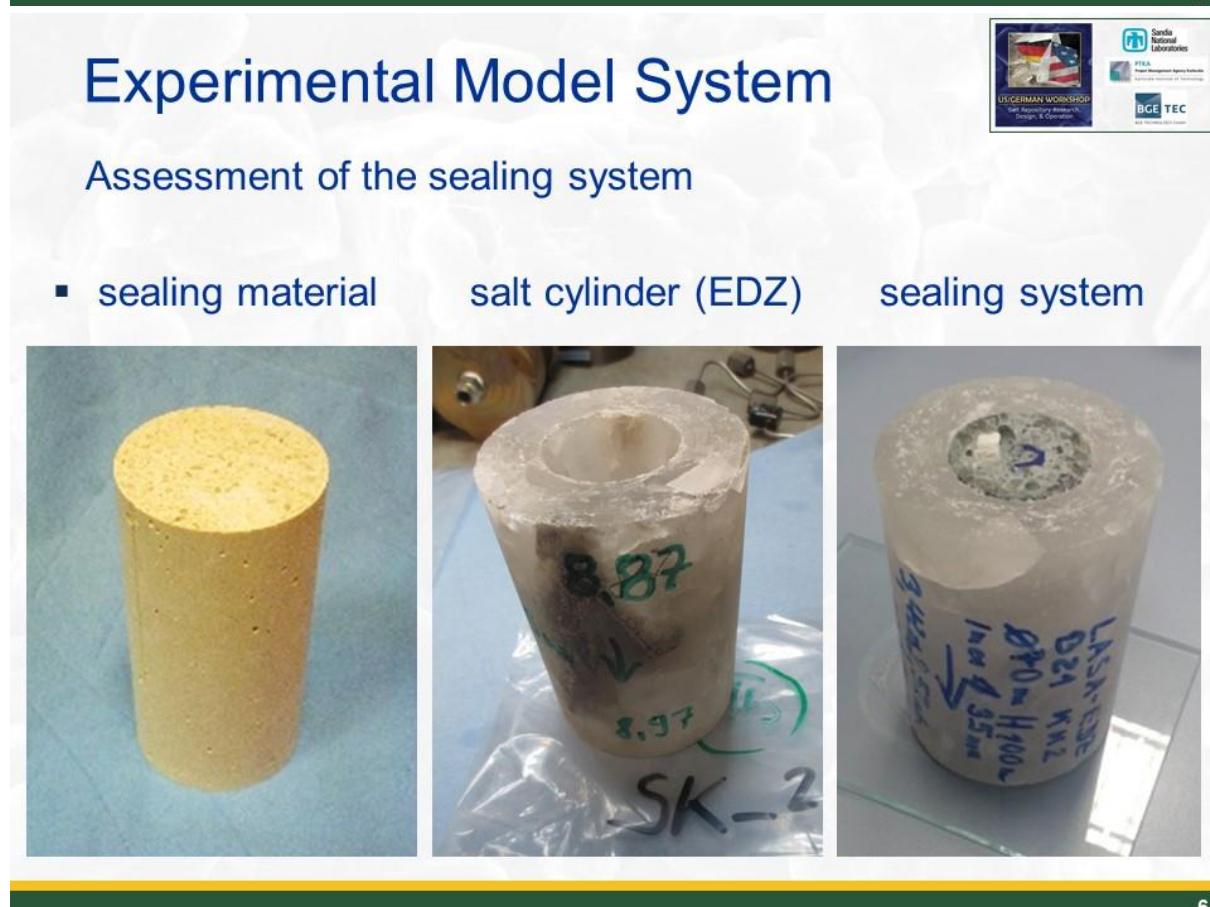


[Stahlmann 2013]

4

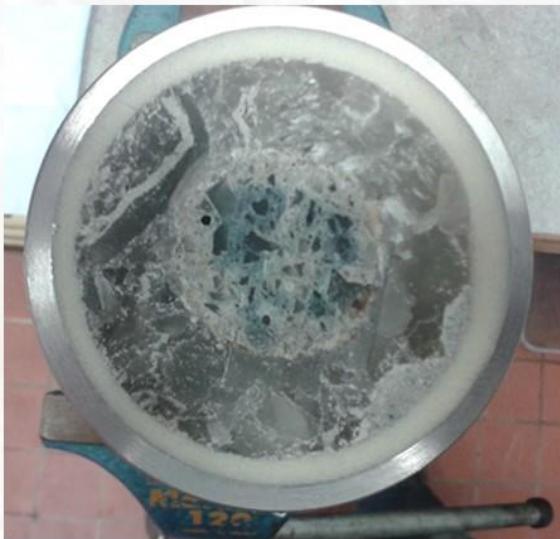


5



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



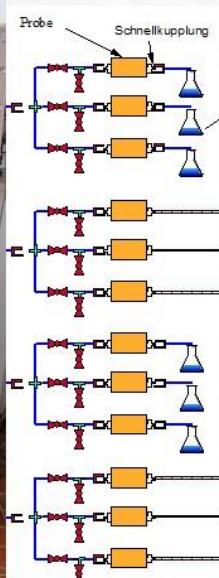
Sorel concrete A1 (318-Rezeptur)		Sorel concrete D4 (518-Rezeptur)	
11,3 wt% MgO (reactivity 200 – 250 sec)		15,95 Ma-% MgO (reactivity 200 ± 50 sec)	
63,7 wt% crushed salt (4 mm)		68,1 Ma-% gravel /sand (0–8 mm)	
25,0 wt% MgCl <sub>2</sub> solution (4-5 molal)		15,95 Ma-% MgCl <sub>2</sub> solution (5 molal)	

In-situ samples  
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



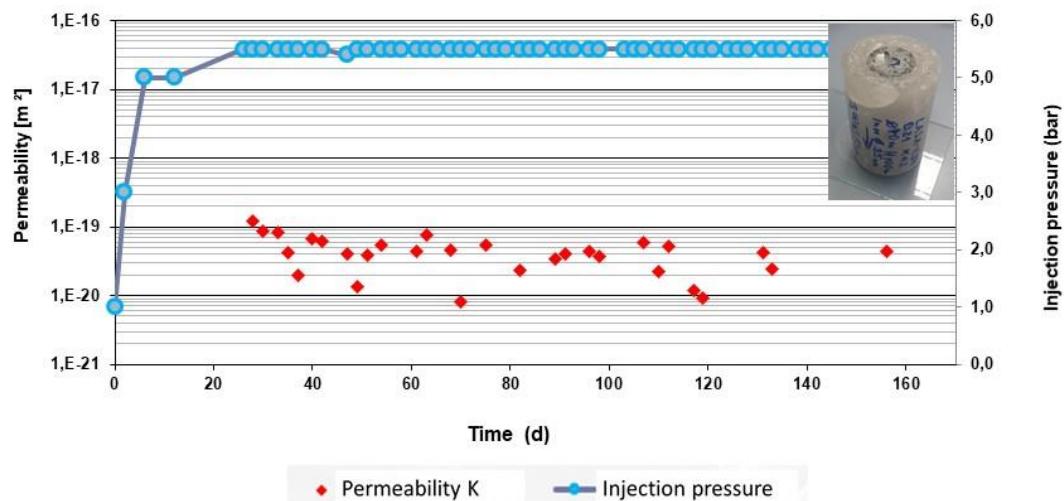
- permeability measurement - no confining pres.
- advection cells
- fluids: NaCl, IP21 (Q-TEC 4.0)
- $P_{\text{Solution}}$  up to 2 MPa
- $T = 25^\circ \text{ C}$
- monolithic samples (sealing material)
- combined samples (sealing system)

9

# HC - Investigations



- Salt concrete (M2\_KP\_6) / NaCl solution

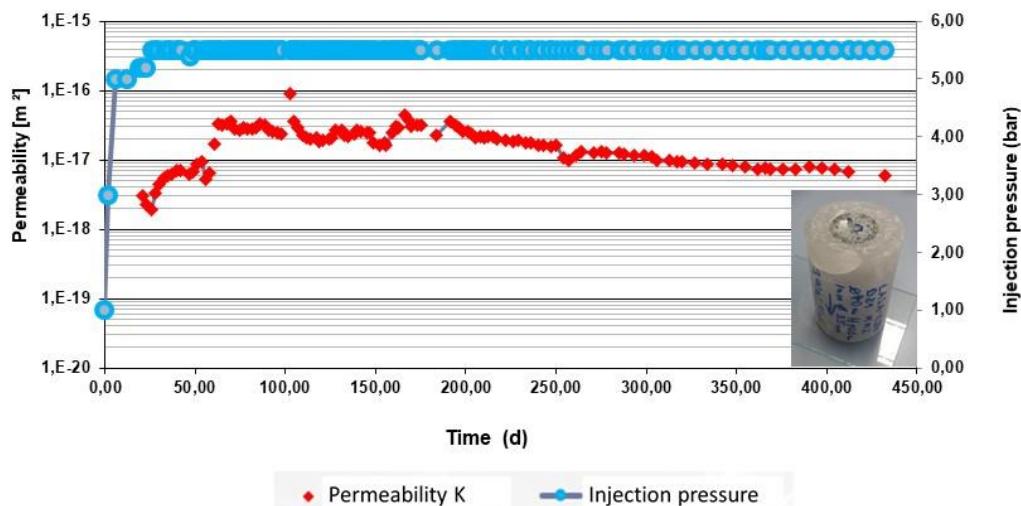


10

## HC - Investigations



- Salt concrete (M2\_KP\_7) / IP21 solution



11

## THC - Investigations



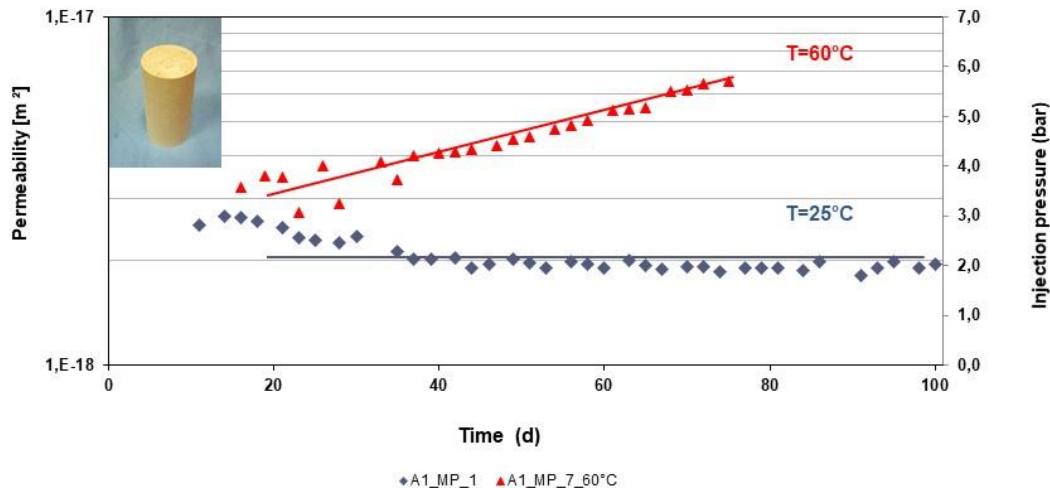
- advection cells
- permeability measurement
- no confining pressure
- $P_{\text{Solution}}$  up to 2 MPa
- $T = 60^\circ \text{ C}$
- monolithic sample (sealing material)
- combined samples (sealing system)

12

# THC - Investigations



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

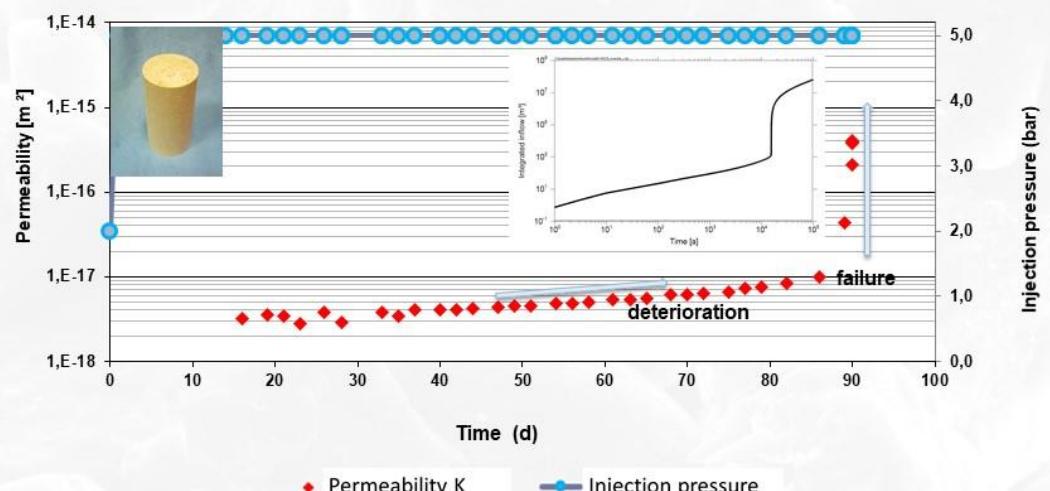


13

# THC - Investigations



- Sorel concrete A1 at 60° / NaCl solution



14

## THC - Investigations



15

## THC - Investigations

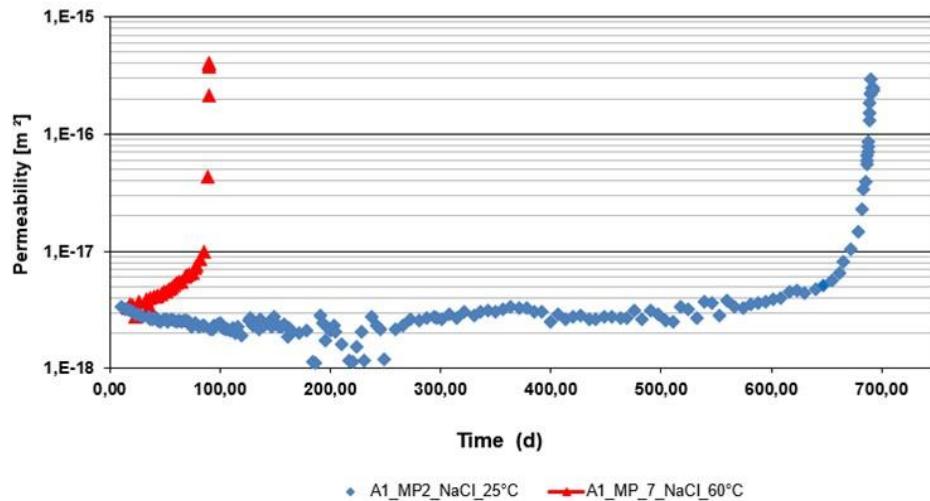


16

# THC - Investigations



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

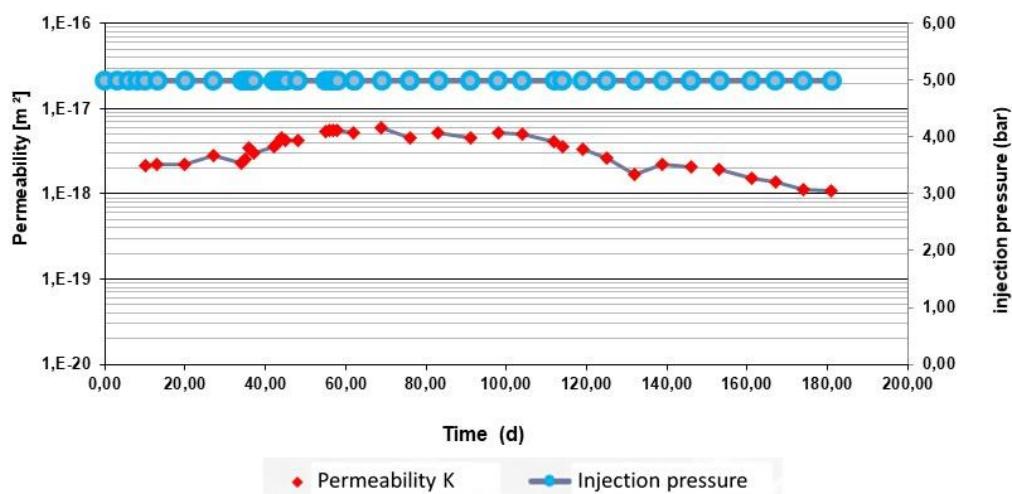


17

# THC - Investigations



- Salt concrete (M2\_KP\_11) at 60°C



18

# HMC - Investigations



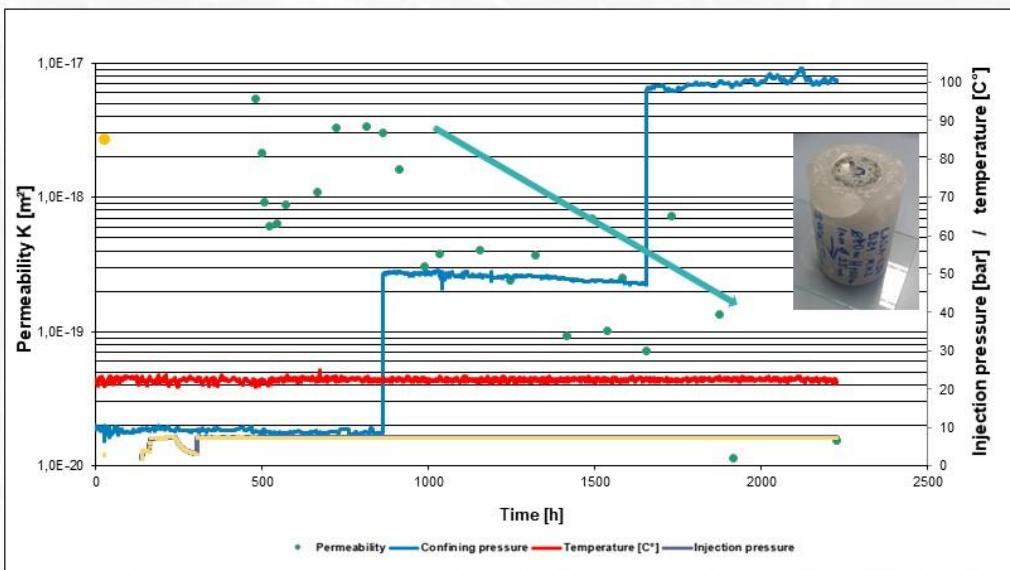
- permeability measurements
- autoclaves
- confining pressure
- $P_{\text{conf}}$  up to 10 MPa
- $T = 25^\circ \text{ C}$
- monolithic sample (sealing material)
- combined samples (sealing system)

19

# HMC - Investigations



- Salt concrete M2 (M2\_KP\_4) / IP21

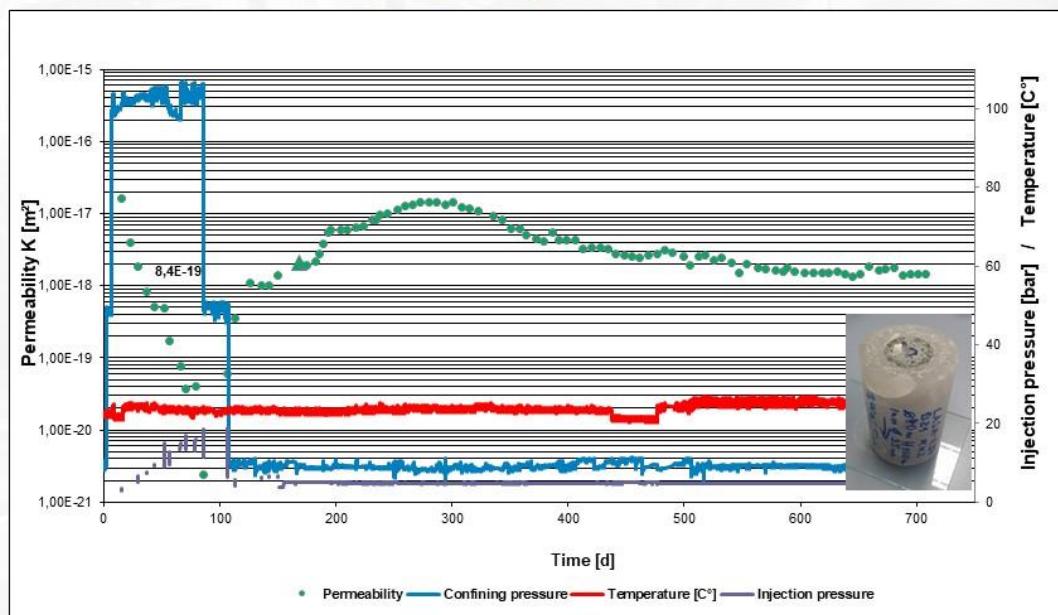


20

## HMC - Investigations

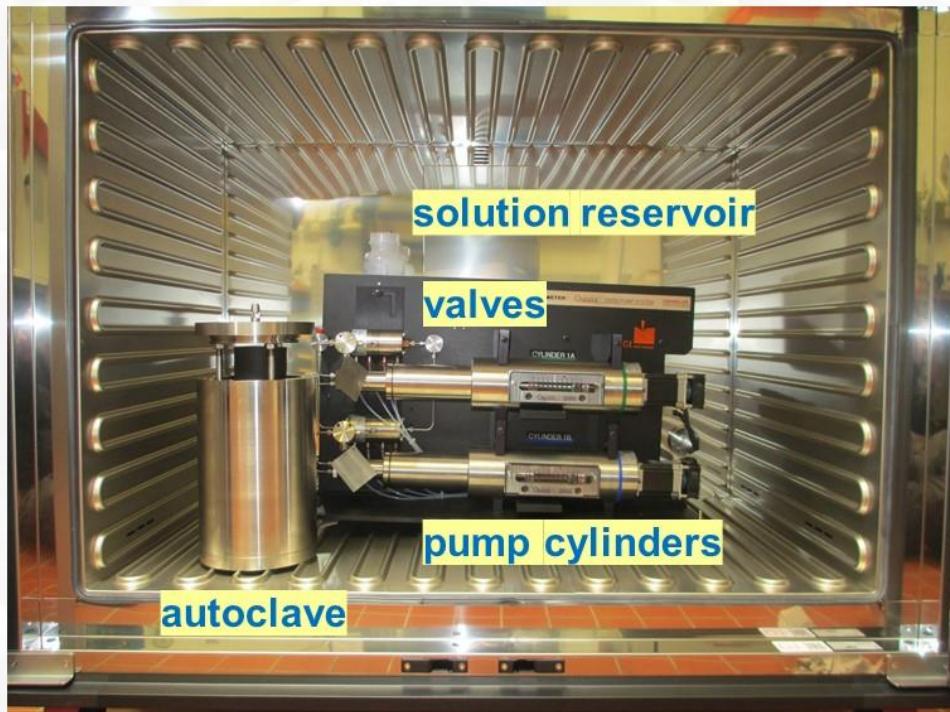


- Sorel concrete A1 (A1\_KP8) / IP21



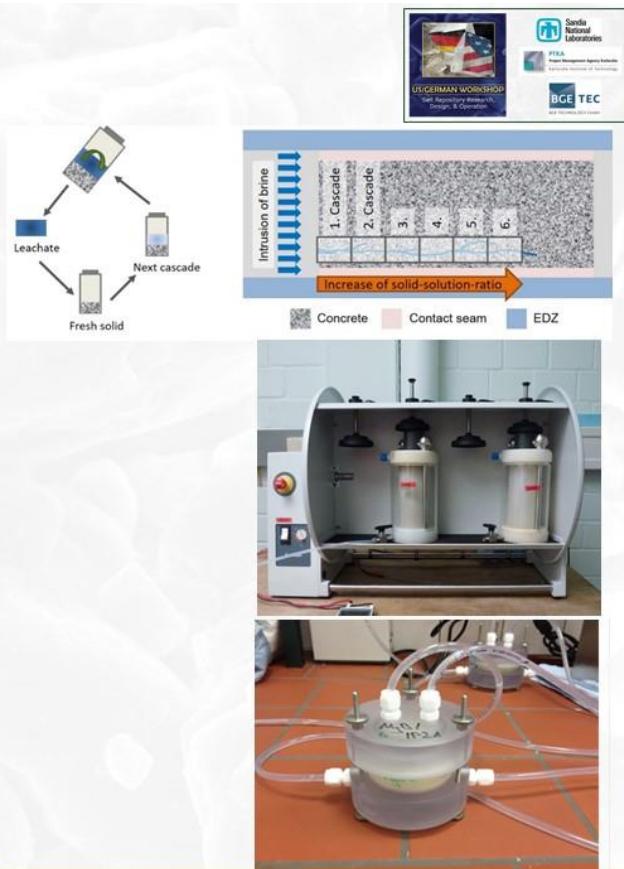
21

## THMC - Investigations



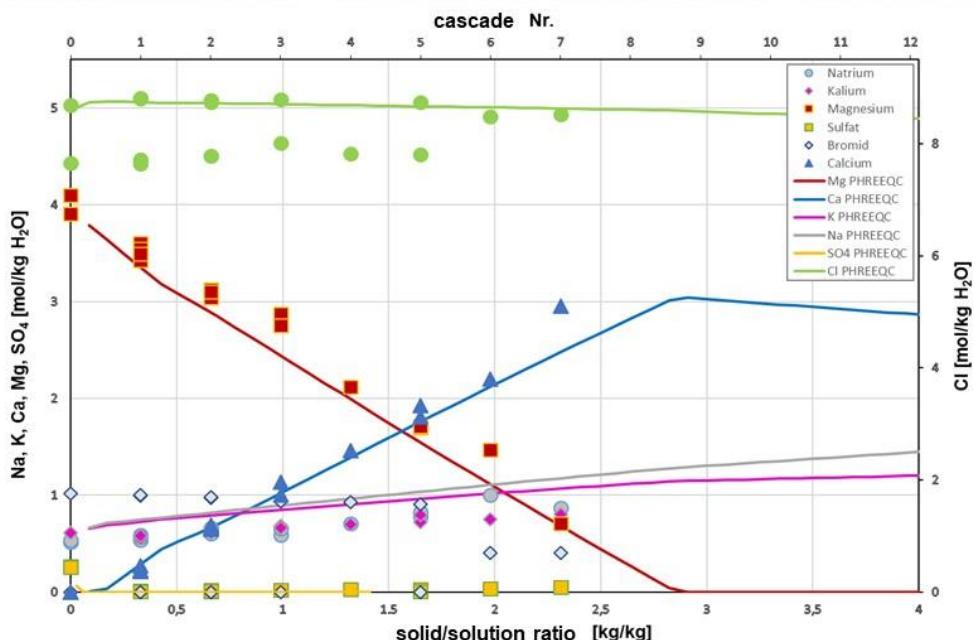
## C - Investigations

- **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

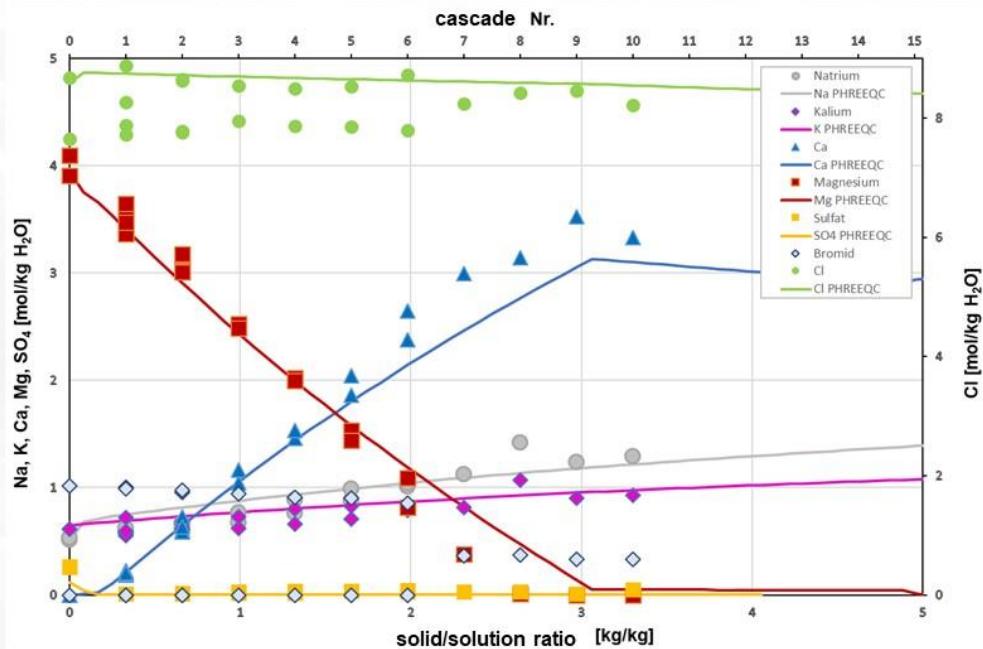
- Salt concrete M2 / Q-TEC 4.0 (reference solution)



## C – Cascade Experiments



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



25

## Summary



- Results of T-H-M-C investigations
  - C-experiments
    - geochemical milieu
      - 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
    - kinetic aspects
    - Comparison of THC and long-term experiments

26

# 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

27

## 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



BUNDESGESELLSCHAFT  
FÜR ENDLAGERUNG

28



## Clay Seam Laboratory Testing

### 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation



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:



on the basis of a decision  
by the German Bundestag

MANAGED BY



**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**



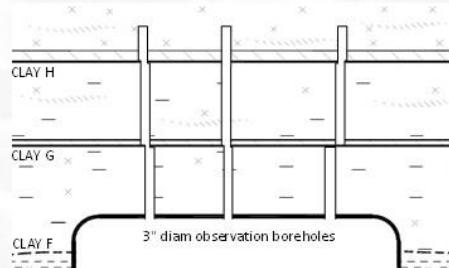
## Pictures of Clay Seams at WIPP



- 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

# Motivation

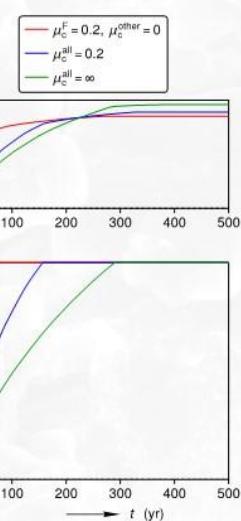
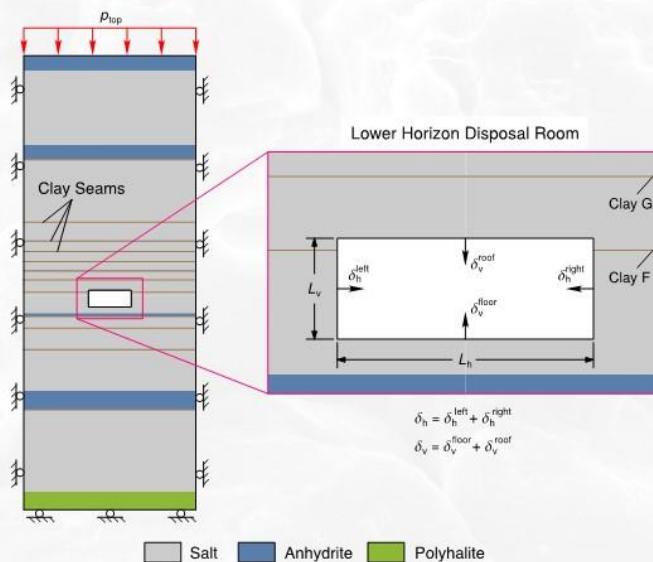
## Interface Sliding



- 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.

5

## 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

## 1<sup>st</sup> series samples



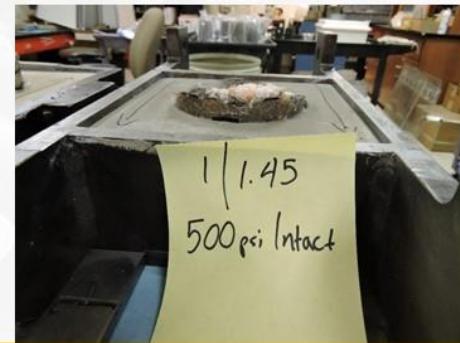
**Salt/clay interface  
Fracture shown is  
typical of all tests**



**Intact test,  
 $\sigma_n = 500$  psi  
(3.4 MPa),  
side view**



**Intact test,  
 $\sigma_n = 1500$  psi  
(10.3 MPa);  
salt crystals  
cross through  
interface**



7

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



### Shear tests of interfaces in salt

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.

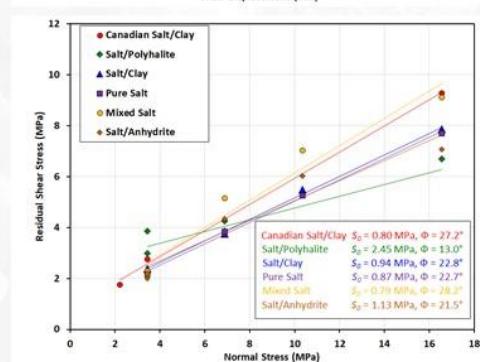
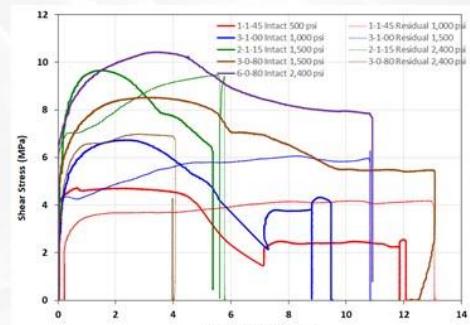
Some repeatability observed in maximum residual shear stress at same normal stress after interface fractured in intact test, fractured samples sheared in residual test.

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 ( $\frac{1}{4}$ ,  $\frac{1}{2}$  inches);
  - 3 different normal pressures of 3.4, 6.8, 10.3 MPa (500, 1000, 1500 psi).



9

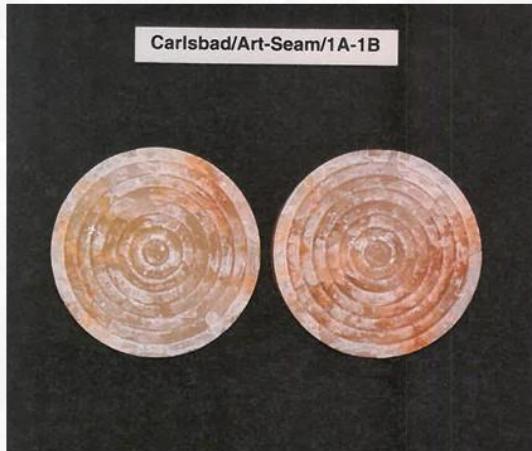
## Artificial clay seam shear tests – Description



- 8 samples total: 4 with seam with pre-consolidation thickness 6 mm ( $\frac{1}{4}$ "), 4 with thickness 12 mm ( $\frac{1}{2}$ ")
- 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 ( $\frac{3}{16}$ "); 6 mm down to 1.6 mm ( $\frac{1}{16}$ ")
- 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

10

# 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 ( $\frac{1}{4}$ " or  $\frac{1}{2}$ ") 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

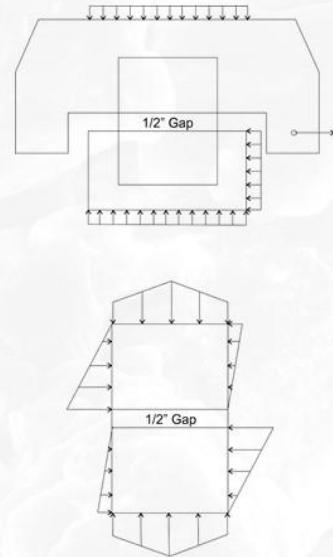
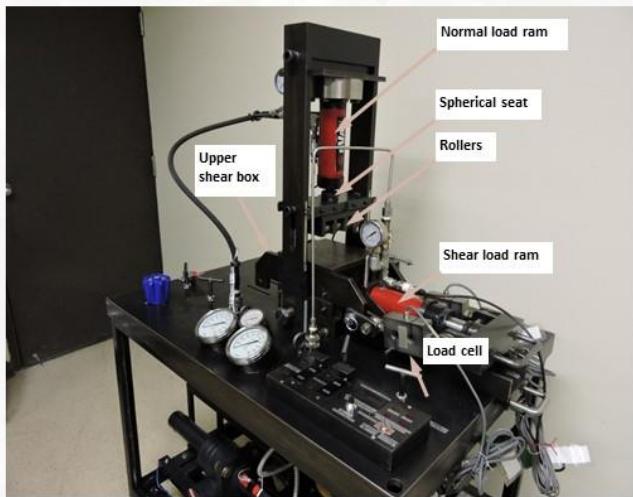


- 4 specimens with initial seam thickness of 6 mm
- 4 specimens with initial seam thickness of 12 mm
- Consolidated
  - 14 days at 20,7 MPa (3000 psi) hydrostatic stress and 21C
  - Excess pore fluid vented
- After consolidation
  - Approximately 1/3 of pre-consolidation thickness
  - Clay hardened
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

Consolidated Seam Thickness

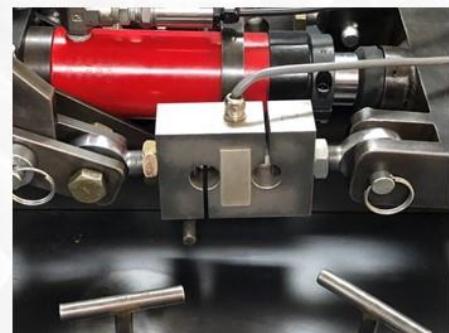
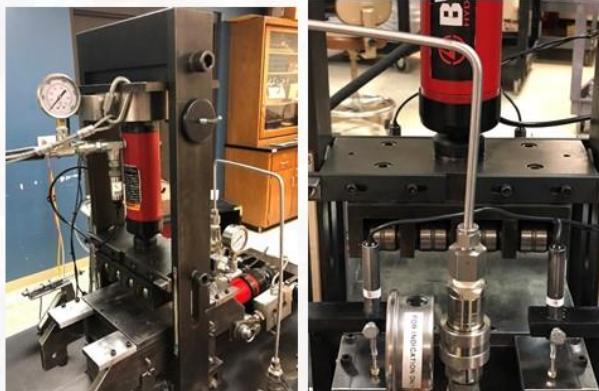


## Direct Shear Test Setup



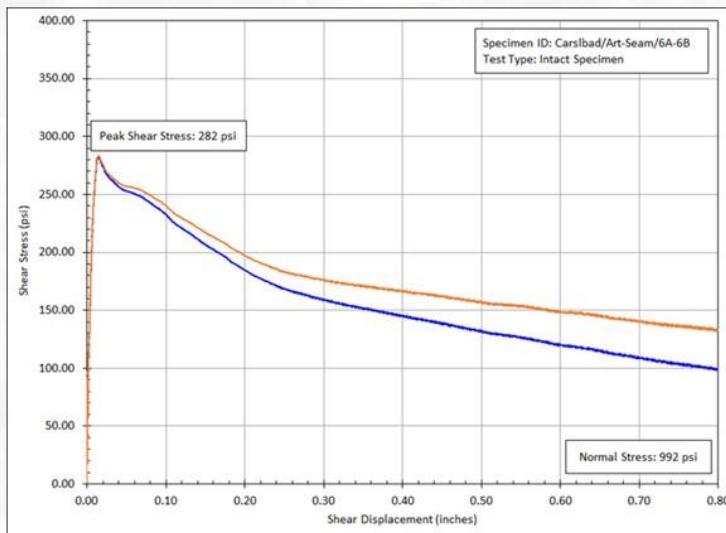
Note: All force profiles depend on contrast in stiffness between the specimen and grout.

## Direct Shear Test Machine



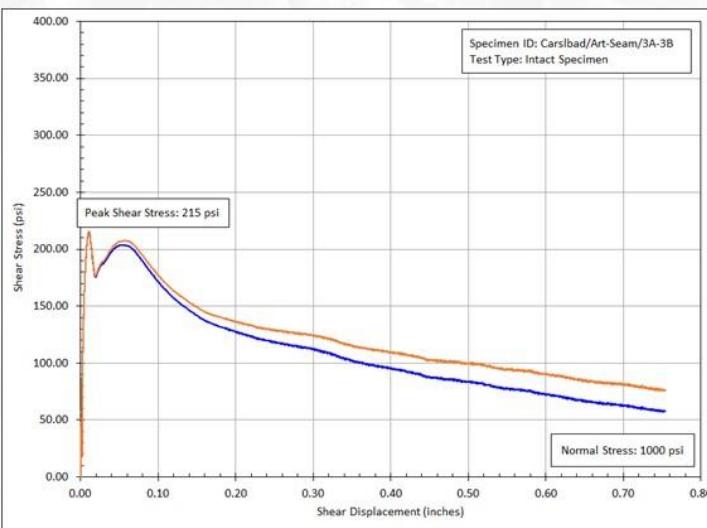
- S-shaped load cell – gaps opened during some tests
- 4 normal displacement gages, average displacement used to calculate stiffness

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



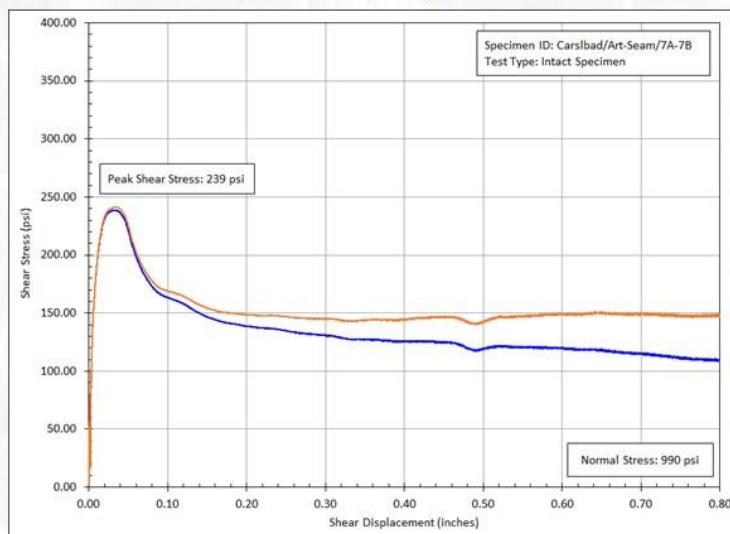
- Blue: Stress calculated with constant contact area
- Orange: Stress calculated with contact area modified by shear displacement
- Actual nominal normal stress = 992 psi (6.84 MPa)
- Peak shear stress = 282 psi (1.94 MPa)
- Never reached residual stress after initiation of shear movement

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



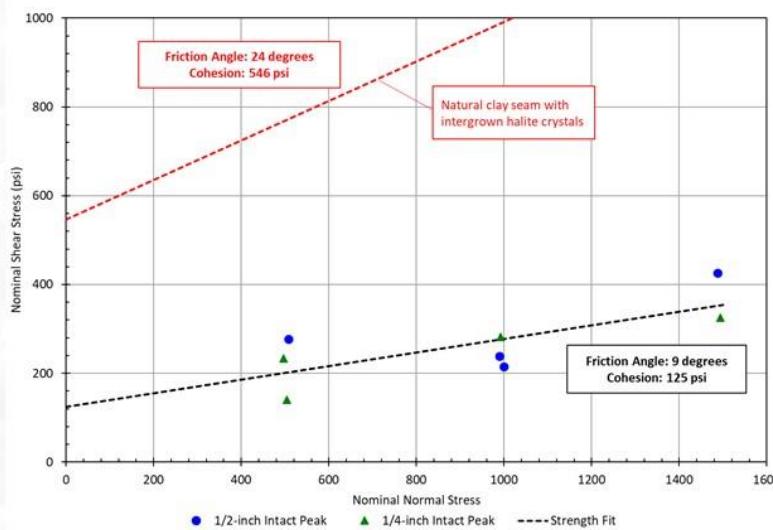
- Blue: Stress calculated with constant contact area
- Orange: Stress calculated with contact area modified by shear displacement
- Actual nominal normal stress = 1000 psi (6.89 MPa)
- Peak shear stress = 215 psi (1.48 MPa)
- Never reached residual stress after initiation of shear movement
- Power-related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

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



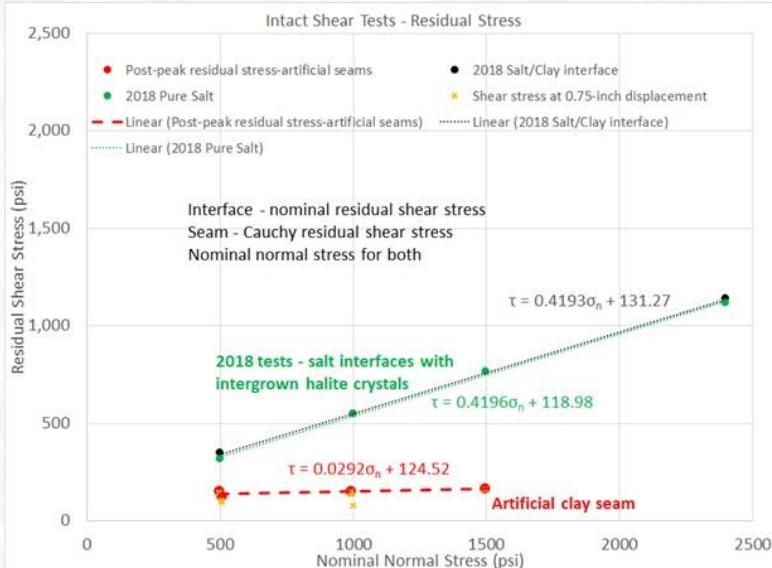
- Repeat of Test #3 due to power-related disturbance near beginning of test
- Actual nominal normal stress = 990 psi (6.83 MPa)
- Peak shear stress = 239 psi (1.65 MPa)
- Reached apparent residual stress of ~150 psi (1.03 MPa) at 0.75" (19 mm) shear displacement after initiation of shear movement
- “Apparent”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

## Intact Peak Stresses



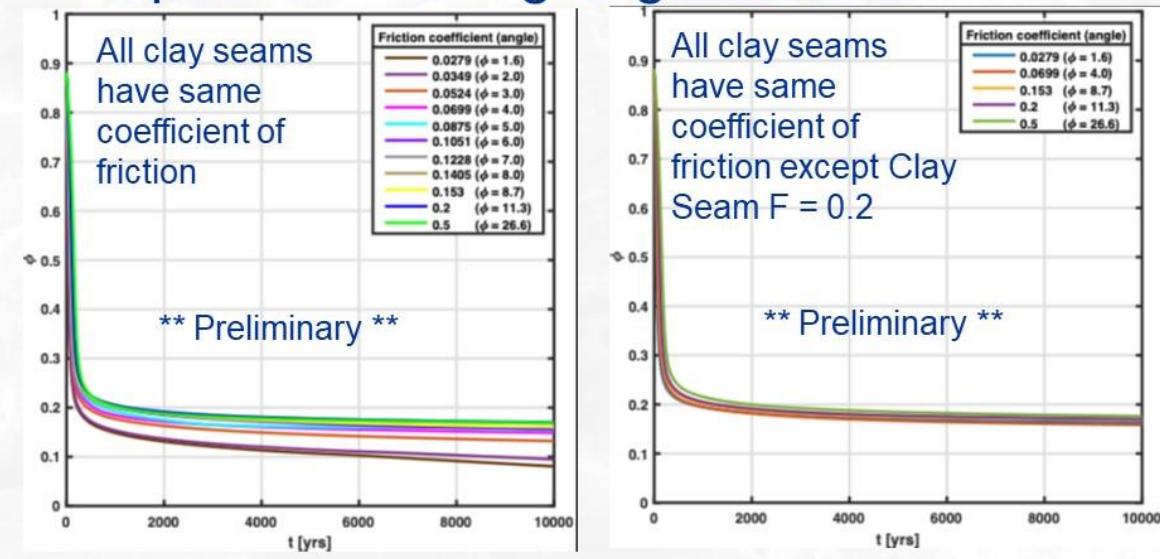
- Average friction angle  $8.7^\circ$ , average cohesion 125 psi (0.86 MPa)
- Much lower than for previous salt interface tests: friction angle 24°, cohesion 546 psi

# Intact shear tests – Residual Stresses



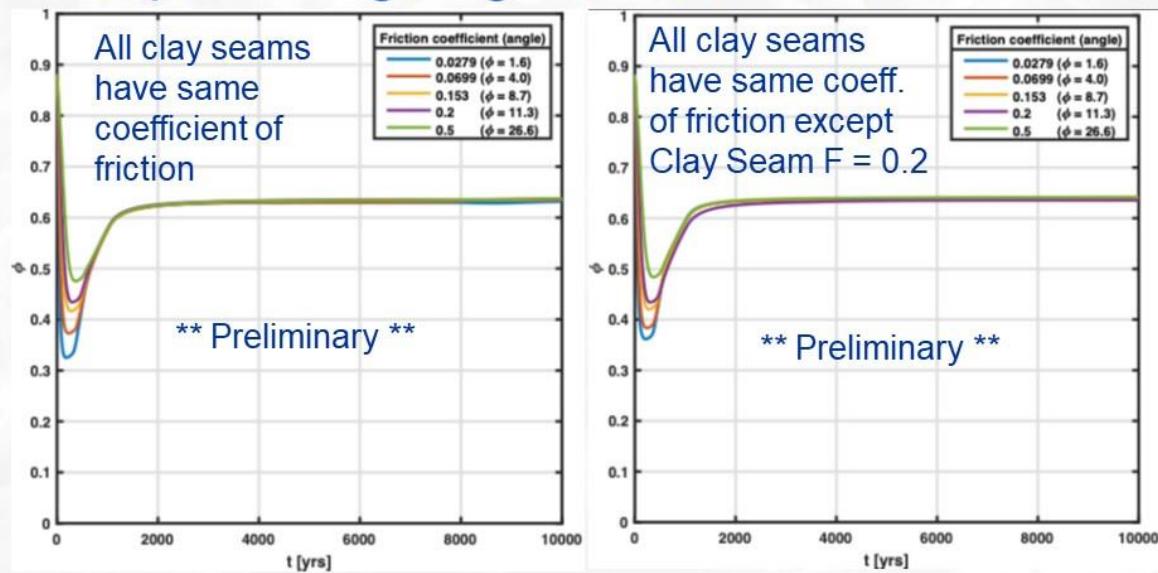
- Only 4 of 8 tests attained apparent residual stresses after initiation of shear displacement
- Friction angle 1.7°, cohesion ~125 psi (0.86 MPa)
- Lower friction angle than for previous salt interface tests: angle 13-23°, cohesion 119-355 psi (0.82-2.45 MPa)
- Values much lower than expected; softness 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.

# 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.

25

## 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.

26

# Questions?



Thank you for your attention!

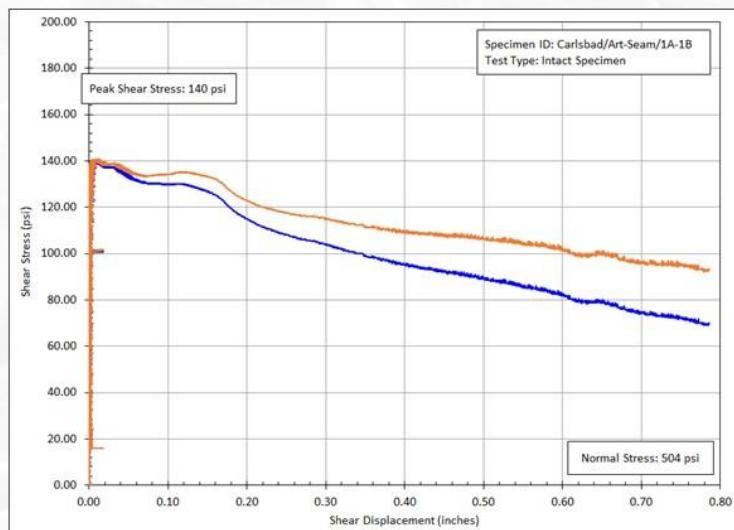
27



Results of the other artificial seam shear tests

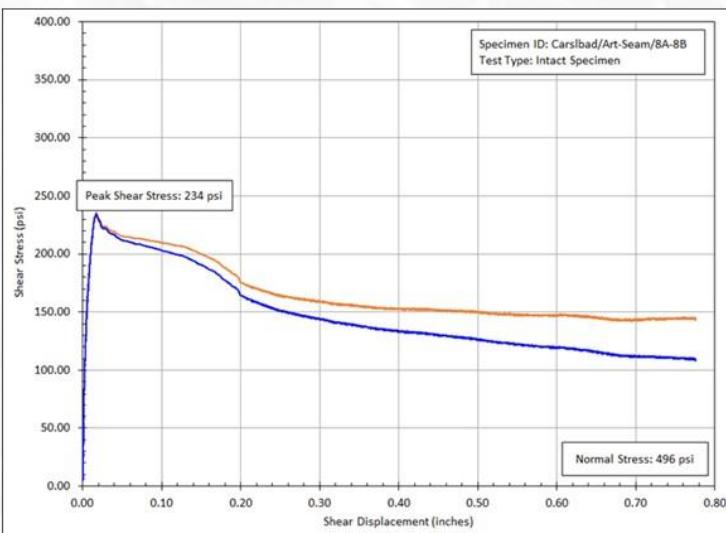
28

## Shear Stress vs. Shear Displacement: Sample #1, $\frac{1}{4}$ " seam pre-consolidation, 500 psi normal stress



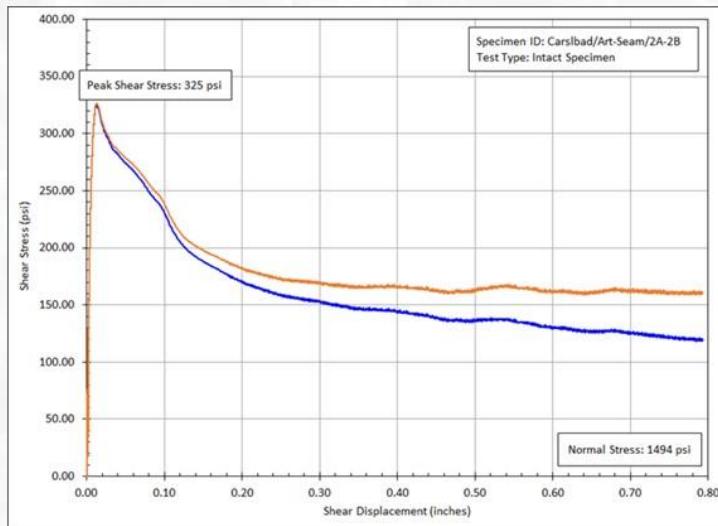
- Blue: Stress calculated with constant contact area
- Orange: Stress calculated with contact area modified by shear displacement
- Actual normal stress = 504 psi
- Peak shear stress = 140 psi
- Never reached residual stress after initiation of shear movement
- Test data was very noisy, although probably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

## Shear Stress vs. Shear Displacement: Sample #8, $\frac{1}{4}$ " seam pre-consolidation, 500 psi normal stress



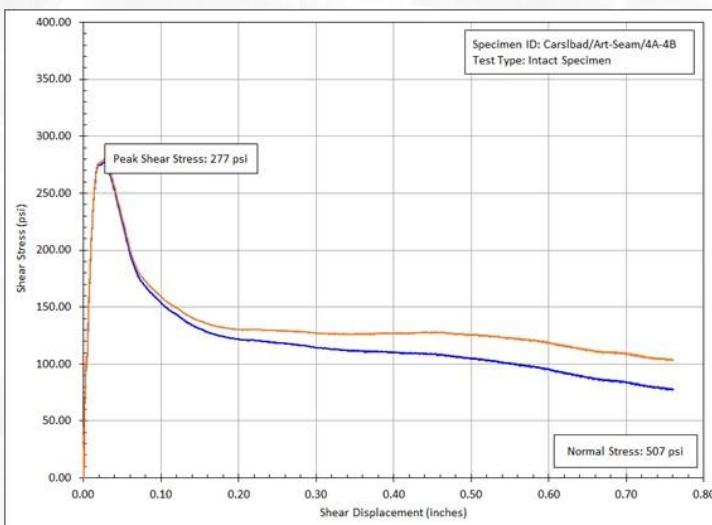
- Blue: Stress calculated with constant contact area
- Orange: Stress calculated with contact area modified by shear displacement
- Actual normal stress = 496 psi
- Peak shear stress = 234 psi
- Reached residual stress of ~150 psi after initiation of shear movement

## Shear Stress vs. Shear Displacement: Sample #2, $\frac{1}{4}$ " seam pre-consolidation, 1500 psi normal stress



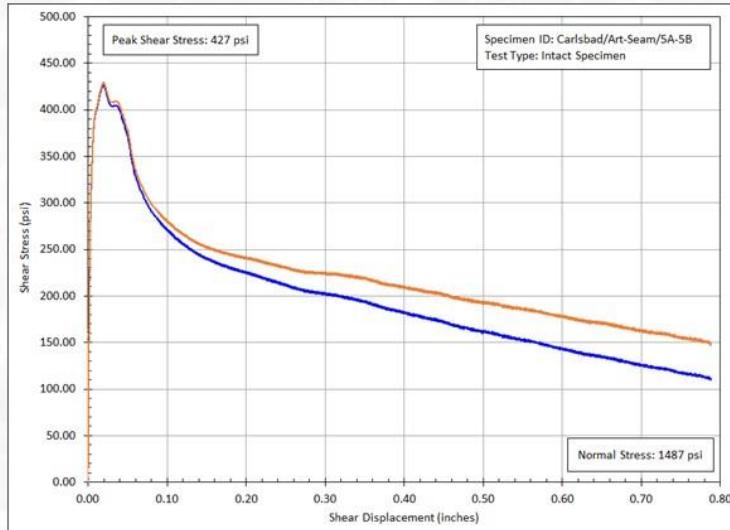
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 1494 psi**
- **Peak shear stress = 325 psi**
- **Reached residual stress of ~170 psi after initiation of shear movement**

## Shear Stress vs. Shear Displacement: Sample #4, $\frac{1}{2}$ " seam pre-consolidation, 500 psi normal stress



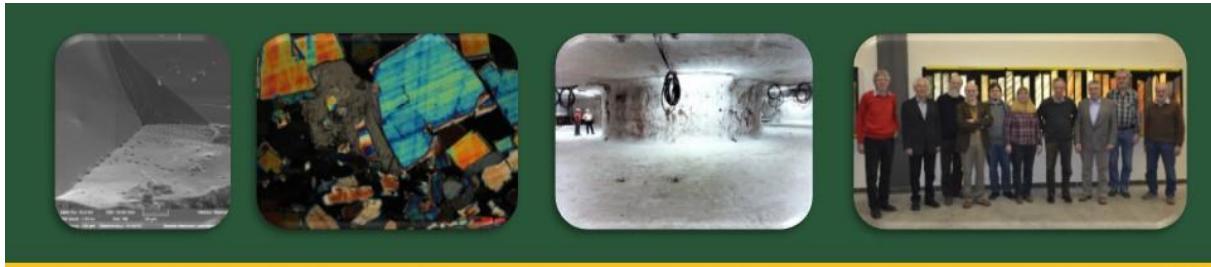
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 507 psi**
- **Peak shear stress = 277 psi**
- **Reached residual stress of ~130 psi after initiation of shear movement**

## Shear Stress vs. Shear Displacement: Sample #5, $\frac{1}{2}$ " 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





## 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design and Operation

### STROEFUN III

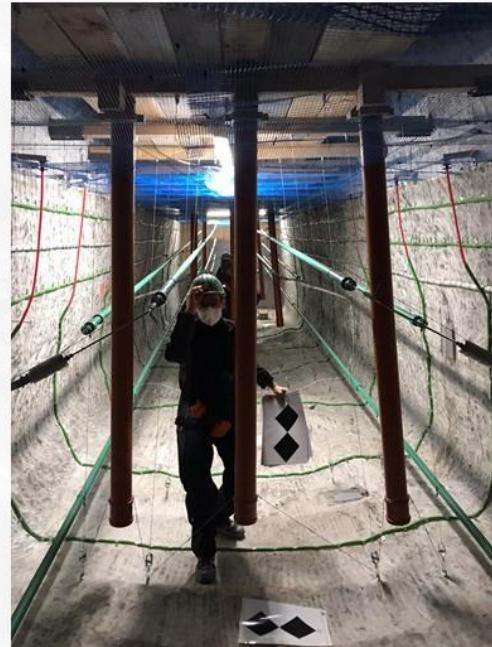


Julius Bauermeister  
TU Clausthal

Part 3 of the online workshop  
September 08, 2021

### Table of content

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



# STROEFUN III- Introduction



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



Supported by:



on the basis of a decision  
by the German Bundestag

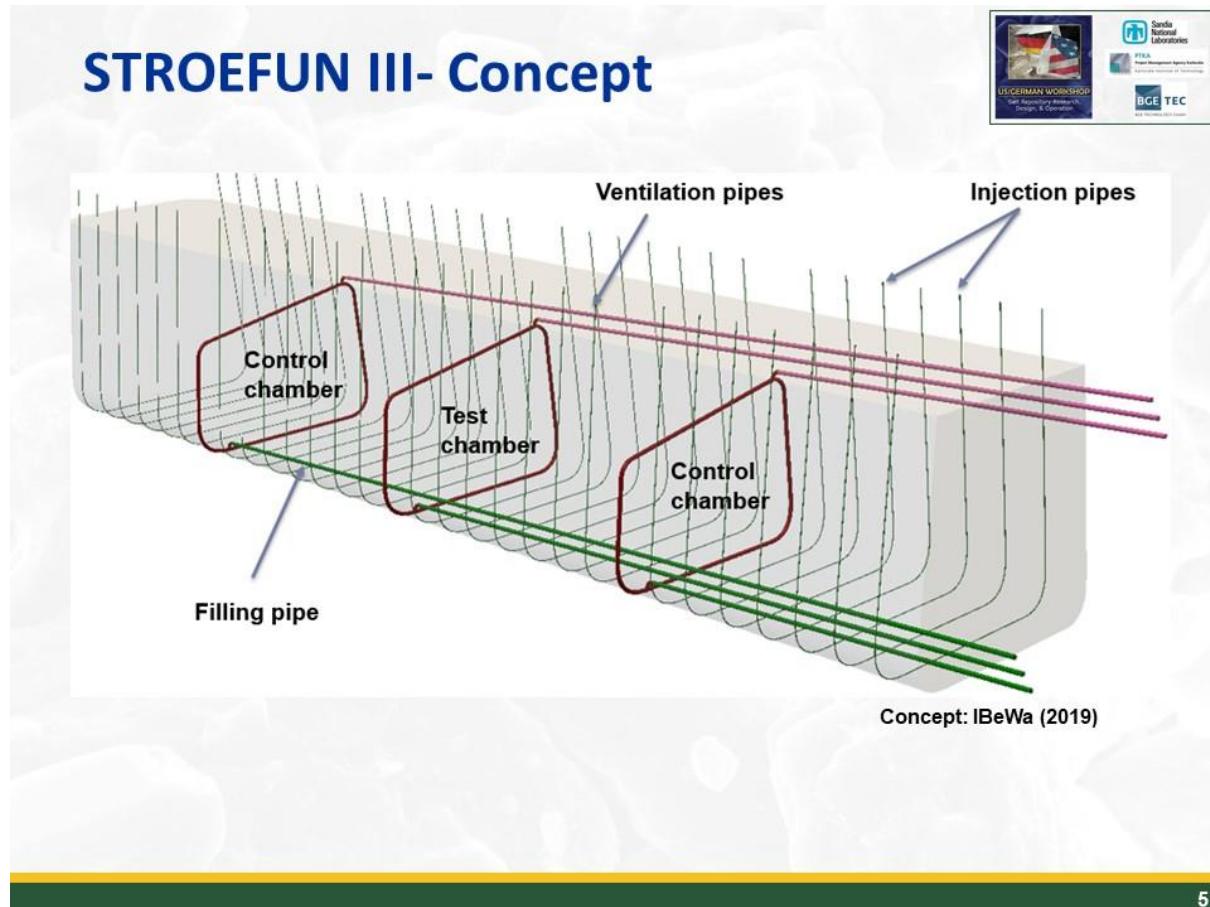
3

# STROEFUN III- Goals

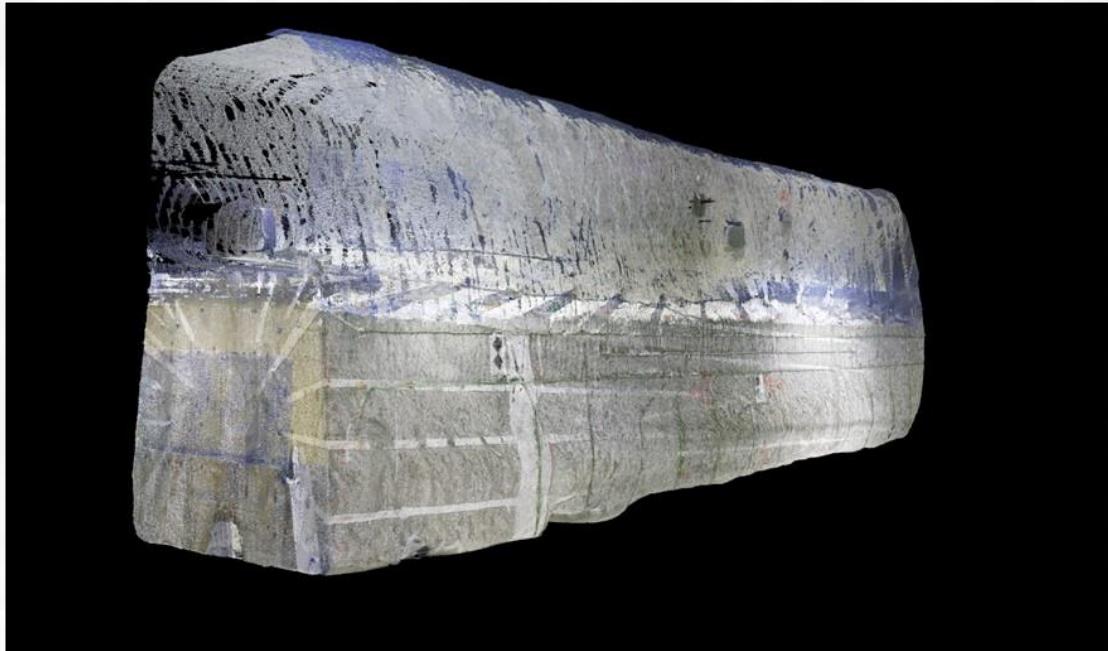


- Developing a concept for proving the fluidic properties of a closure structure
- Measures for the subsequent modification of higher permeability in the contact zone
- Testing of the treatment concept on a laboratory and semi-technical scale (in situ)

4



## STROEFUN III- Virtual tour



7

## STROEFUN III- Dam construction



- The concrete is based on the A1-recipe from the BGE Tec
  - Anhydrite 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 27<sup>th</sup>, 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



10

## STROEFUN III- Dam construction



- Firm connection between the concrete and the surrounding salt
- Small gap between the sewer pipe and the sorel concrete

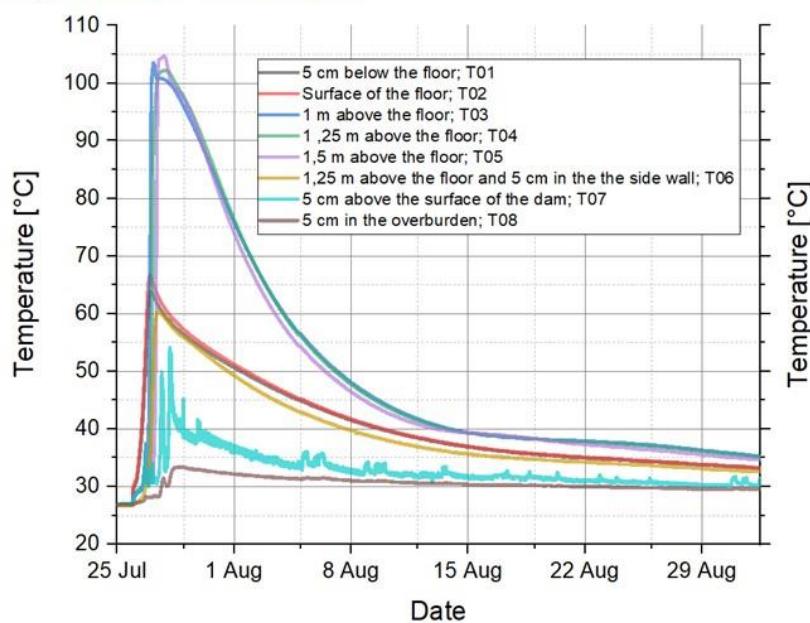


11

## STROEFUN III- Pressure and temperature

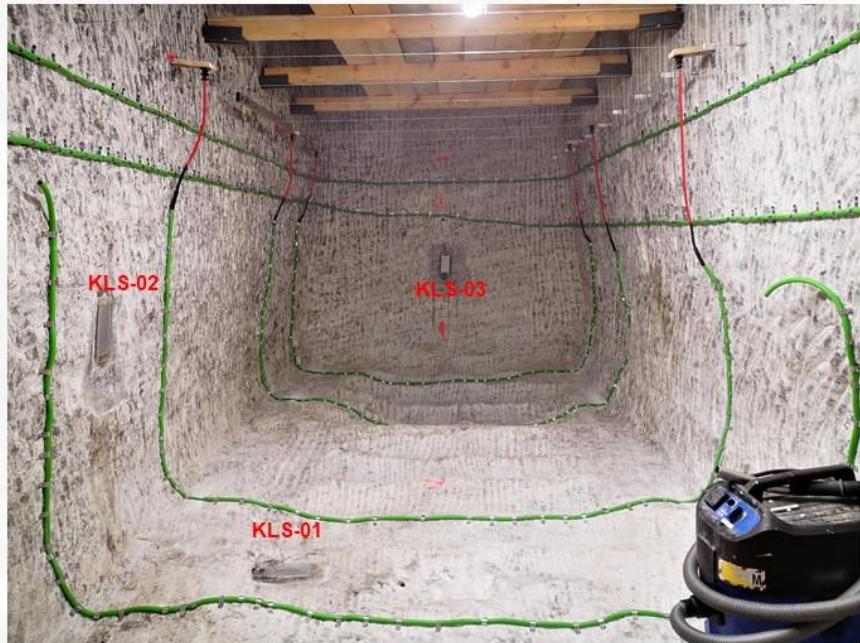


- Temperature detection



12

## STROEFUN III- Pressure and temperature



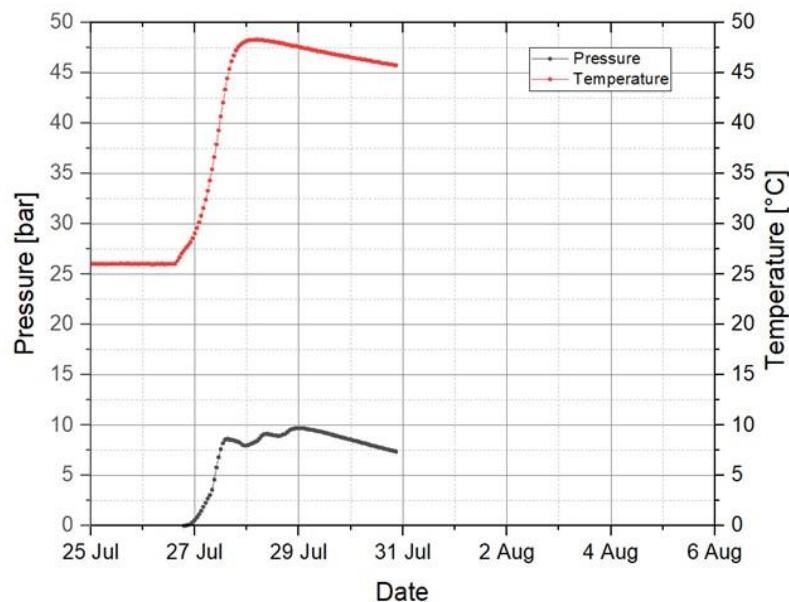
Source: IBeWa (2021)

13

## STROEFUN III- Pressure and temperature



- Wireless sensor 1 (KLS 01)



14

## STROEFUN III- Pressure and temperature



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



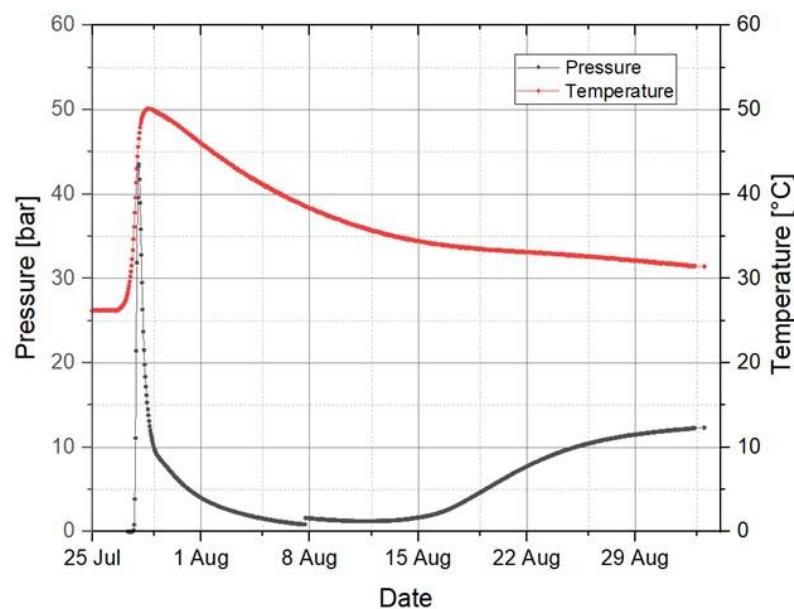
Source: IBeWa (2021)

15

## STROEFUN III- Pressure and temperature



- Wireless sensor 2 (KLS 02)

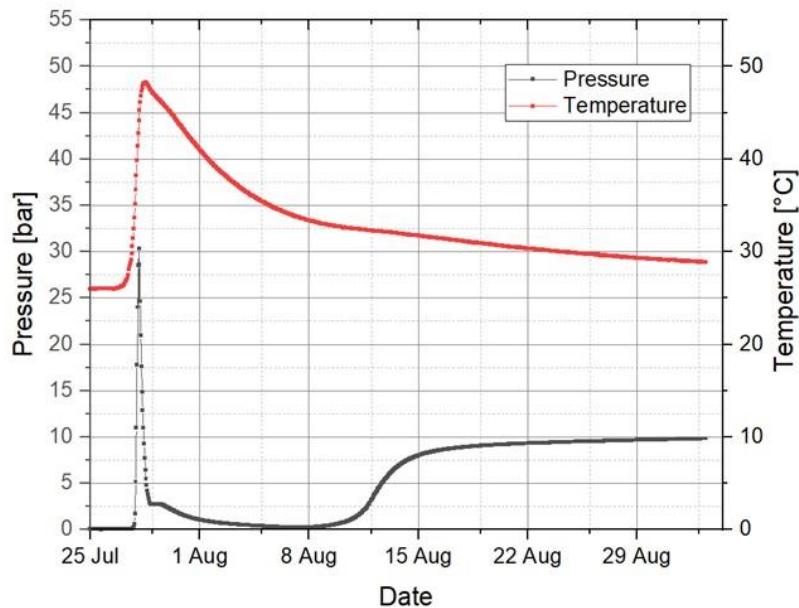


16

## STROEFUN III- Pressure and temperature



- Wireless sensor 3 (KLS 03)



17

## STROEFUN III- Outlook



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



18

## STROEFUN III- Questions



- Feel free to ask questions ☺

**Appendix D – Program and Presentations of Part 4 (9<sup>th</sup> September 2021)**

Berlin time		9 <sup>th</sup> September 2021 – Day 2	
16:00	16:10	Welcome by the organizers	M. Bühler/PTKA W. Bollingerfehr/ BGE TEC
<b>Modelling</b> 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 <sup>2</sup> M and TH <sup>2</sup> M 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



## 11<sup>th</sup> US/German Workshop on Salt Repository Research, Design, and Operation

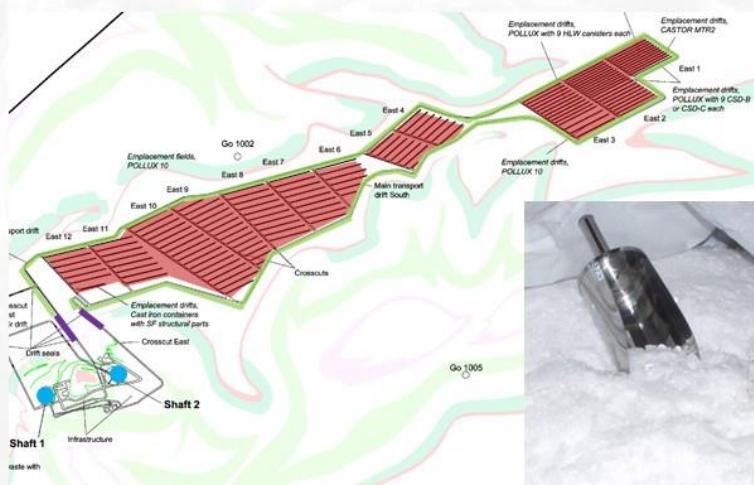
### UVERSTOFF – The Viscous Behavior of MgO-Concrete



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:

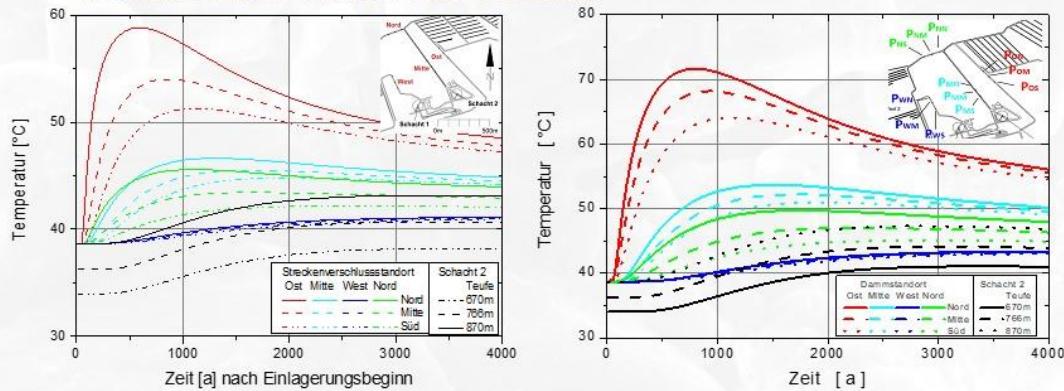
- Dry crushed salt in emplacement drifts and cross-cuts
- Humid crushed salt in access drifts
- Drift seals (made of MgO-concrete)
- Shaft seals include humid crushed salt sealing elements

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

## 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?



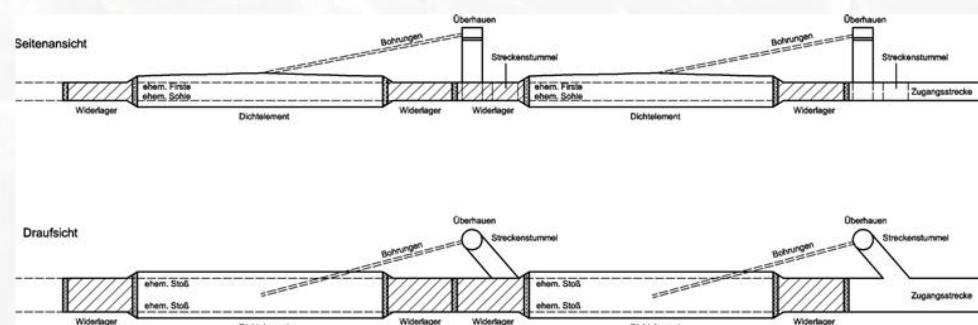
- Argumentation so far: The MgO-concrete structure was subjected to higher temperatures in its past
- However, the only significant thermal load considered is hydration heat at early age (mass concrete)
- Does this argumentation hold?

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 validity 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



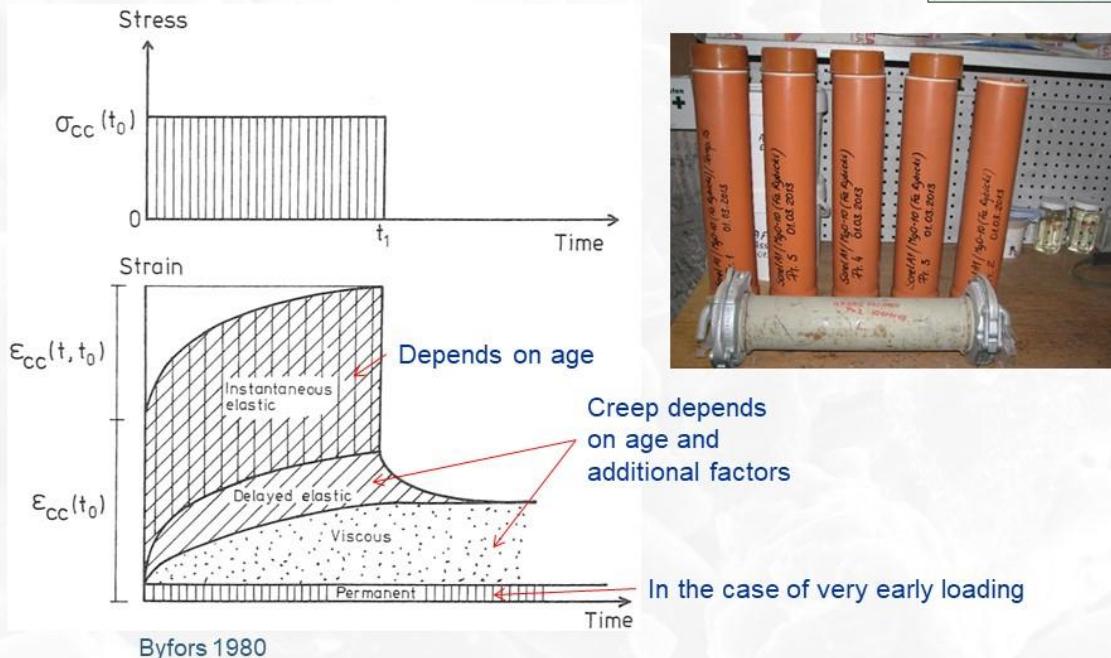
### Knowledge on material behavior of conventional mass concrete

- 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)

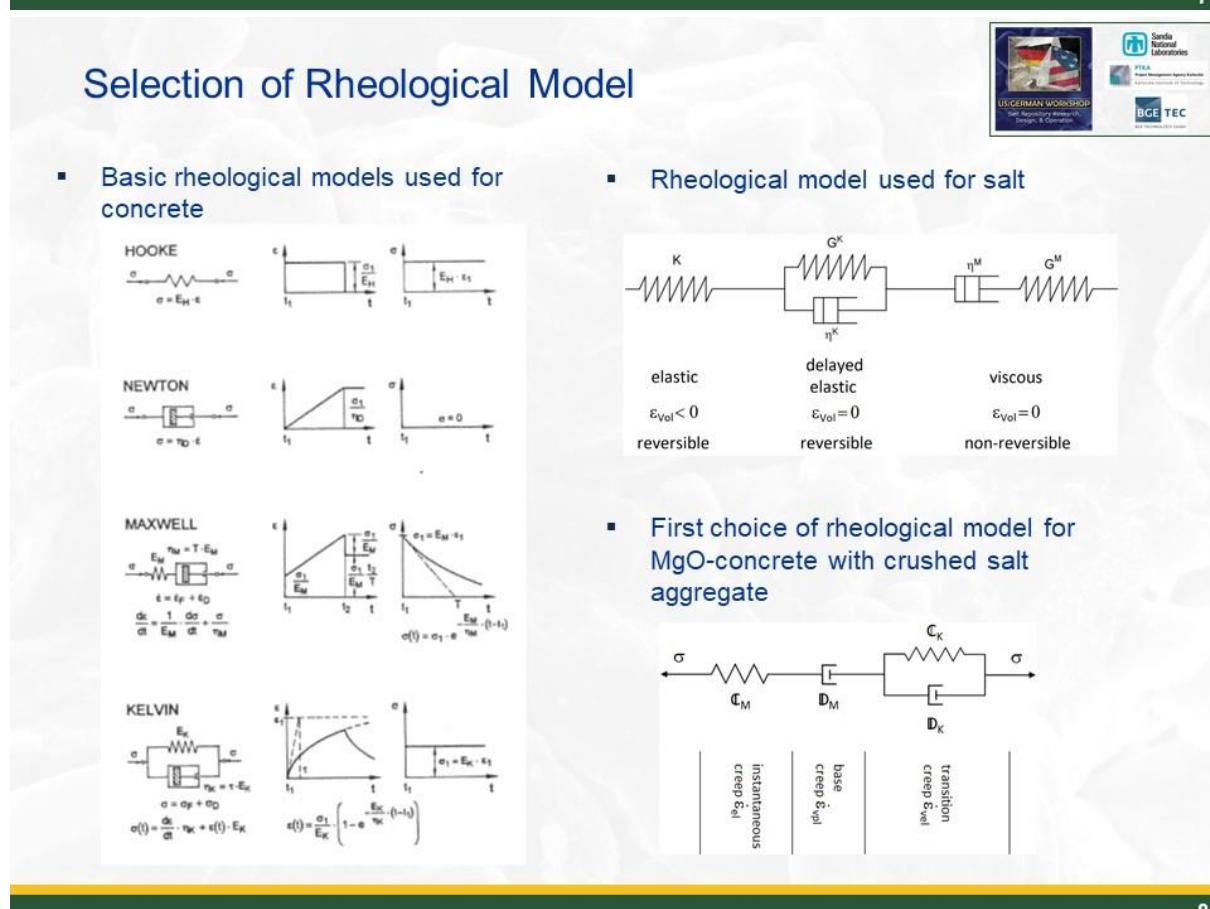
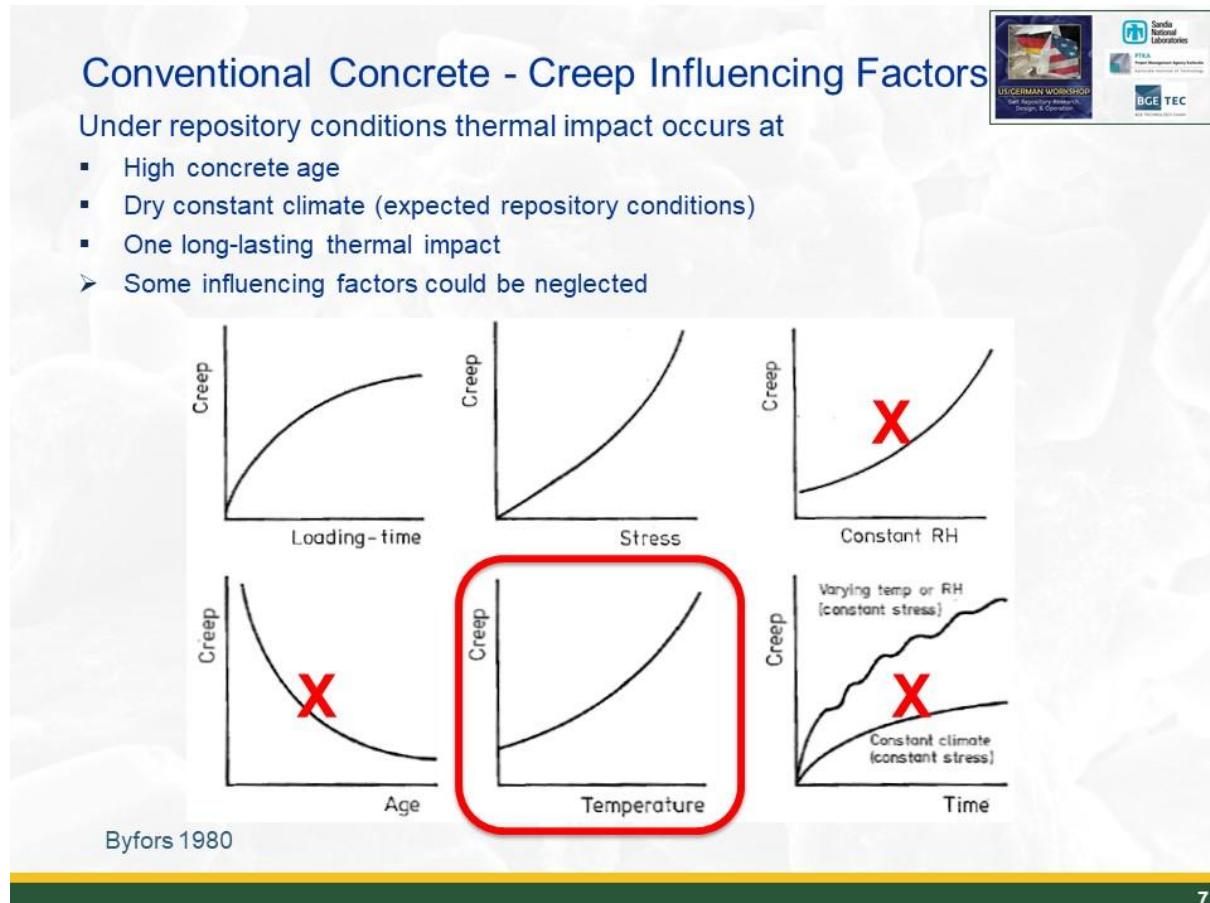
\* The existence of one or two types of creep was frequently discussed in the past and the scientific discussion is ongoing. Presently, the discussion tends to two parts.

5

## Conventional Concrete – Decomposition of Strains



6



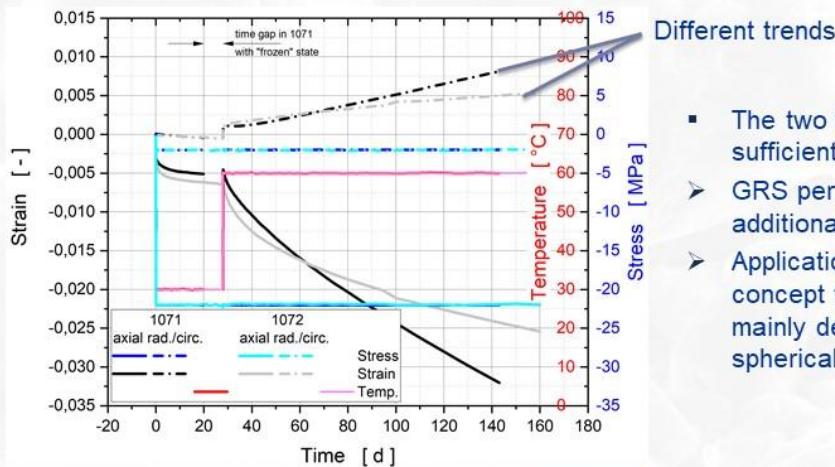
## MgO-Concrete - Laboratory Investigations



- 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

9

## 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

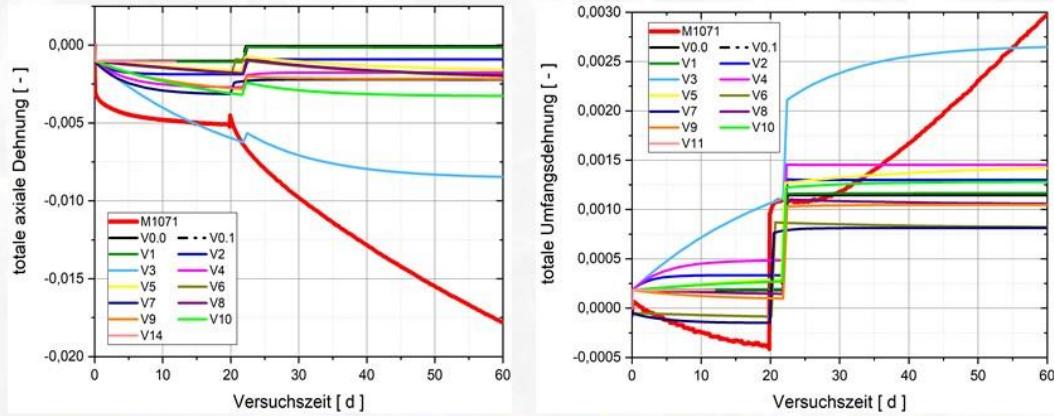


10

## Experimental Results and Numerical Adjustments



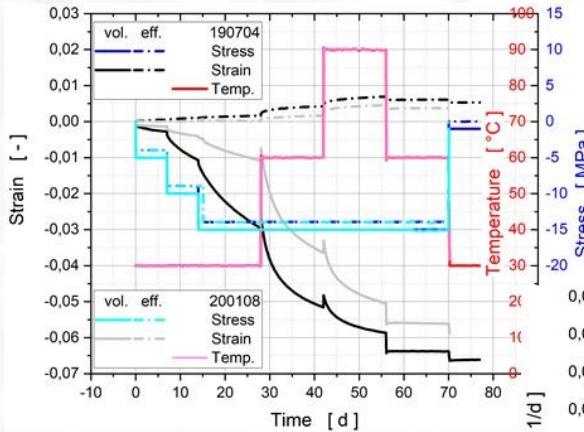
Some numerical adjustments to available tests in the waiting period for additional test results



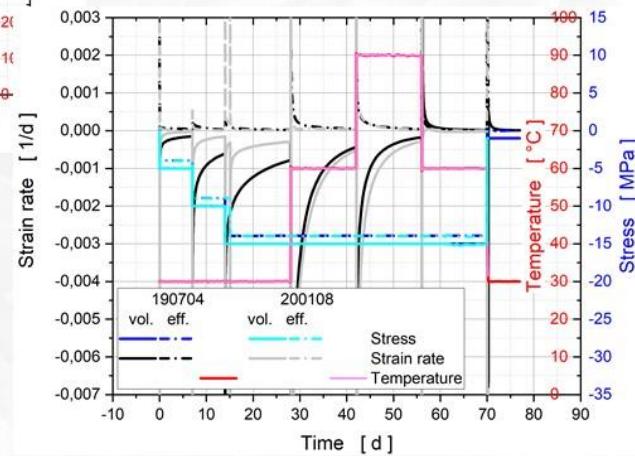
- Hein's crushed salt approach for the Maxwell element supplemented by an Arrhenius term
- Linear Kelvin element with constant elastic module and constant viscosity supplemented by an Arrhenius term
- Accompanying checks whether parameter values remained within reasonable limits
- Numerical adjustments were too stiff
- The increasing trend in the lab test was assumed not to be plausible

11

## Results from (Additional) Mainly Spherical Tests

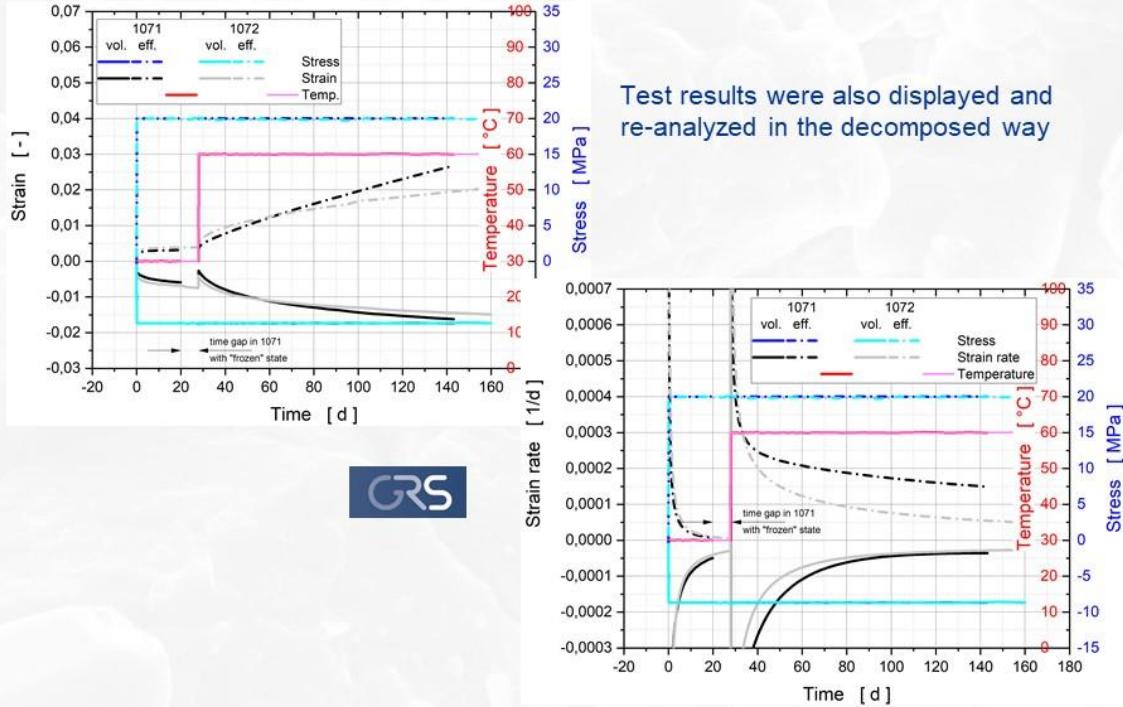


Decomposition of test regime in mainly spherical and mainly deviatoric tests utilizes the mathematical orthogonality of spherical tensor and deviator in the material model



12

## Results from Mainly Deviatoric Tests

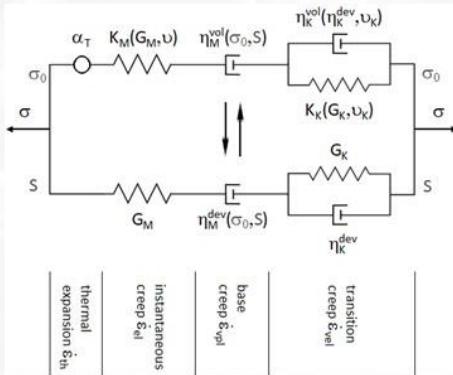


13

## Material Model for high aged MgO-concrete



### Initial state



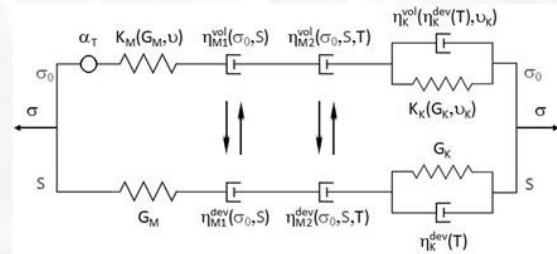
$$\dot{\varepsilon}_{th} = \alpha_{th} \dot{T} I$$

$$\dot{\varepsilon}_{el} = \mathbb{C}^{-1} \dot{\sigma}$$

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

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

### Current state



$$\dot{\varepsilon}_{th} = \alpha_{th} \dot{T} I$$

$$\dot{\varepsilon}_{el} = \mathbb{C}^{-1} \dot{\sigma}$$

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

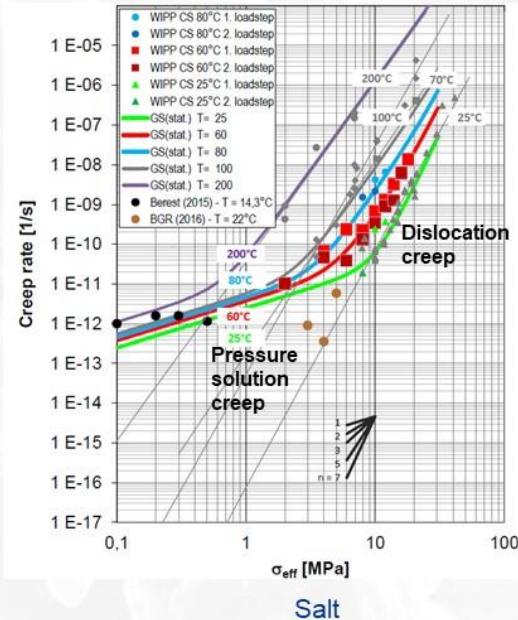
$$\dot{\varepsilon}_{vel} = e^{-\frac{Q_K}{RT}} \mathbf{D}^{-1} (\sigma - \mathbb{C} \varepsilon_{vel})$$

14

## Maxwell Element and Successive Parameter Identification

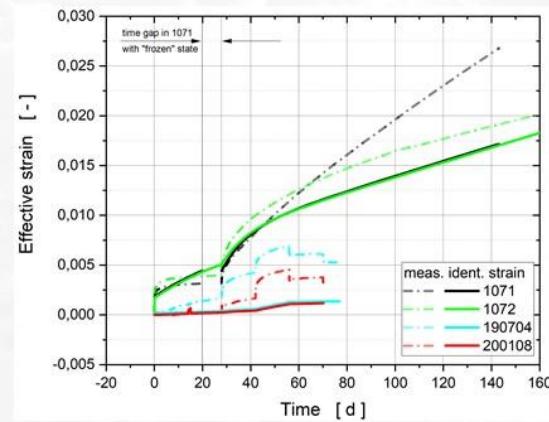
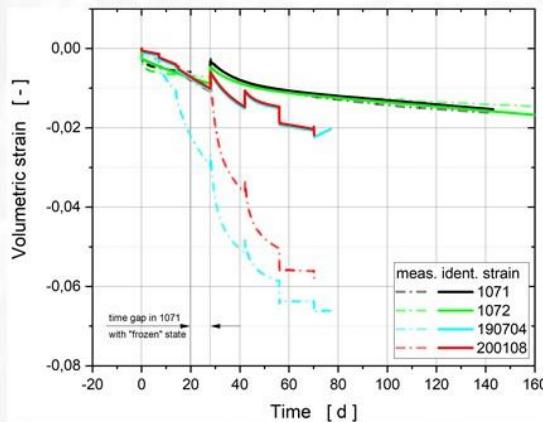


- Parameter values and their explanation:
- Exponents: 1 - 3
- Indicating main influence of pressure solution creep
- Spherical activation energy shows negligible dependency on temperature
- Deviatoric activation energy shows dependency on temperature in the range of salt



15

## Kelvin Element and Parameter Identification



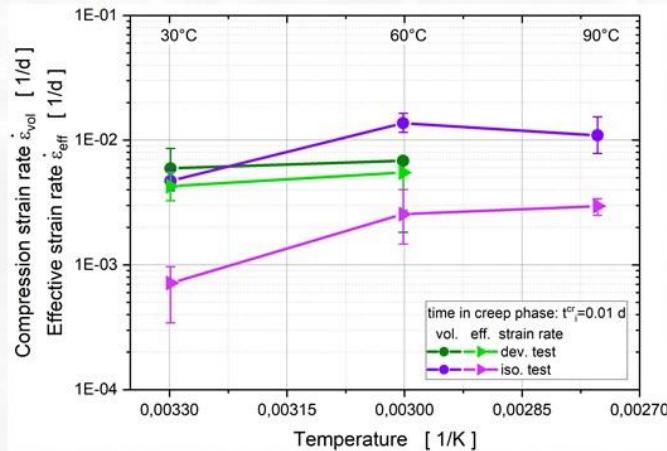
- Requiring that all experiments should be captured by the same set of parameters the identified parameter set is unsatisfactory as the Kelvin element remains too stiff
- Typically, thermal activation plays a role of „softening“ the material
- Consequently, temperature dependency of strain rate immediately after mechanical/thermal load step was investigated in detail (assuming that in this time period the Kelvin element dominates the strain rate)

16

## 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

17

## 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

18

## Summary and Outlook



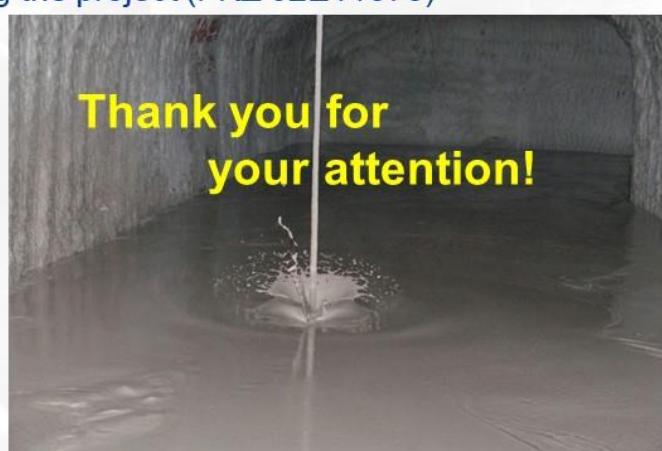
- A material model for MgO-concrete was established consisting of rheological elements - Maxwell and Kelvin type - and being able to capture thermal activation
- Experimental results gained from complex experiments formed the basis for parameter identification
- The Maxwell element shows thermally activated 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

19

## 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

20





## RANGERS: Methodology and Numerical Applications

### 11<sup>th</sup> 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. SANDIA-22-0001. 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 zur **Auslegung** und zum **Nachweis** von **geo-technischen Barrieren** für ein **HAW Endlager** in **Salzformationen** 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**

## 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.

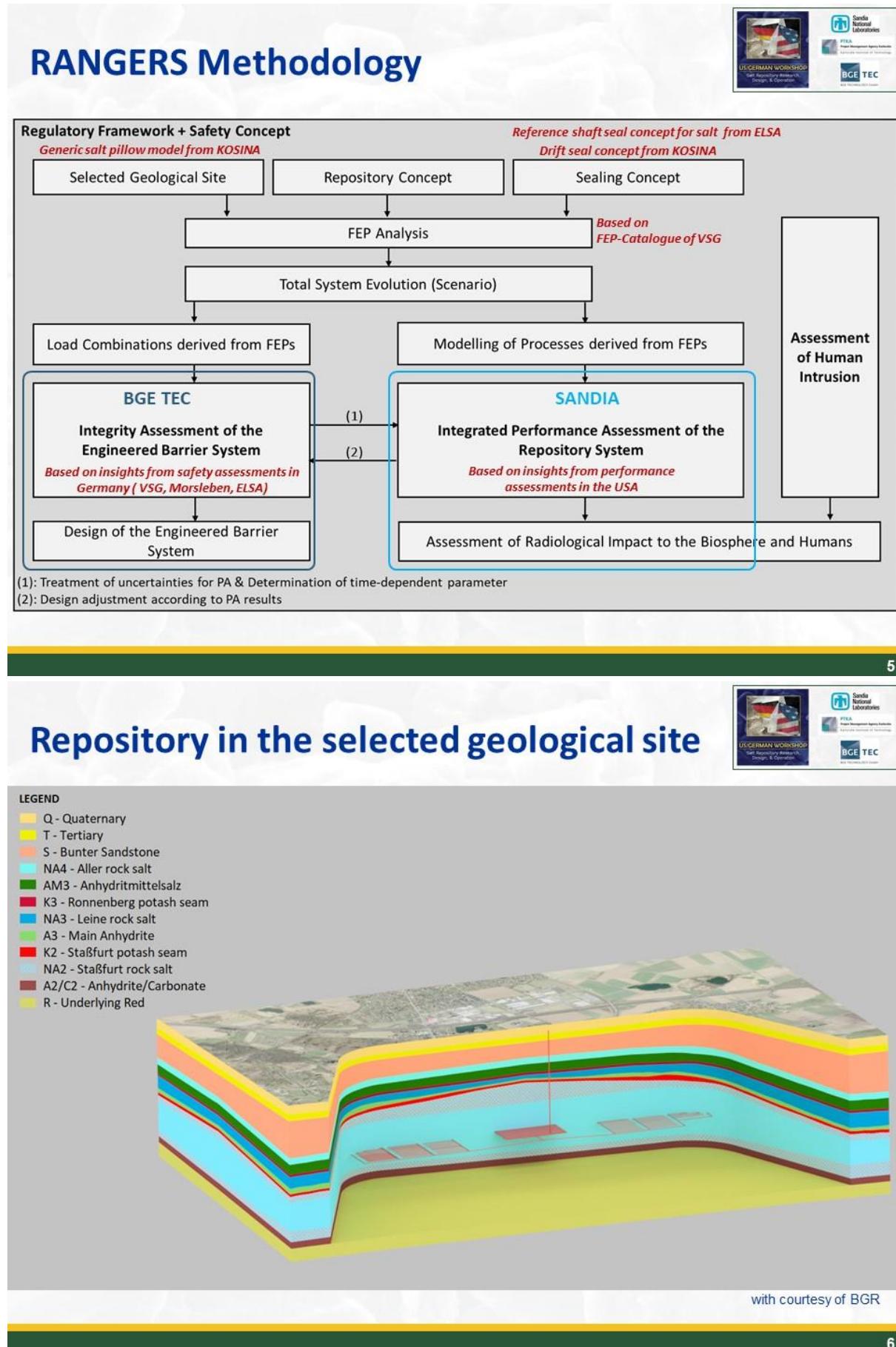
3

## Project Goals

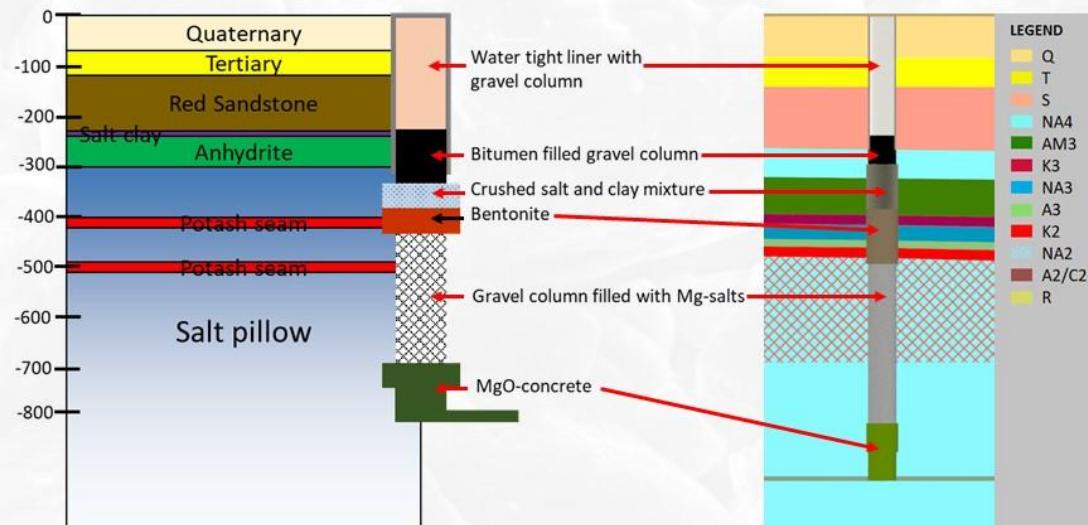


- **Secondary goals:**
  - Estimation of the optimization potential of EBS in salt repositories
  - Analysis of the impact of gases on EBS in salt
  - Exploiting synergy effects between BGE TEC and SANDIA in the numerical treatment of EBS in the course of the overall safety assessment of salt repositories:
    - 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

4

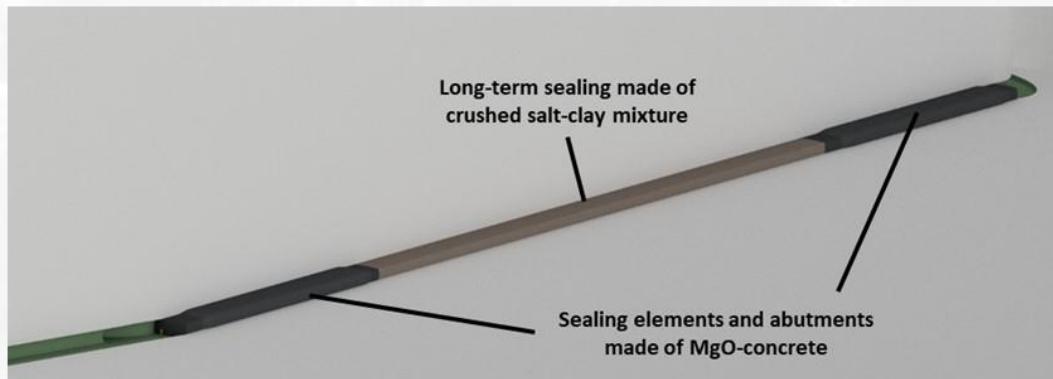


## Sealing concept: Shaft seals



7

## Sealing concept: Drift seals



8

## 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	
Components		1: Drift seal															
		3: Drift Backfill															
		10: Concrete injection															
		7: EDZ															
		XX: ...															
Processes/ Events	Mechanical	Example: Earthquake	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
	Hydraulic	Example: Gasflow 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		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 emplacement field.	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	x	x	x	x	x	x

9

## Scenario relevant for EBS



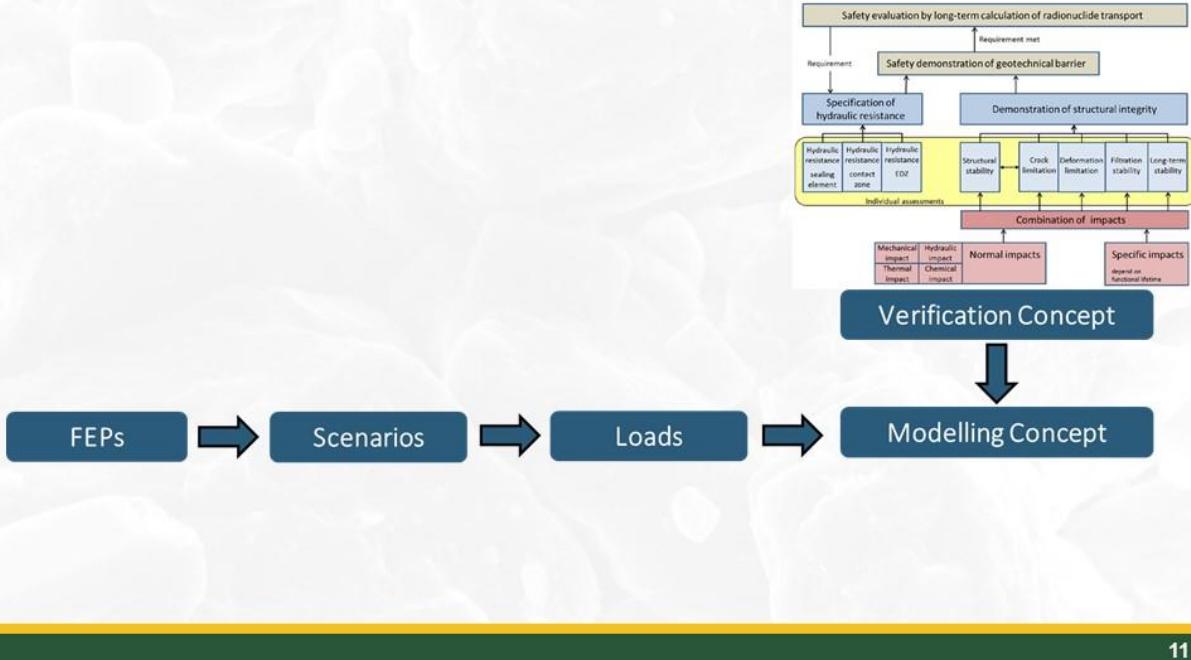
- **Reference Scenario:** The EBS **retains** its function over 50000 years
  - Case 1: Water flow from overburden through the shaft to the disposal zones
  - Case 2: Gas production inside the repository from corrosion of the casks
  - Case 3: Water source inside the repository from inter-/ intragranular 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

10

# Modelling Concept



- **Integrity assessment:**



11

# 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
<b>Reference Scenario: The EBS retains its function over 50000 years</b>								
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 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 $\text{pg} \leq \text{sig min}$ 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 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	

BGE TEC

SANDIA

12

**Modelling Concept**

US GERMAN WORKSHOP  
Salt Repository Research, Design & Operation

Sandia National Laboratories  
Project Management Agency California  
Argonne National Laboratory  
BGE TEC  
BGE TEC 2021 Edition

▪ **Performance assessment**

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

Verification Concept

FEPs → Scenarios → Processes → Modelling Concept

13

**Modelling Concept**

US GERMAN WORKSHOP  
Salt Repository Research, Design & Operation

Sandia National Laboratories  
Project Management Agency California  
Argonne National Laboratory  
BGE TEC  
BGE TEC 2021 Edition

▪ **Performance assessment**

	Processes							Target Criteria
	Nuclide decay	Advection	Diffusion	Convection/conduction	2-Phase-flow	Boiling	Recondensation	
<b>Reference Scenario: The EBS retains its function over 50000 years</b>								
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

14

# Modelling Concept



- Interactions between integrity and performance assessment

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

	Hydraulic resistance overlying material	Hydraulic resistance Target zone	Hydraulic resistance overlying material	Structural integrity	Crack initiation	Deflection	Hydrogen	Long-term stability
<b>Reference Scenario: The EBS retains its function over 50000 years</b>								
Case 1: Water flow from overburden through the shaft to the disposal zones	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
Case 2: Gas production inside the repository from intergranular salt	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
Case 3: Water flow from the repository from intergranular salt to the overburden	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant

	Processes	Long-term decay	Advection	Diffusion	Convection / conduction	2-Phase flow	Boiling	Recon- stitution	Target Criteria
<b>Reference Scenario: The EBS retains its function over 50000 years</b>									
Case 1: Water flow from overburden through the shaft to the disposal zones	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
Case 2: Gas production inside the repository from intergranular salt	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
Case 3: Water flow inside the repository from intergranular salt to the overburden	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant

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

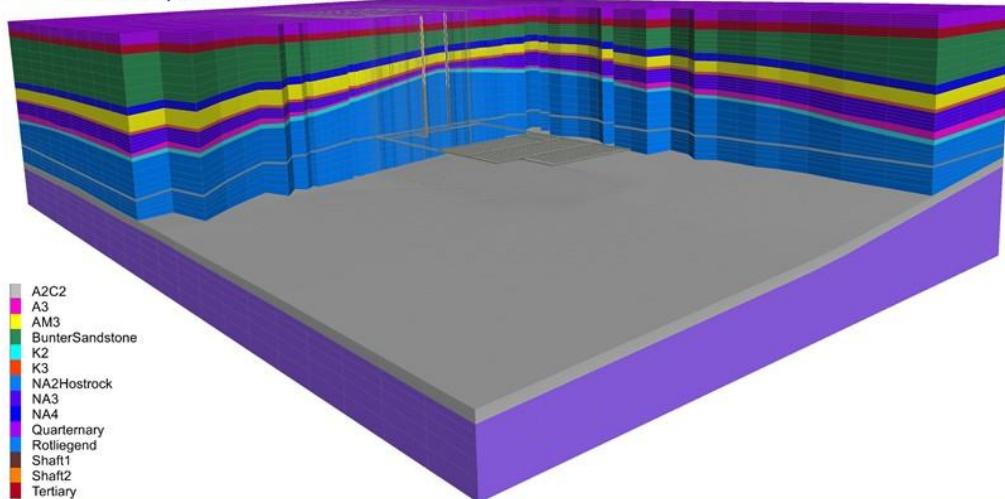
BGE TEC SANDIA

15

# 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



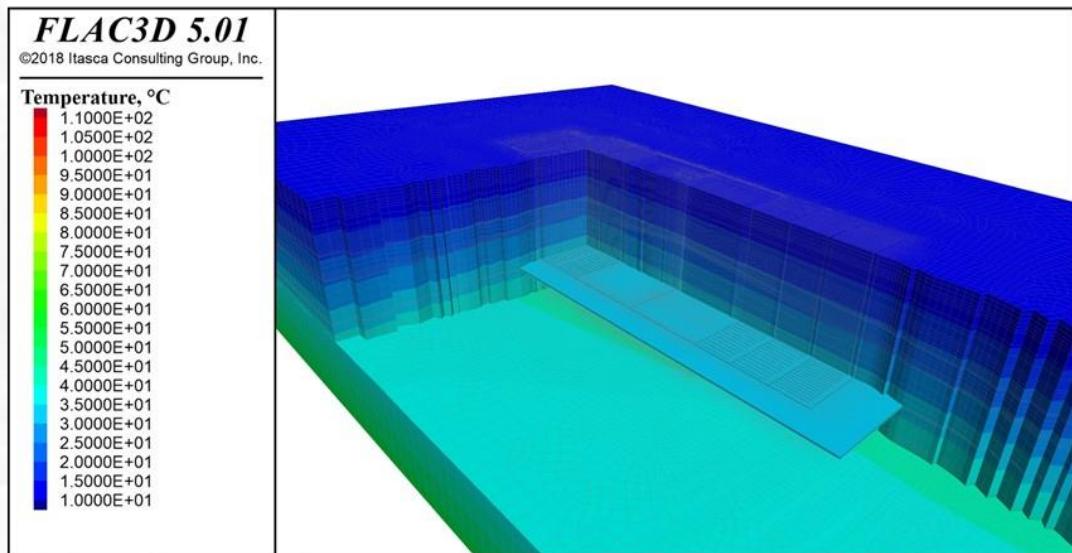
16

# Thermal evolution in the repository (BGE TEC)



- Goal: Determination of the temperature increase in the EBS

5 a

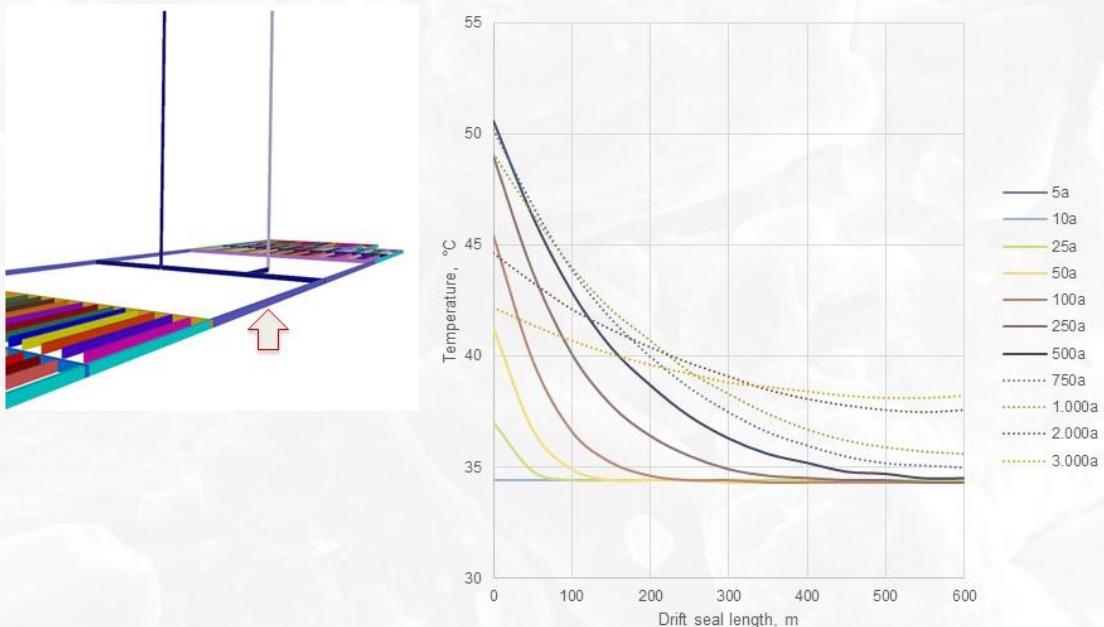


17

# Thermal evolution in the repository (BGE TEC)



- Temperature evolution in the drift seal

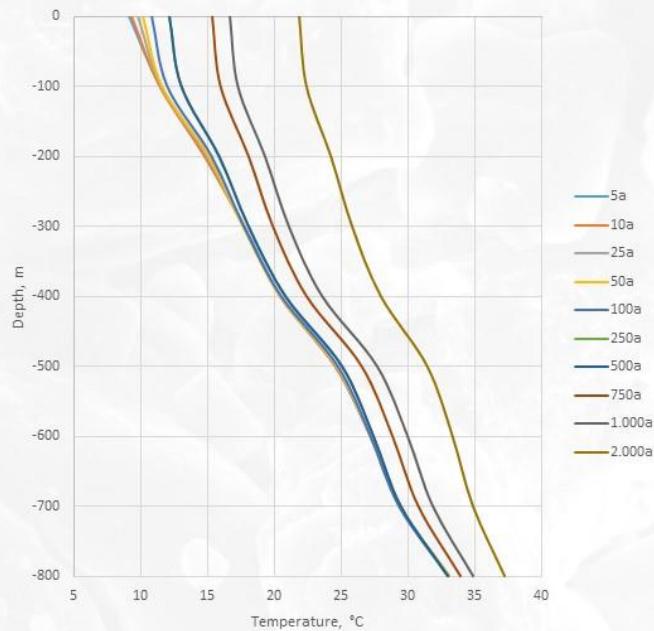
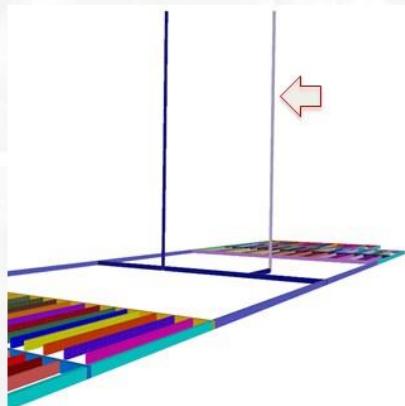


18

## Thermal evolution in the repository (BGE TEC)



- Temperature evolution in the shaft



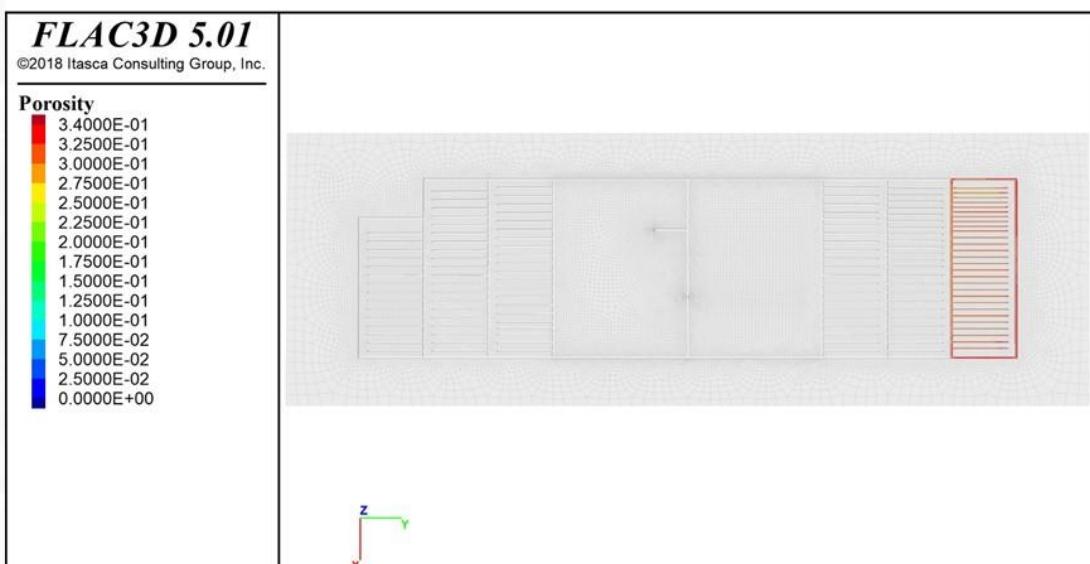
19

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



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

5 a



20

## Demonstration PFLOTRAN Simulations (SANDIA)



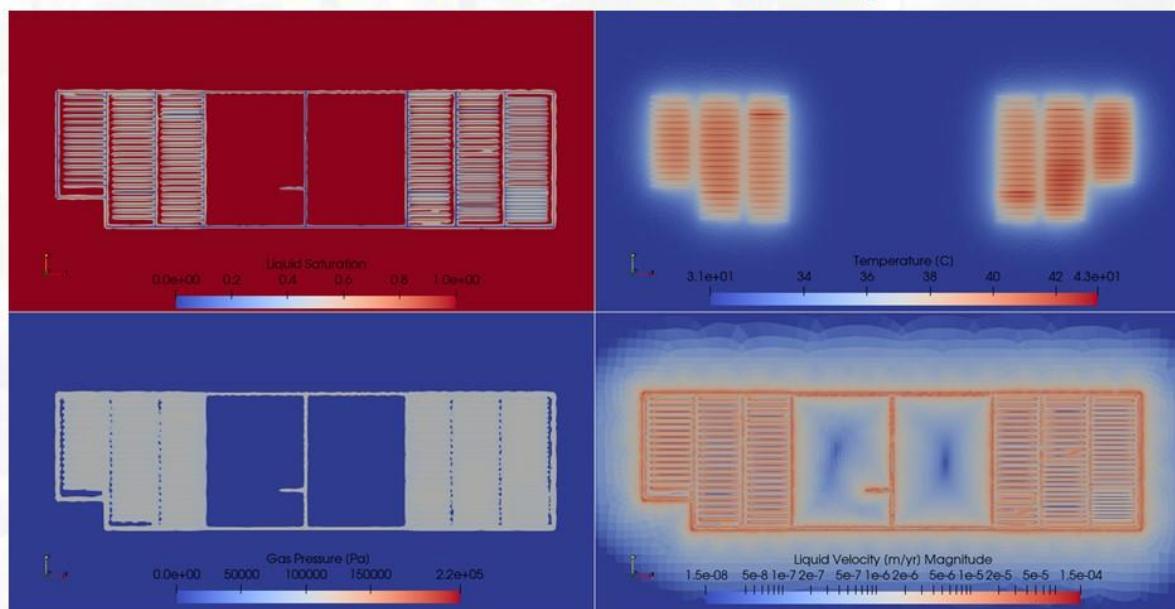
- **Goal: Test of the capacity of PFLOTRAN to simulate the relevant processes considered in the scenario evolution**
- Assumption for the test case:
  - Two-phase flow of air and water
  - Drifts, seals, and shafts are initially air-filled
  - Host rock is initially water-filled
  - 20 years pressure 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

21

## PFLOTRAN Simulations (200 yr)



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

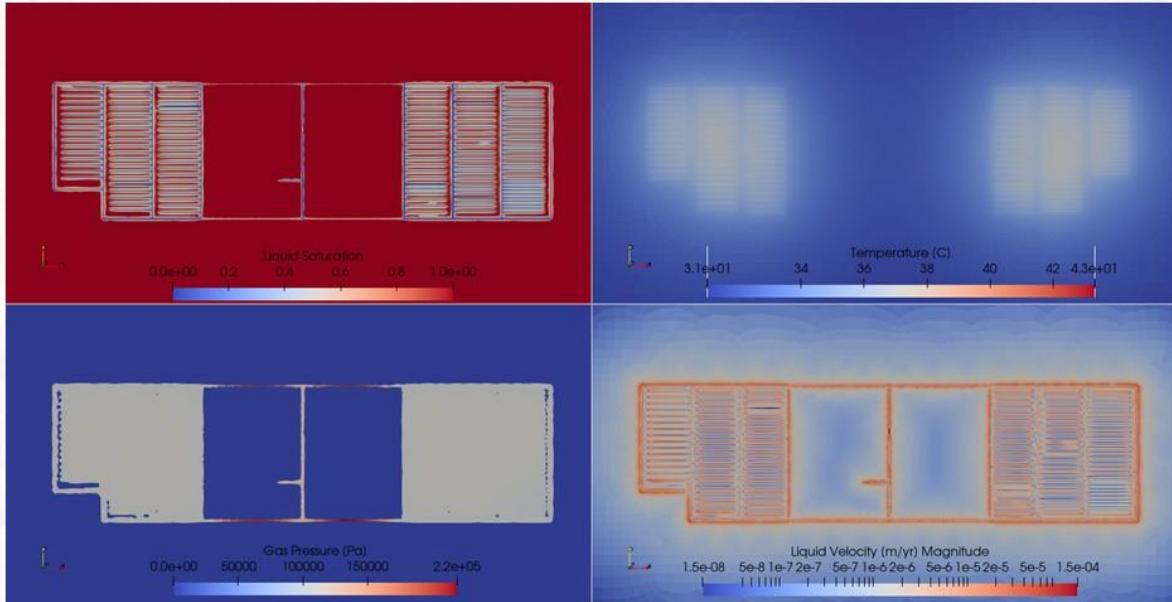


22

## PFLOTRAN Simulations (2000 yr)



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



23

## 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

24

## 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

25

## Questions?



Thank you for your attention!

26





**BEN  
VASIM**

**Benchmarking Results for  
Heterogeneous H<sup>2</sup>M and TH<sup>2</sup>M Models**

Michael Rutenberg et al.  
Clausthal University of Technology et al.

Part 4 of the online workshop  
September 9, 2021



**Authors/Benchmarking Partners**

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Jürgen Hansmann
- Oliver Czaikowski,  
Larissa Friedenberg
- Stephan Hotzel
- Jonny Rutqvist,  
Mengsu Hu
- Antonio P. Rinaldi

# Contents



- Considered TH<sup>2</sup>M processes and applied simulators  
(H<sup>2</sup>: two-phase flow – liquid and gaseous phases with water and air)
- Some simulation results for a H<sup>2</sup>M-coupled model
- Some simulation results for a TH<sup>2</sup>M-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  $\varphi$* ), 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:**  $\frac{1}{M_{\varphi}} \dot{p}_{\varphi} + \frac{\phi}{S_{\varphi}} \dot{S}_{\varphi} = \alpha \dot{\varepsilon}_{vol}$

- **H→T coupling:**

advection transport of energy, saturation-dependent thermal parameters of the bulk ( $\lambda$  and  $c$ )

- **T→H coupling:**

temperature-dependent hydraulic properties

5

# Processes and Simulators



→ Simulators used by the partners

- **BGR** → OpenGeoSys

- **ENSI** → TOUGH-FLAC, OpenGeoSys, COMSOL Multiphysics

- **GRS** → CODE\_BRIGHT, TFC  
(2 teams)

- **LBNL** → TOUGH-FLAC

*Kolditz et al. (2012)  
Rutqvist (2011); Rinaldi et al. (2018)  
COMSOL (2012)  
UPC (2017)  
Hotzel (2014)  
Lux et al. (2015)*

- **TUC** → FTK

*Pruess et al. (2012); Jung et al. (2018); Itasca (2009/2012)*

6

## H<sup>2</sup>M Model: Basic Scenario



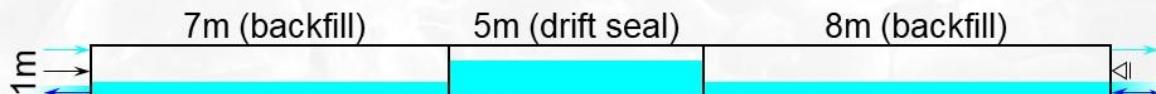
$$\begin{array}{lll}
 \sigma_{tot;lhs} = 5 \text{ MPa} & \sigma_{tot0} = 5 \text{ MPa} & u_{rhs} = 0 \text{ m} \\
 p_{g;lhs} = 4 \text{ MPa} & \underset{\text{backfill}}{p_{g0}} = 0.25 \text{ MPa} & \underset{\text{drift seal}}{p_{g0}} = 0.2 \text{ MPa} \quad p_{g;rhs} = 0.25 \text{ MPa} \\
 S_{l;lhs} = 0.20 & \underset{\text{backfill}}{S_{l0}} = 0.25 & \underset{\text{drift seal}}{S_{l0}} = 0.70 \quad S_{l;rhs} = 0.25
 \end{array}$$

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

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

7

## H<sup>2</sup>M Model: Basic Scenario



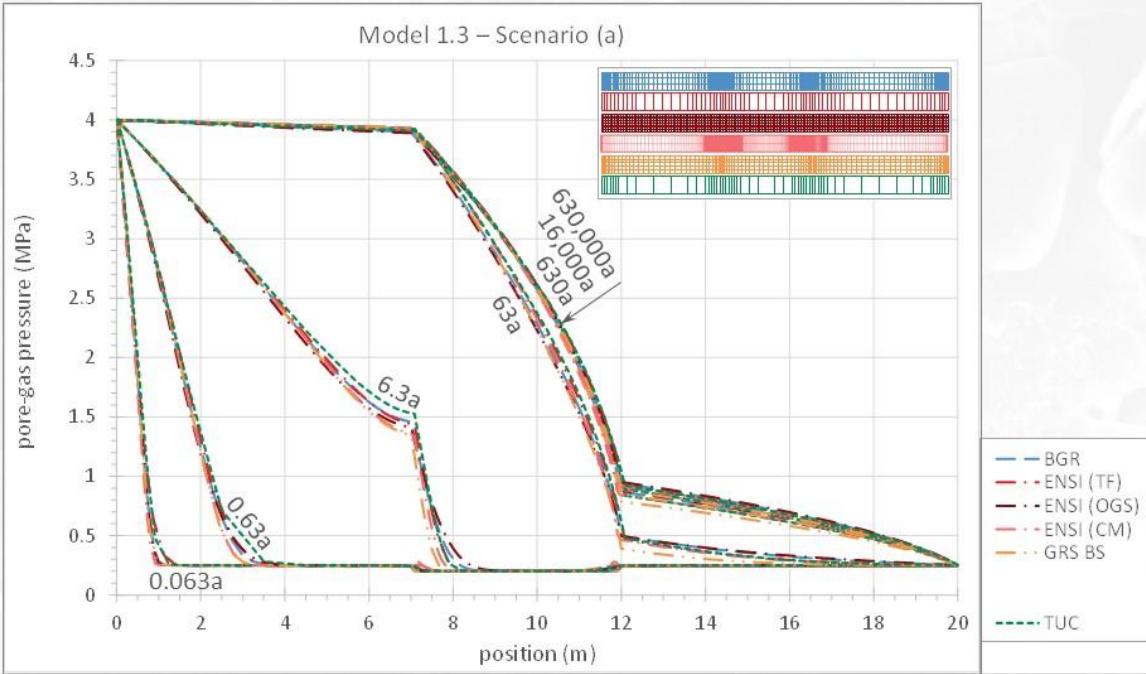
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 \end{array}$$

		backfill	drift seal	
Young's modulus (drained)	$E$	200	600	MPa
porosity	$\phi$	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)

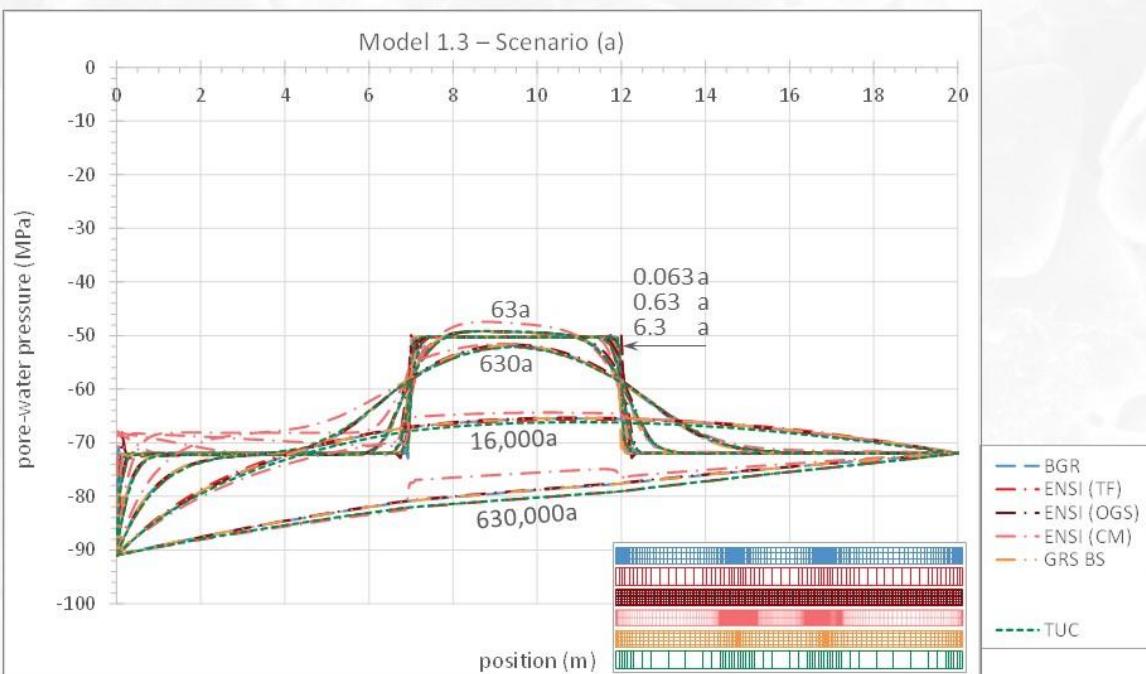
8

## H<sup>2</sup>M Model: Basic Scenario



9

## H<sup>2</sup>M Model: Basic Scenario



10

## H<sup>2</sup>M Model: Mobile Phases



$$\begin{aligned}
 \sigma_{tot;lhs} &= 5 \text{ MPa} & \sigma_{tot0} &= 5 \text{ MPa} & u_{rhs} &= 0 \text{ m} \\
 p_{g;lhs} &= 4 \text{ MPa} & \underset{\text{backfill}}{p_{g0}} &= 0.25 \text{ MPa} & p_{g;rhs} &= 0.25 \text{ MPa} \\
 S_{l;lhs} &= 0.20 & \underset{\text{backfill}}{S_{l0}} &= 0.25 & \underset{\text{drift seal}}{S_{l0}} &= 0.70 & S_{l;rhs} &= 0.25
 \end{aligned}$$

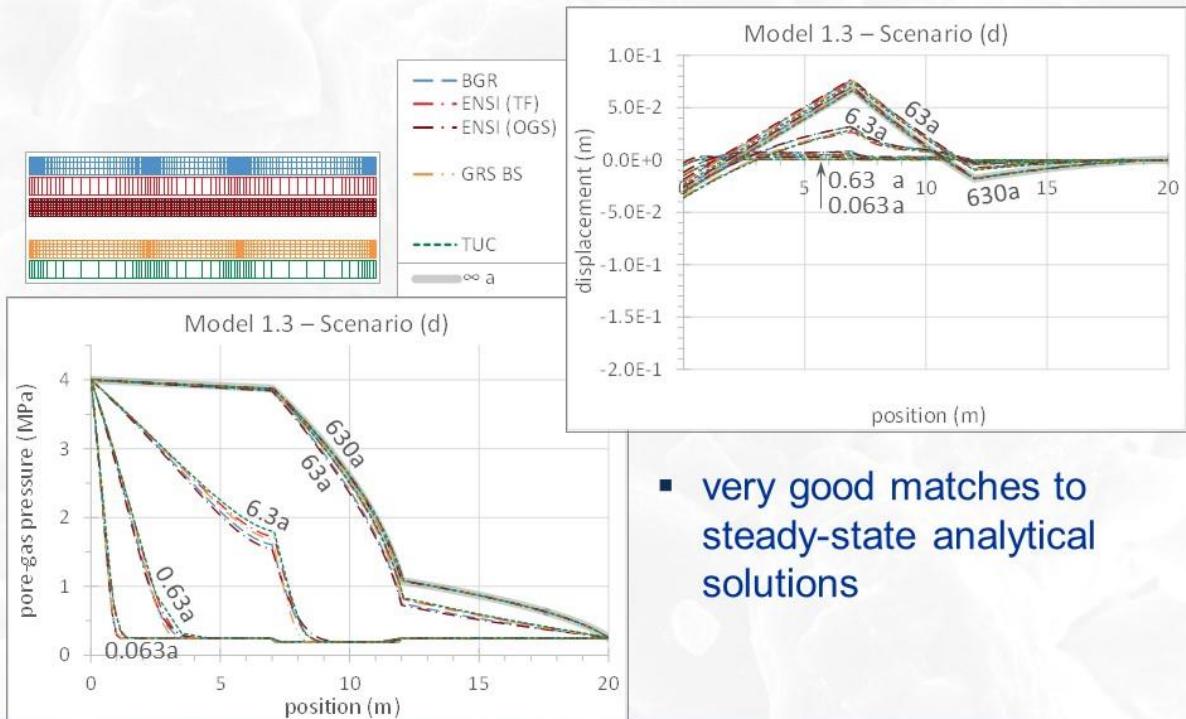
$$K_{rel;\varphi} \equiv 1$$

in place of Mualem/van Genuchten's relative permeability

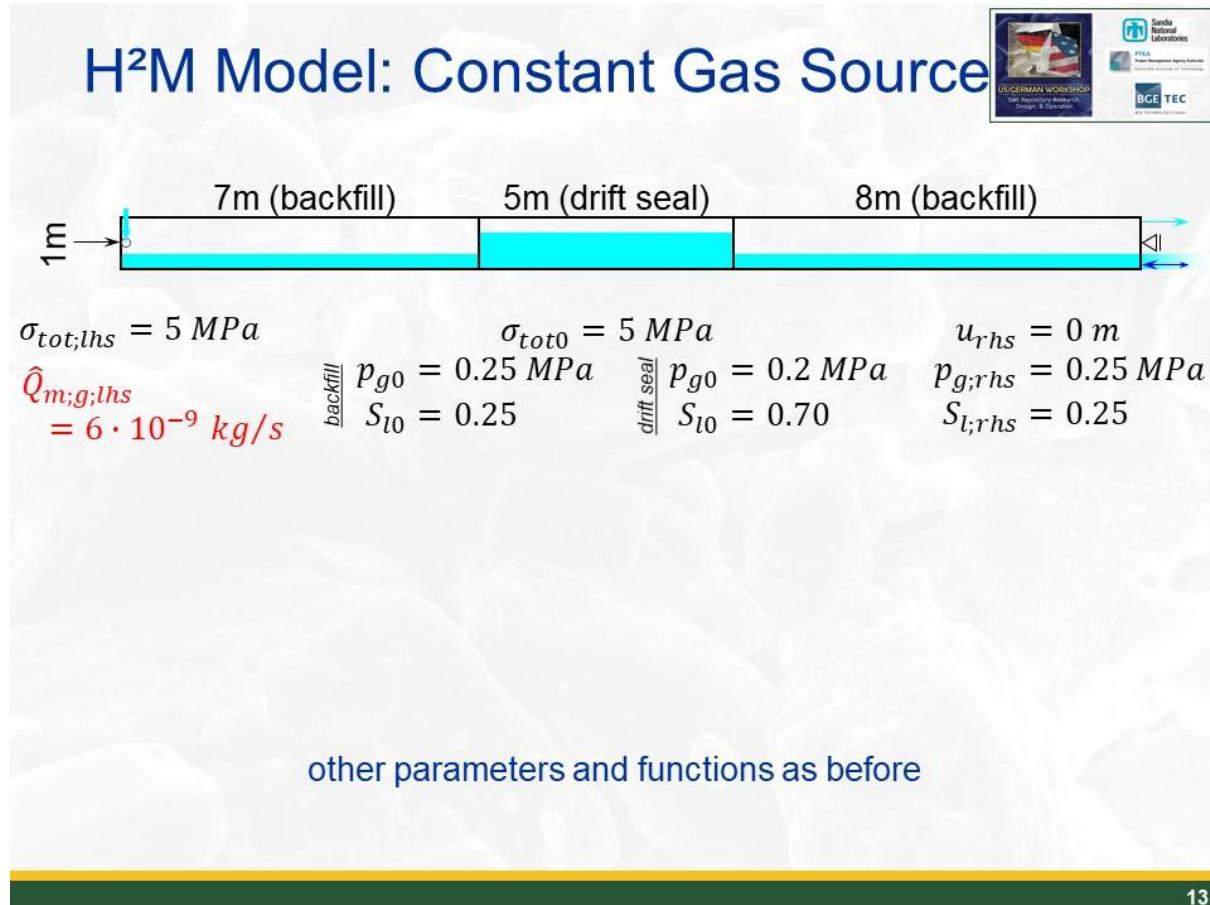
other parameters and functions as before

11

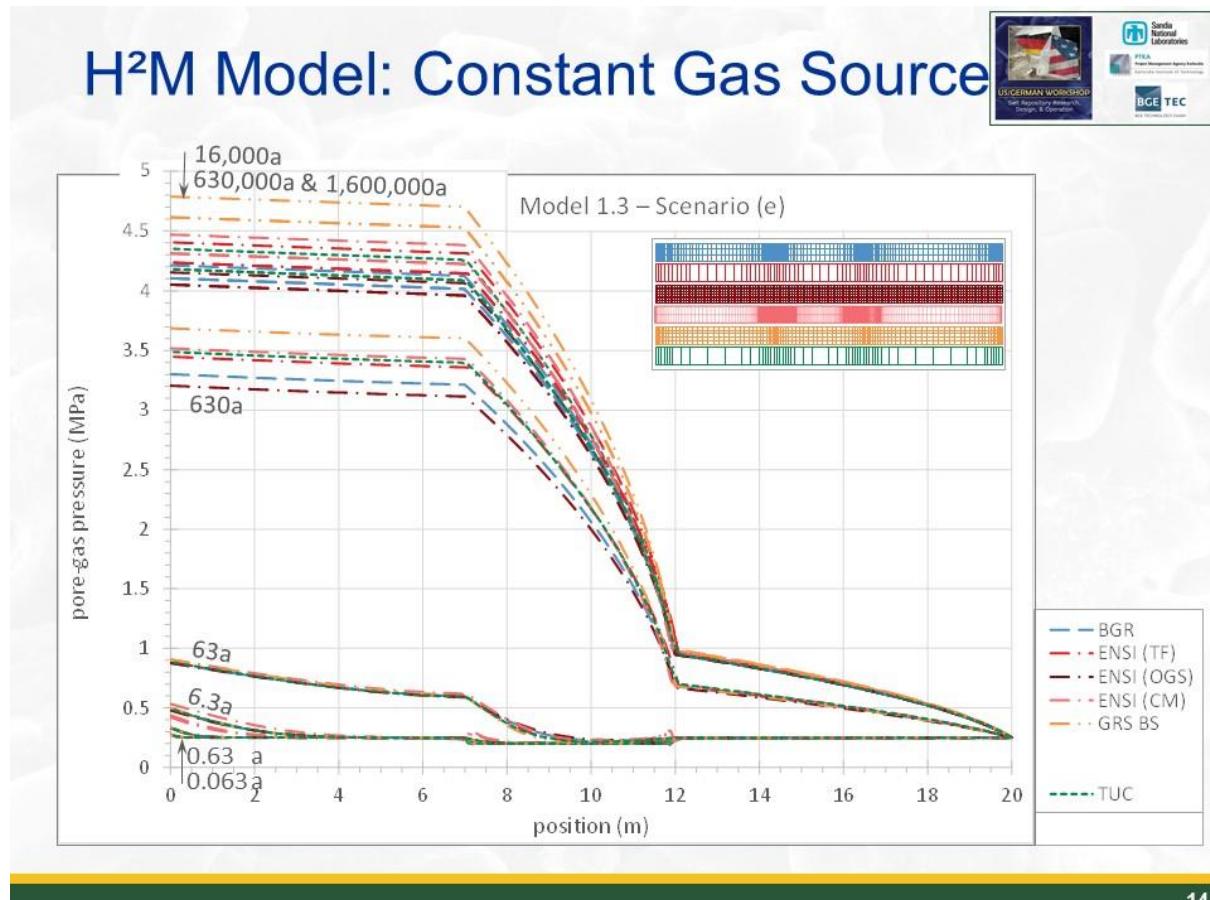
## H<sup>2</sup>M Model: Mobile Phases



12

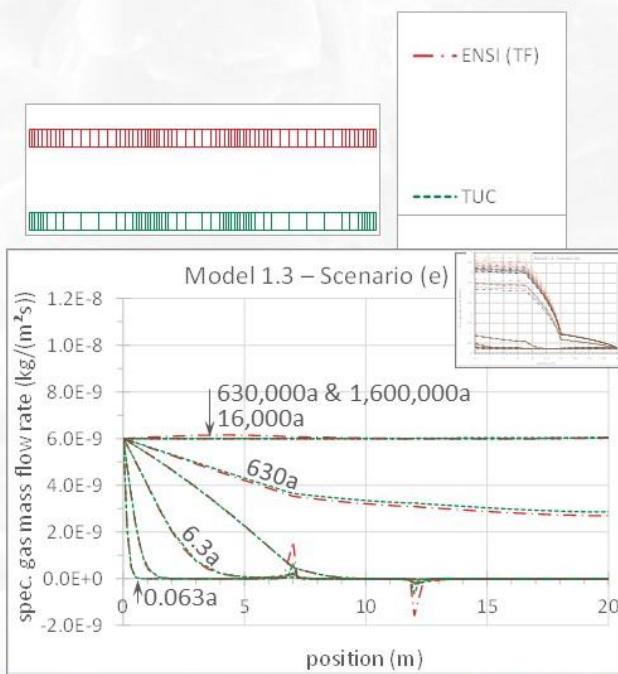


13



14

## H<sup>2</sup>M Model: Constant Gas Source

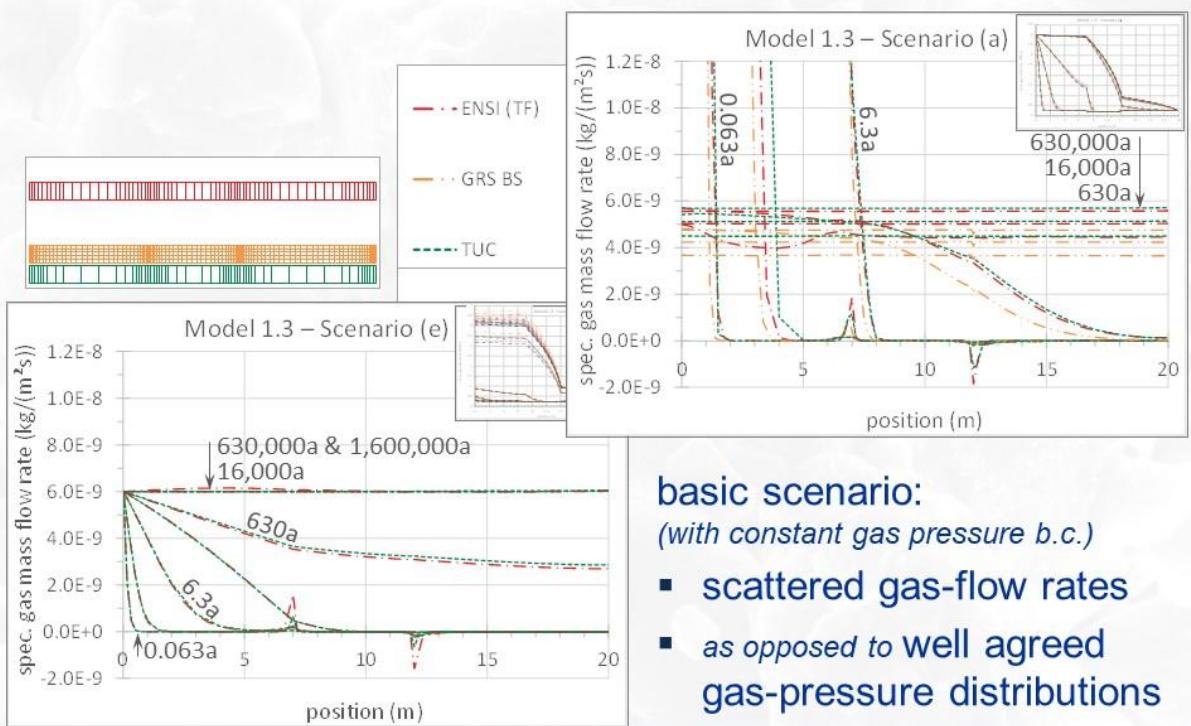


constant gas source:

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

15

## H<sup>2</sup>M Model: Constant Gas Source



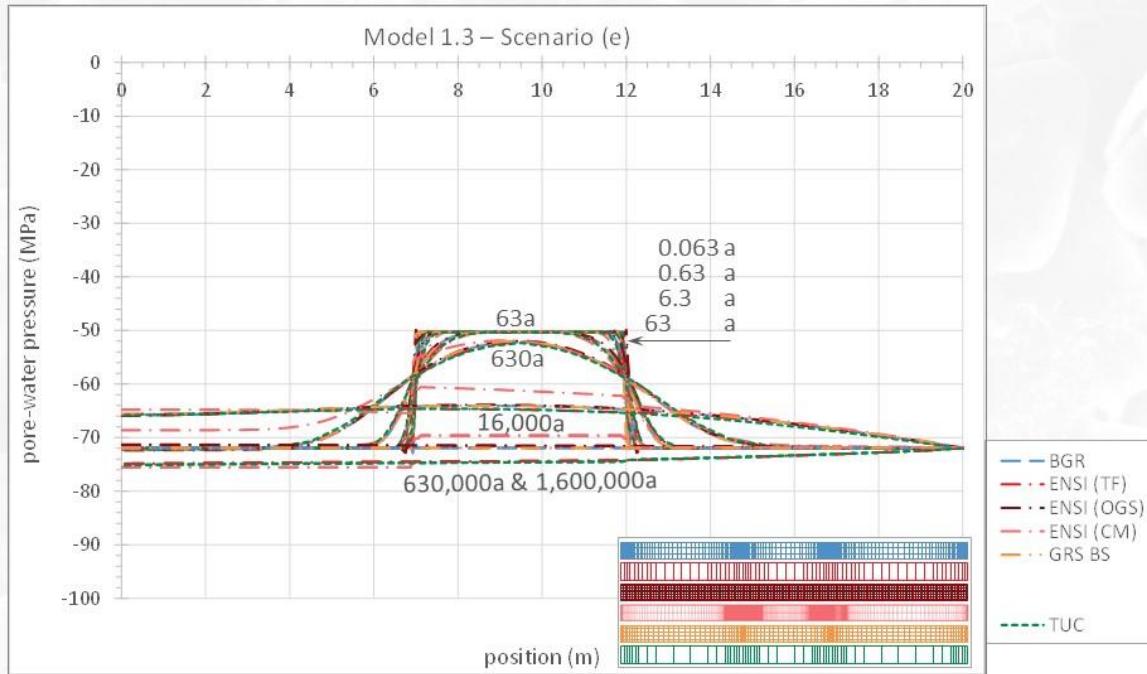
basic scenario:

(with constant gas pressure b.c.)

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

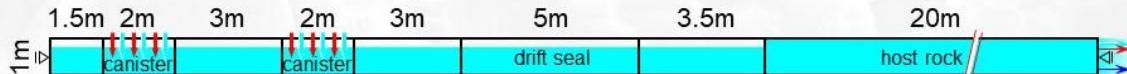
16

## H<sup>2</sup>M Model: Constant Gas Source



17

## TH<sup>2</sup>M Model



$$u_{lhs} = 0 \text{ m}$$

$$\sigma_{tot0} = 8 \text{ MPa}$$

$$u_{rhs} = 0 \text{ m}$$

$$\frac{repo}{sitory} \quad p_{go} = 0.1013 \text{ MPa}$$

$$S_{lo} = 0.75$$

$$MPa \quad \frac{host}{rock} \quad p_{g0} = 4 \text{ MPa}$$

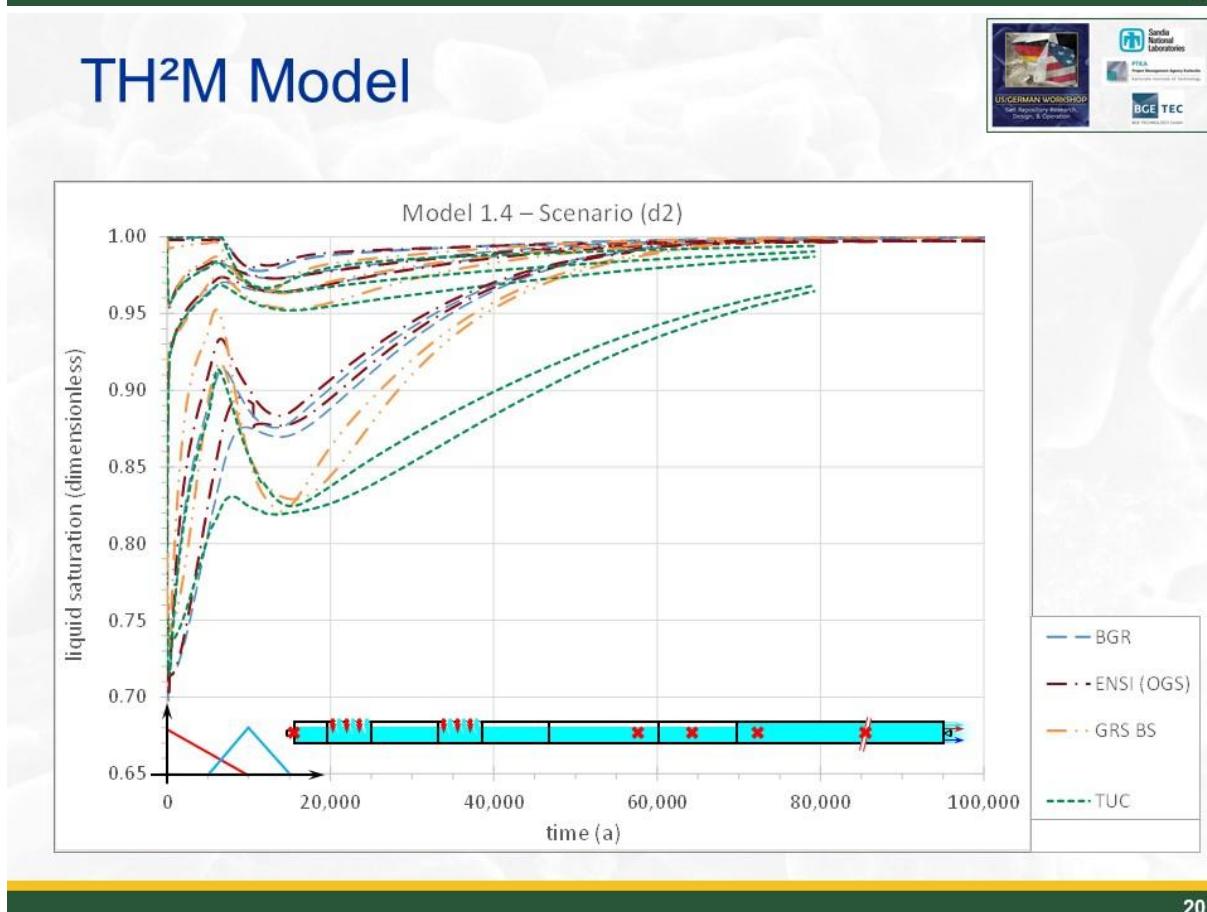
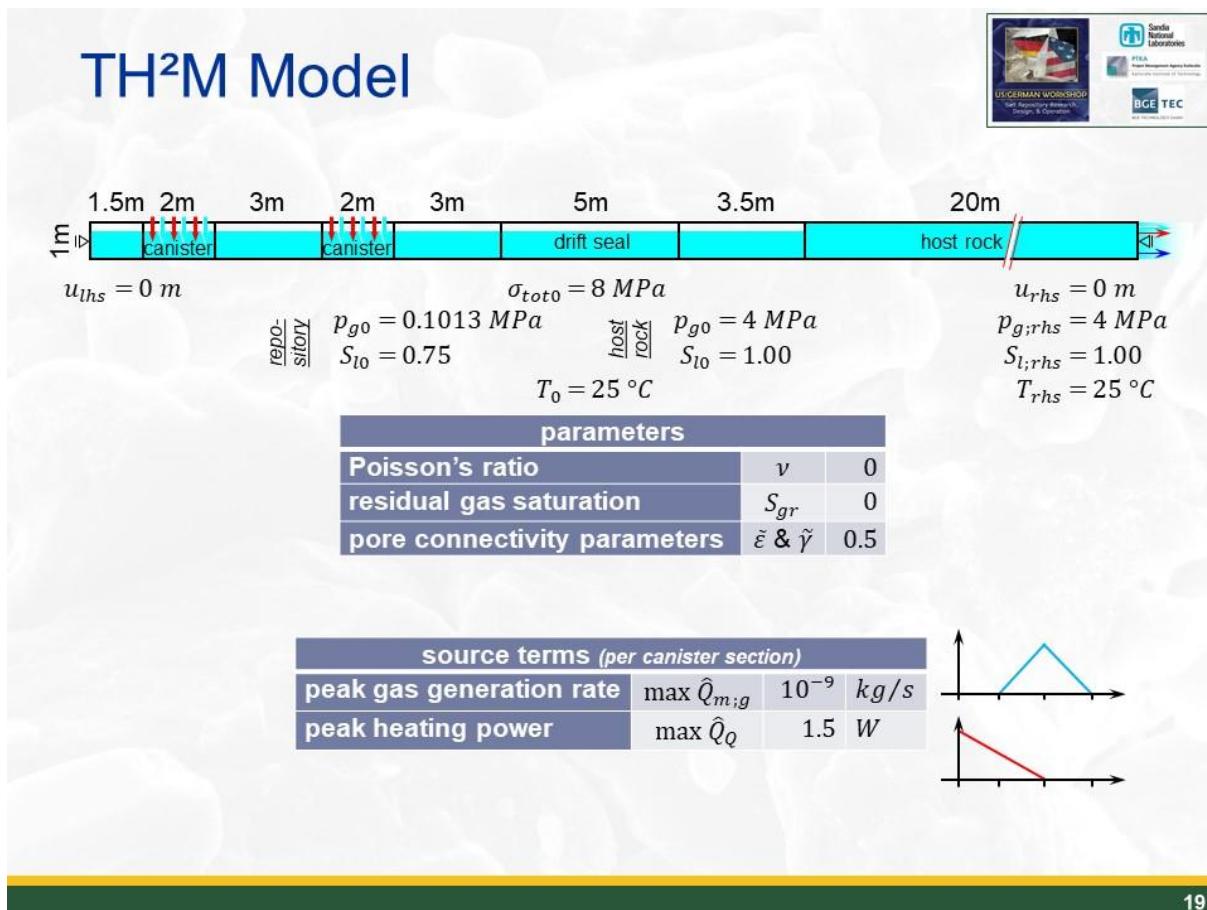
$$p_{g;rhs} = 4 \text{ MPa}$$

$$T_0 = 25^\circ C$$

$$T_{rhs} = 25 \text{ } ^\circ\text{C}$$

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

18

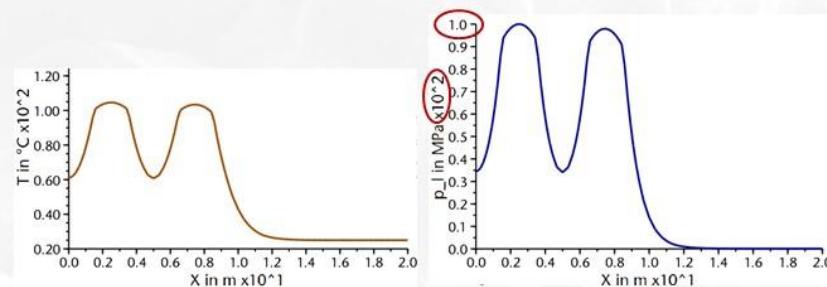


# TH<sup>2</sup>M Model



## → 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 ( $S_i = 100\%$ )



(model yet without host rock area)

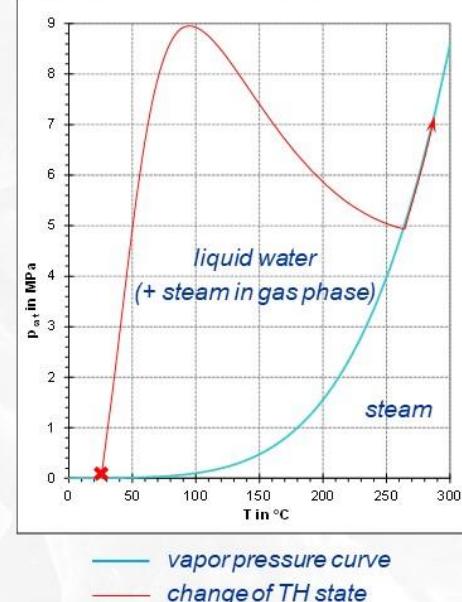
21

# TH<sup>2</sup>M 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

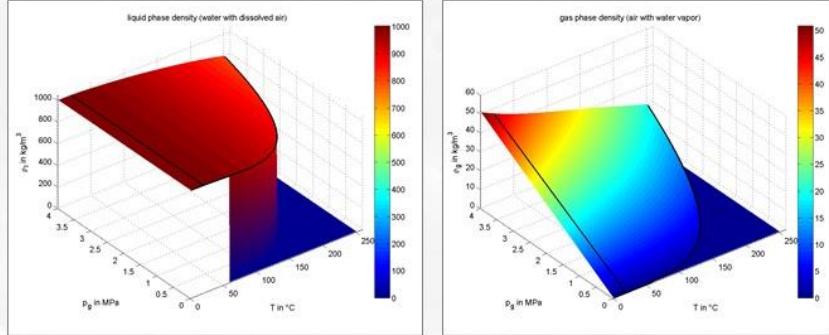


22

## TH<sup>2</sup>M Model



- it is expected that simulators treat the underlying thermodynamical 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

23

## Conclusions



- models look simple, but simulating is not straightforward
- comprehension for TH<sup>2</sup>M 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

Supported by:

**Thank you for your  
attention!**



Federal Ministry  
for Economic Affairs  
and Energy

MANAGED BY



PTKA  
Project Management Agency Karlsruhe  
Karlsruhe Institute of Technology

on the basis of a decision  
by the German Bundestag

24

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- *Lux, K.-H.; Rutenberg, M.; Feierabend, J. (to appear 2021): BenVaSim—International Benchmarking for Verification and Validation of TH<sup>2</sup>M Simulators with Special Consideration of Fluid Dynamical Processes in Radioactive Waste Repository Systems. Final report, BMWi project 02E11567A, TUC, Clausthal-Zellerfeld, Germany.*
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26





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

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



2

# Multi-Lab Team



## Sandia National Laboratories (SNL)

Kris Kuhlman, Melissa Mills, Rick Jayne, Ed Matteo, Courtney Herrick, Charles Choens, Jason Heath, Martin Nemer, Yongliang Xiong, Matt Paul



## Los Alamos National Laboratory (LANL)

Phil Stauffer, Hakim Boukhalfa, Thom Rahn, Eric Guiltinan, Mike Janicke



## 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



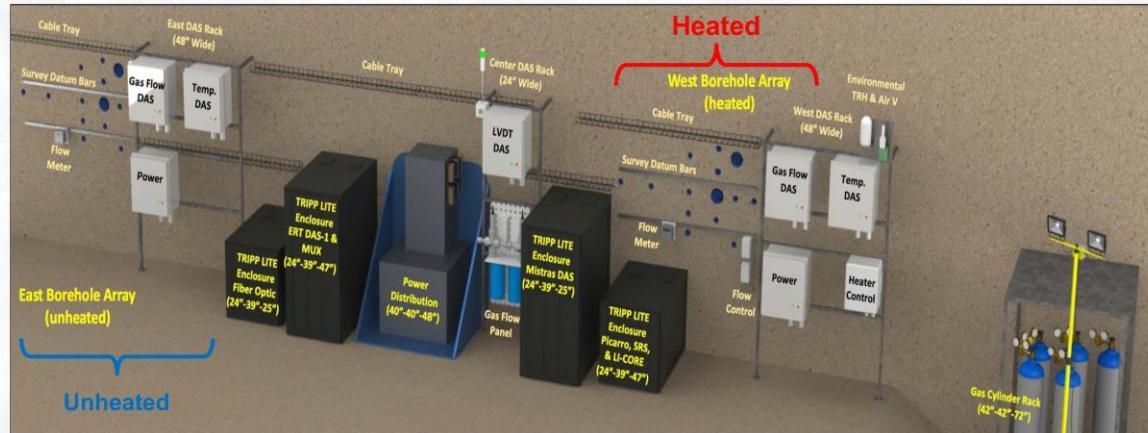
\*Retired March 2021

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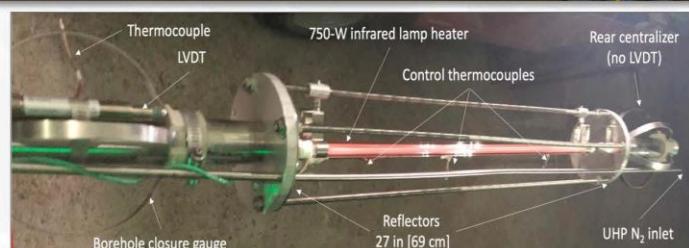
# Test Overview: Phase 1



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



- Behind central packer
  - Circulate dry N<sub>2</sub>
  - Quartz lamp heater (750 W)
  - Borehole closure gage (LVDT)



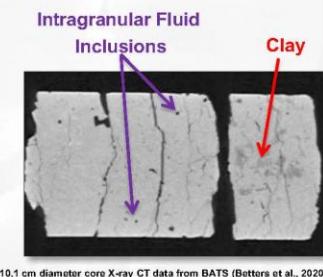
SFWST

## Test Overview: Data Being Collected

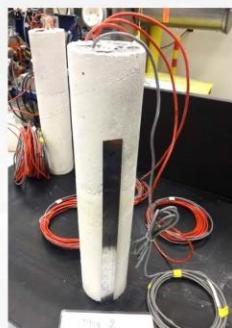


### Samples / Analyses

- 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

5

## BATS 1 Borehole Array Schematic



T = Temp Only Hole  
AE = Acoustic Emissions  
SL = Seal  
D = DSS/DST Source  
E = ERT Electrode  
F = Fiber Optic (T and/or Strain)  
SM = Sampling  
HP = Heater and Packer

## 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 ( $\text{CO}_2$ )
  - Geogenic gases within salt (e.g., He & Ar)
  - Added gas tracers (Ne, Kr &  $\text{SF}_6$ )



### ▪ Gas Stream Humidity

- LI-COR 850  $\text{CO}_2/\text{H}_2\text{O}$
- Drierite canisters weighed ~weekly



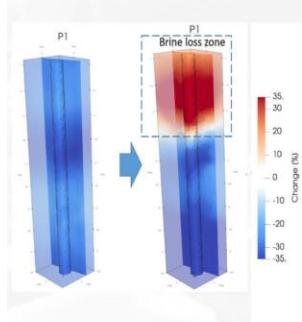
SFWST

## Geophysical Methods



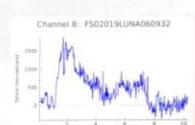
### ▪ Acoustic Emissions (AE)

- 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

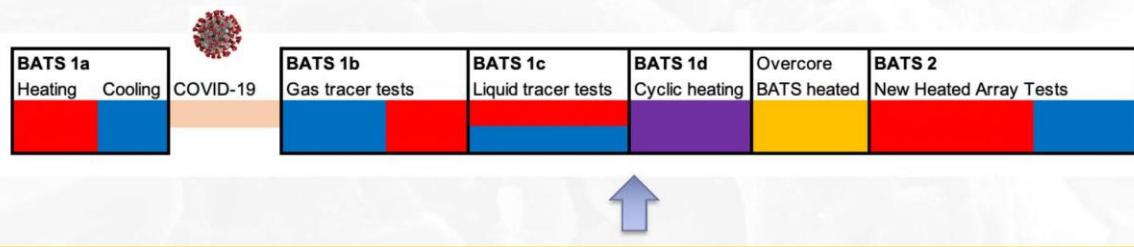
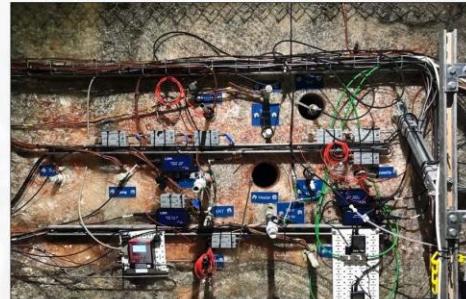


SFWST

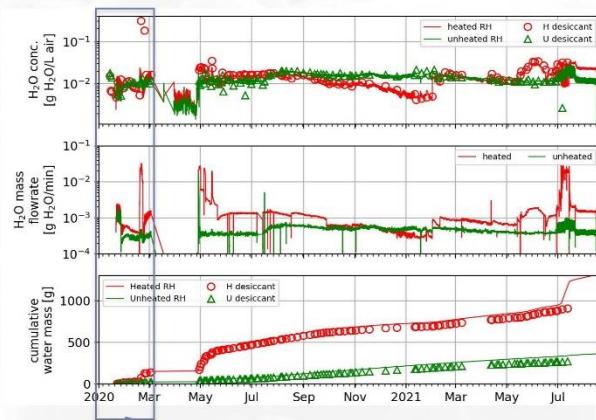
## BATS Stages



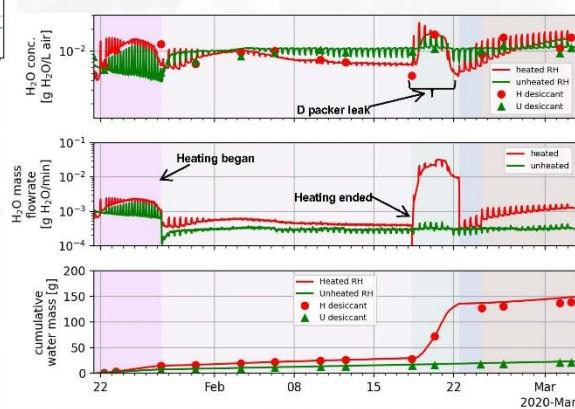
- BATS 1 borehole drilling and install (2019)
- BATS 1a heated phase (Jan-Mar 2020)
- COVID-19
- Gas & liquid tracer tests (Jan-July 2021)
- Cyclic heating (summer-fall 2021)
- New BATS 2 boreholes (October 2021)
  - New array in argillaceous halite (MU-0)
  - Similar heater test in new boreholes



## Brine Inflow Data (Jan 2020 – Aug 2021)



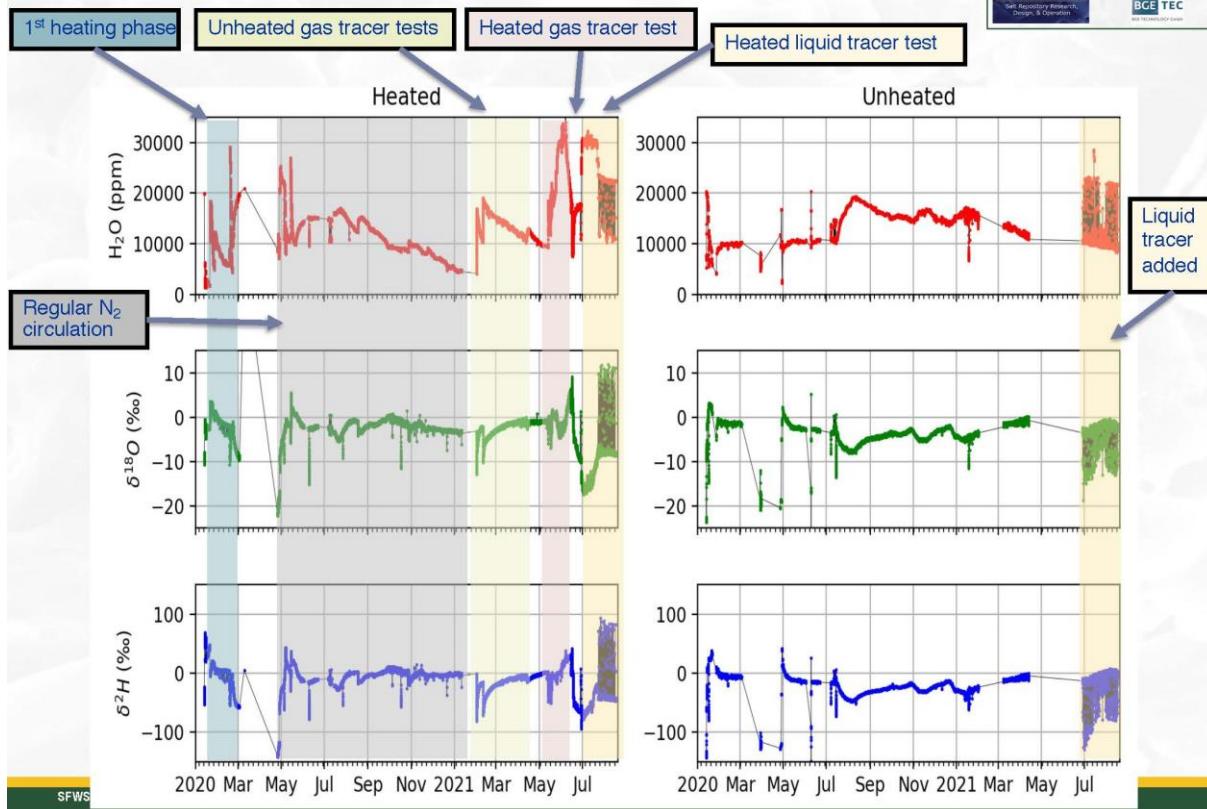
- Collected from outflow of borehole with relative humidity sensors and desiccant weights



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

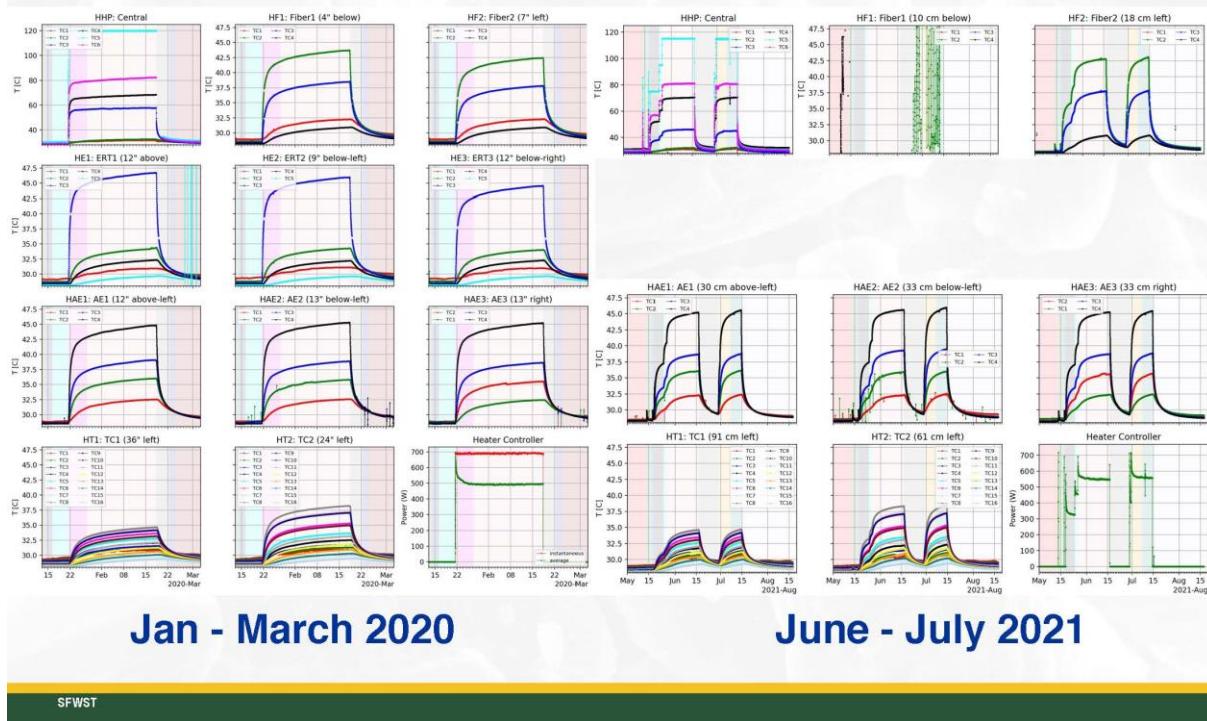
SFWST

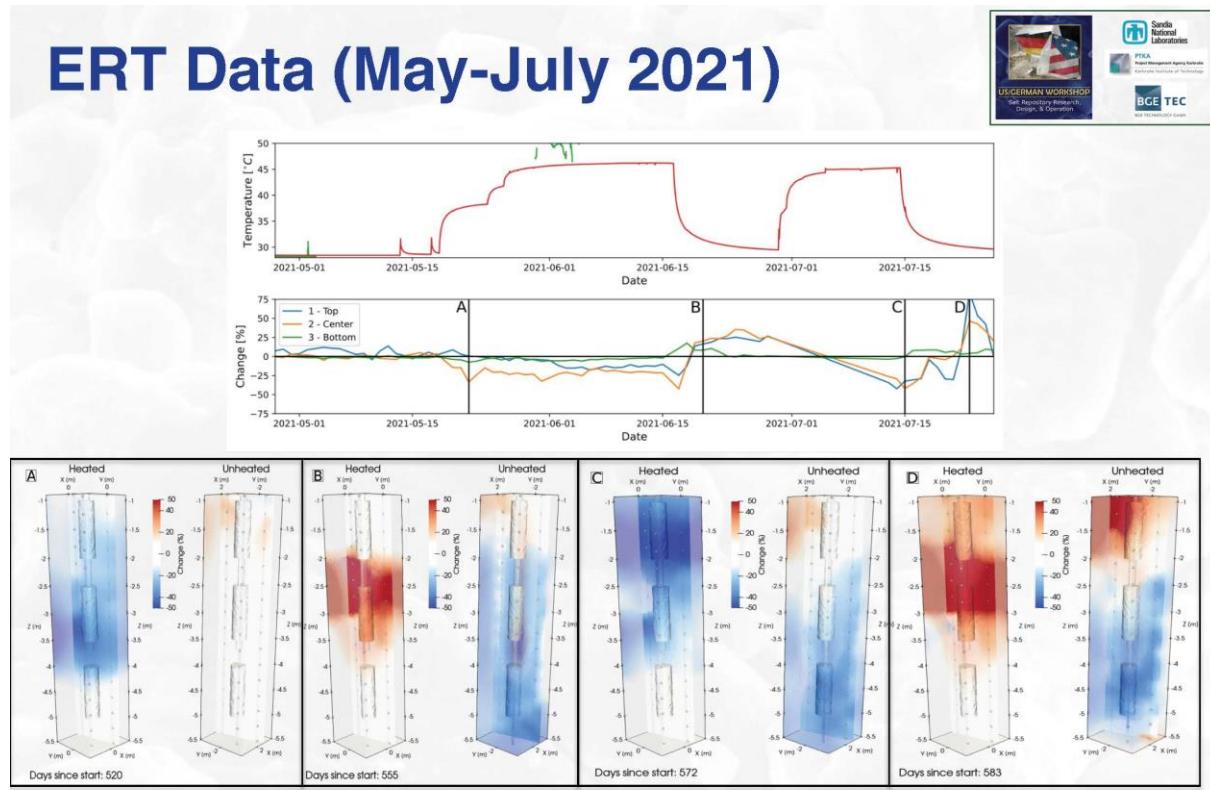
## Isotopic Data (Jan 2020 – Aug 2021)



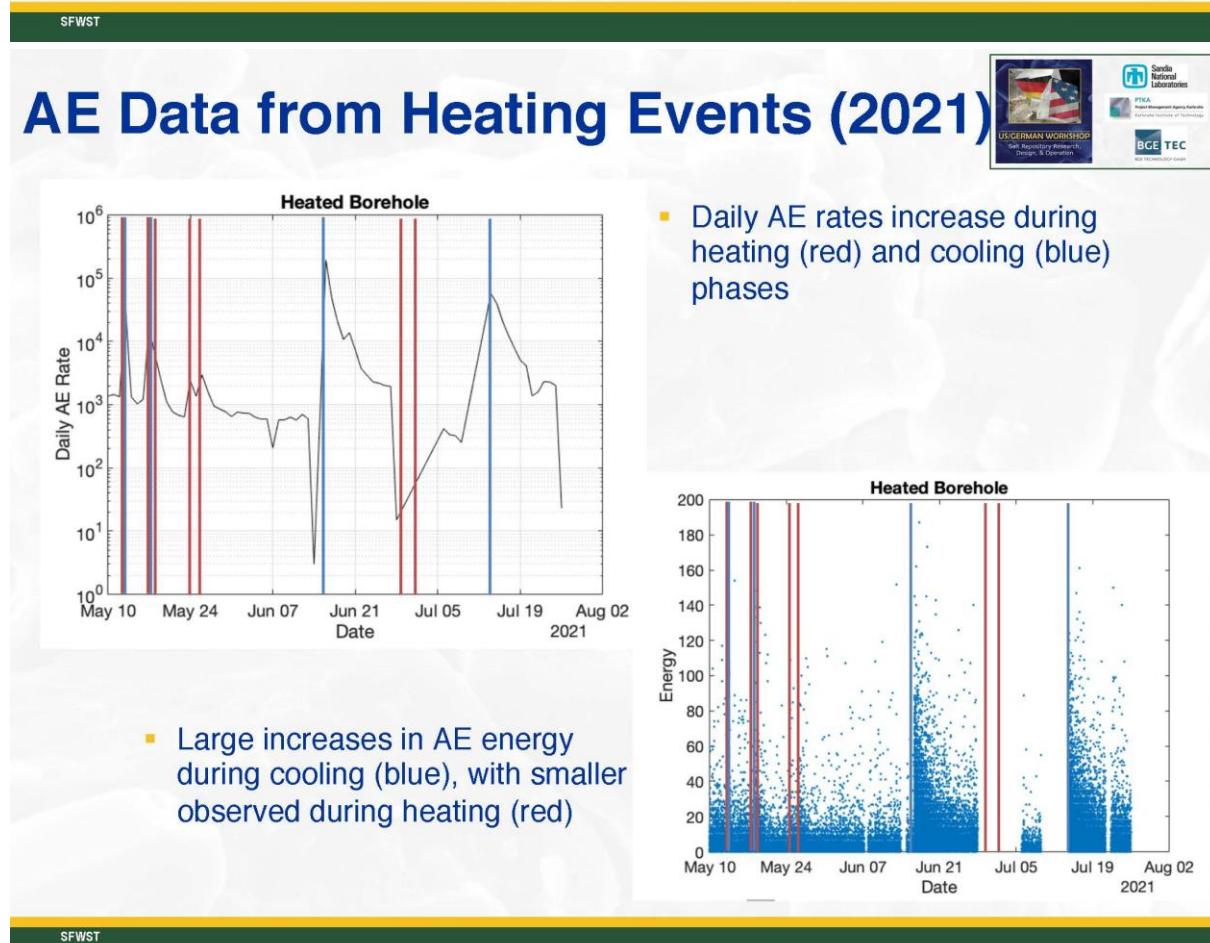
## Temperature Data from Heating Events

- Over 50 thermocouples installed throughout the heated array





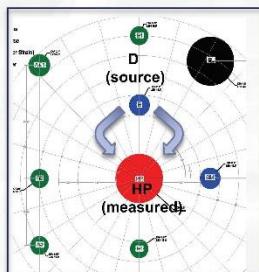
- Changes in both arrays during two heating phases and tracer tests



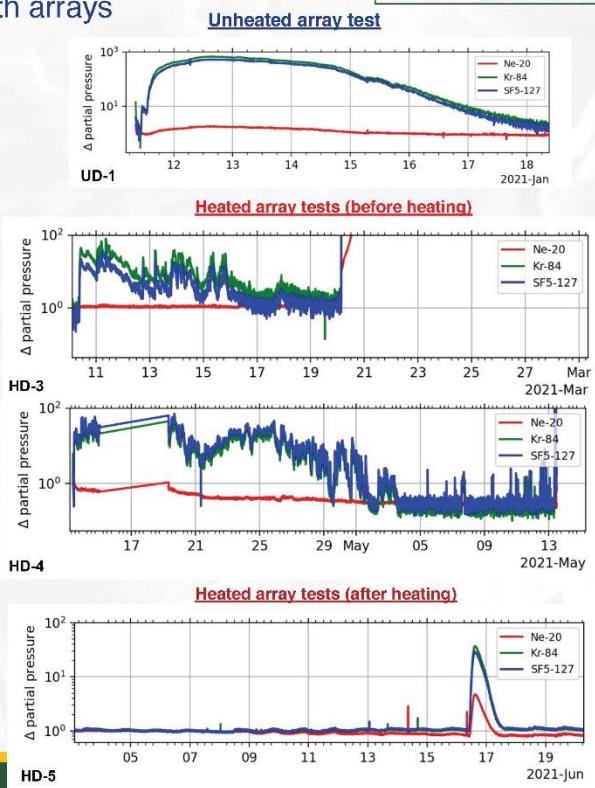
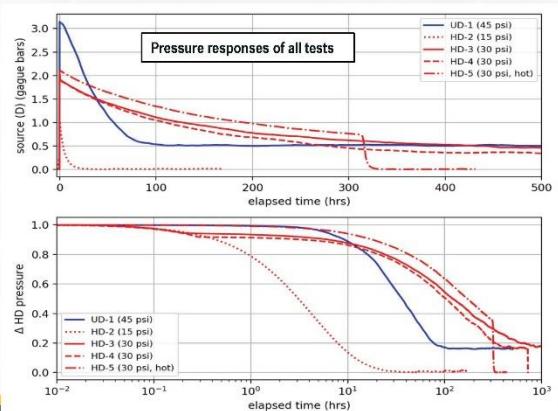
## Gas Tracer Tests (2021)



- Injected gas tracer into D-borehole of both arrays (5 tests total)



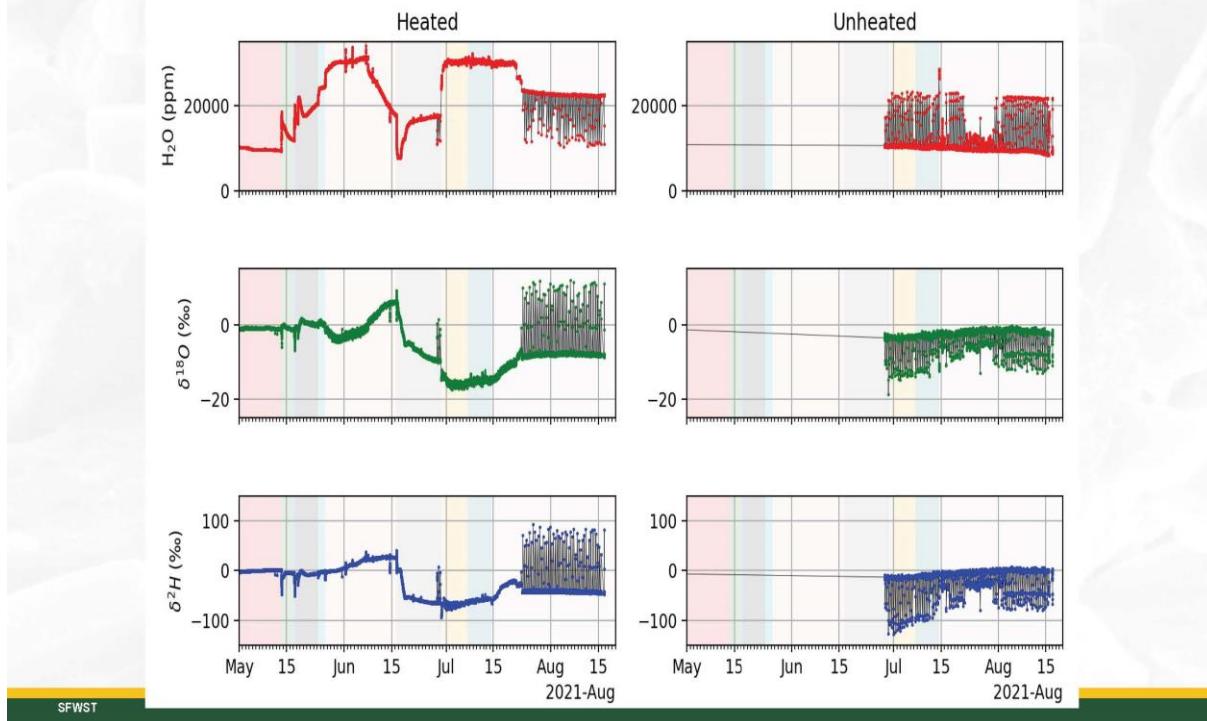
- Composition:
  - 5% Ne
  - 5% Kr
  - 5% SF6
  - 85% N2



## Liquid Tracer Test (July 2021)



- Injected brine made with isotopically light water, a fluorescent tracer, and rhenium

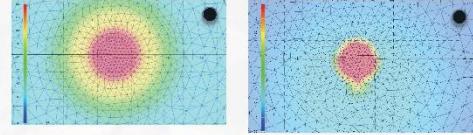


# BATS Outcomes



## ■ 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

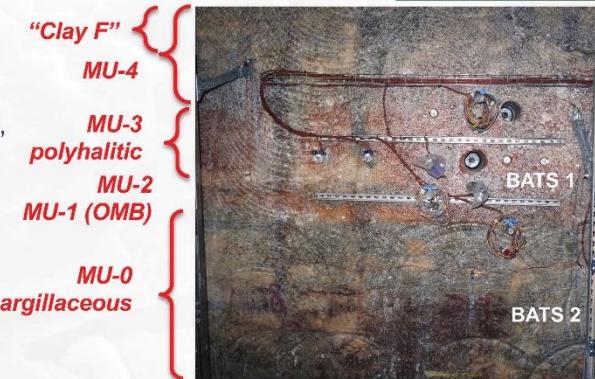
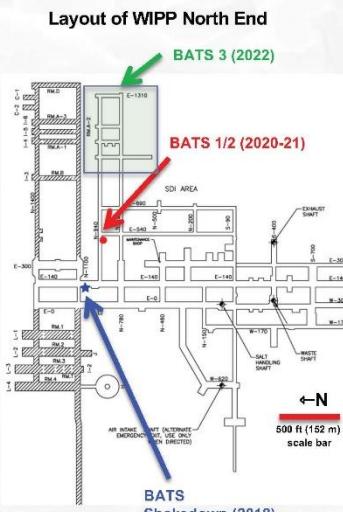
- Significant testing in 1980s (replace retired staff)



# BATS Future Plans



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



## ■ 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





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



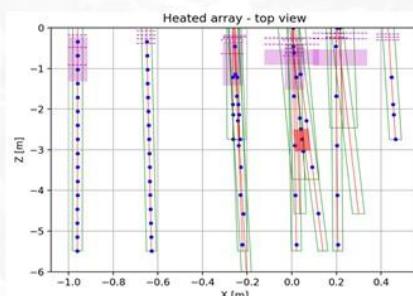
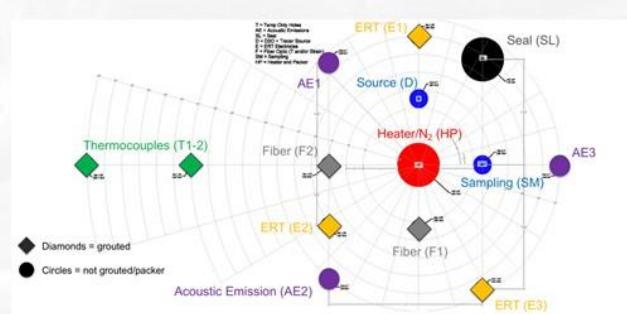
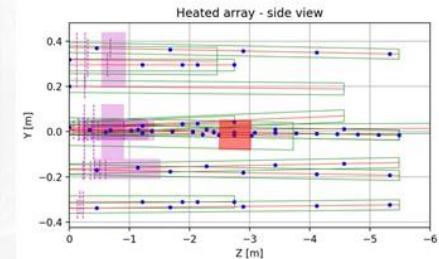
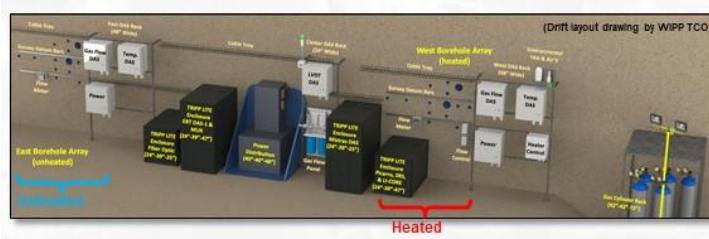
Richard Jayne  
Sandia National Laboratories

Part 4 of the online workshop  
September 9th, 2021

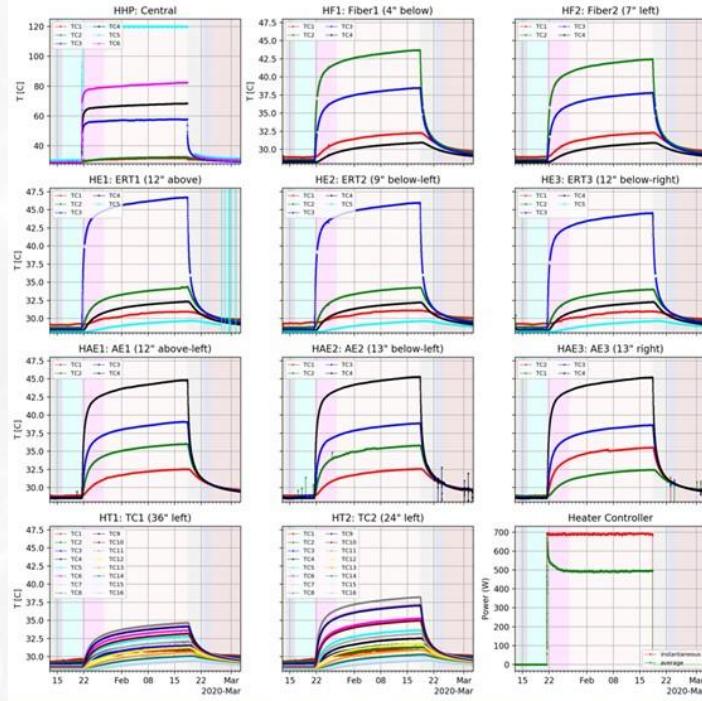
SAND2021-10940 C

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## BATS EXPERIMENTAL SETUP



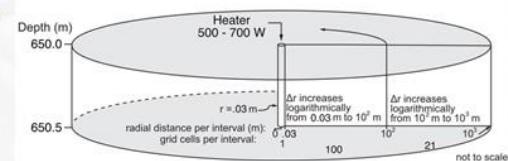
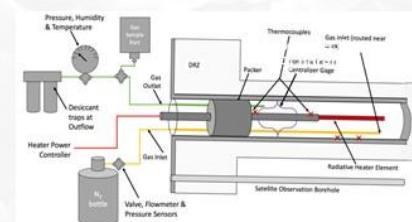
# JANUARY - MARCH 2020 BATS TEST DATA



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



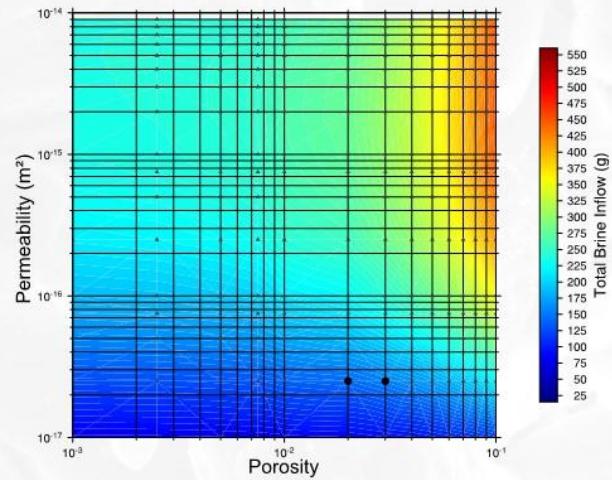
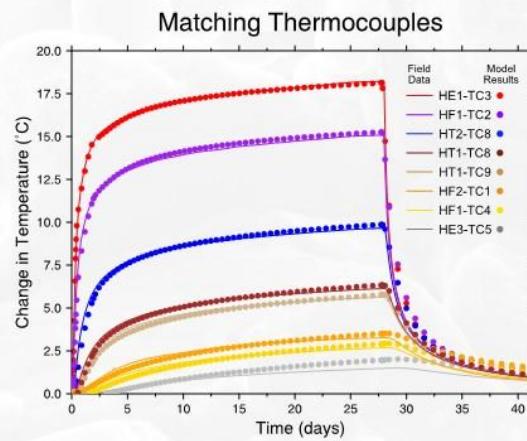
## RESERVOIR PARAMETERS

$P_i = 0.1 - 12.4 \text{ MPa}$	Relative Permeability	Capillary Pressure
$T = 29.5^\circ\text{C}$	$\lambda = 0.412$	$\lambda = 0.412$
$k = 10^{-17} - 10^{-22} \text{ m}^2$	$S_o = 0.2$	$S_o = 0.2$
$\varphi = 0.001 - 0.01$	$S_n = 1.0$	$\alpha (\text{Pa}^{-1}) = 6.5 \times 10^{-5}$
$K = 2.0 - 7.0 \text{ W/m}^\circ\text{C}$	$S_g = 0.2$	$S_g = 0.999$
$c = 366 - 1000 \text{ J/kg}^\circ\text{C}$		

(Jayne and Kuhlman, 2020)

4

# 1-D MODELS WERE EFFECTIVE MATCHING BATS FIELD DATA



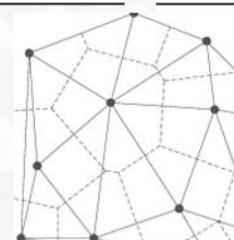
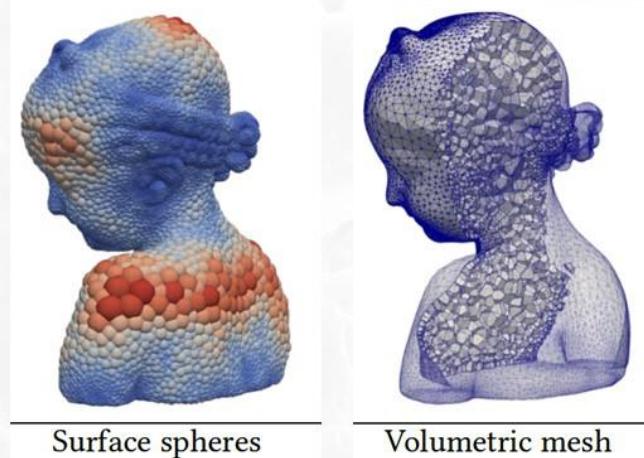
(Jayne and Kuhlman, 2020)

5

## MESHING THE COMPLEX GEOMETRY OF BATS



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

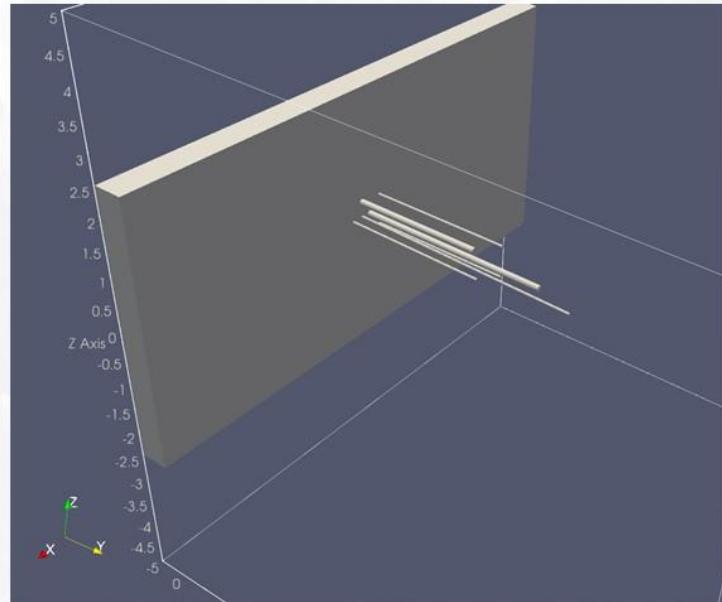


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# MESHING THE COMPLEX GEOMETRY OF BATS

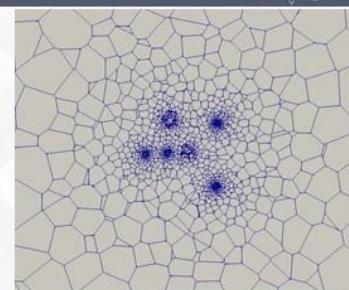
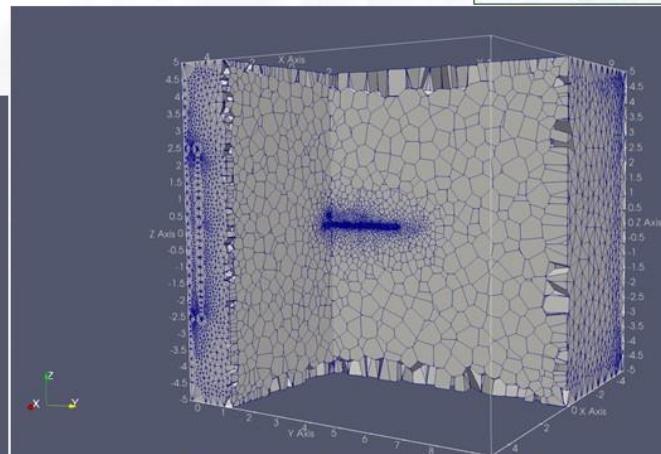
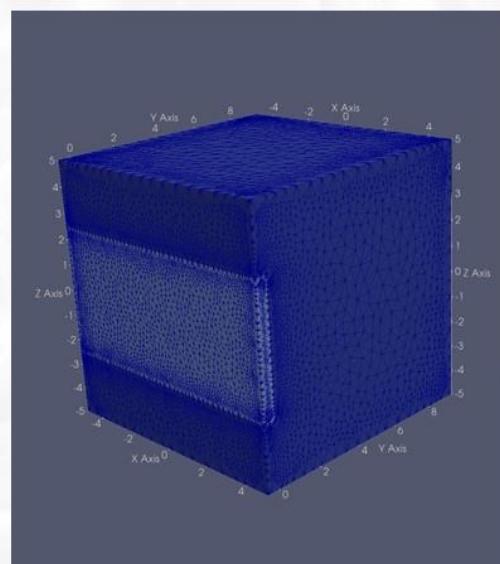


- Create surfaces
  - E.g. LaGrit
- Input for Vorocrust = .obj
- Few required parameters
- Complex geometry with orthogonal discretization

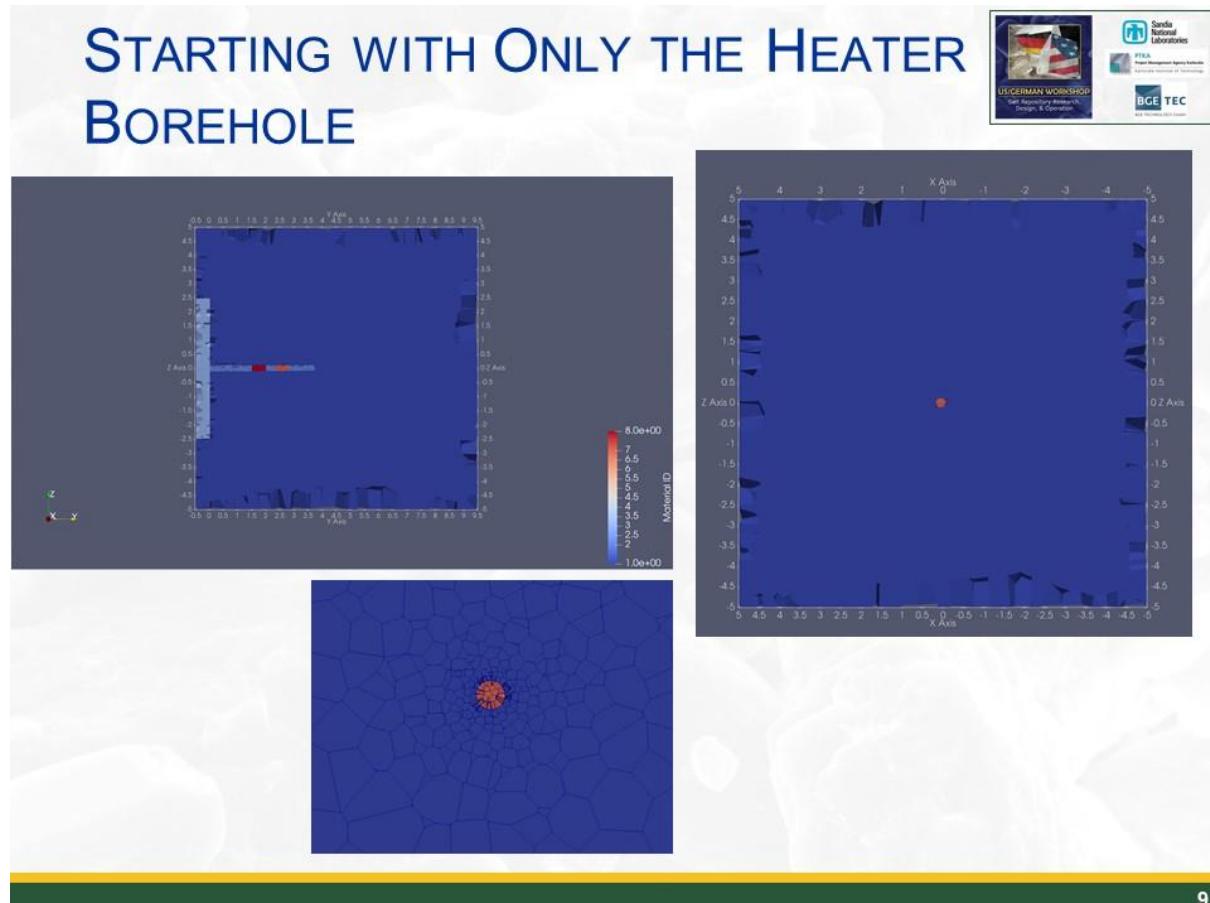


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# MESHING THE COMPLEX GEOMETRY OF BATS



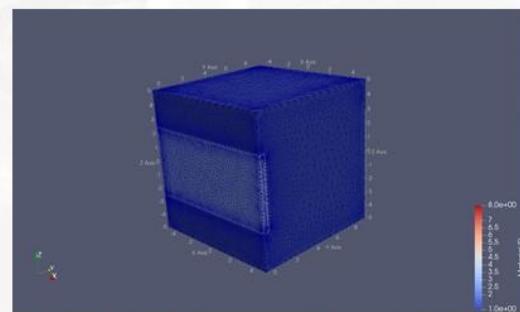
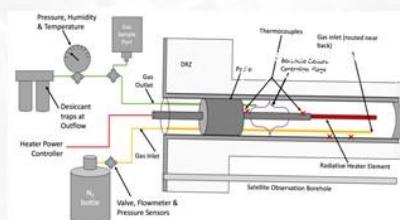
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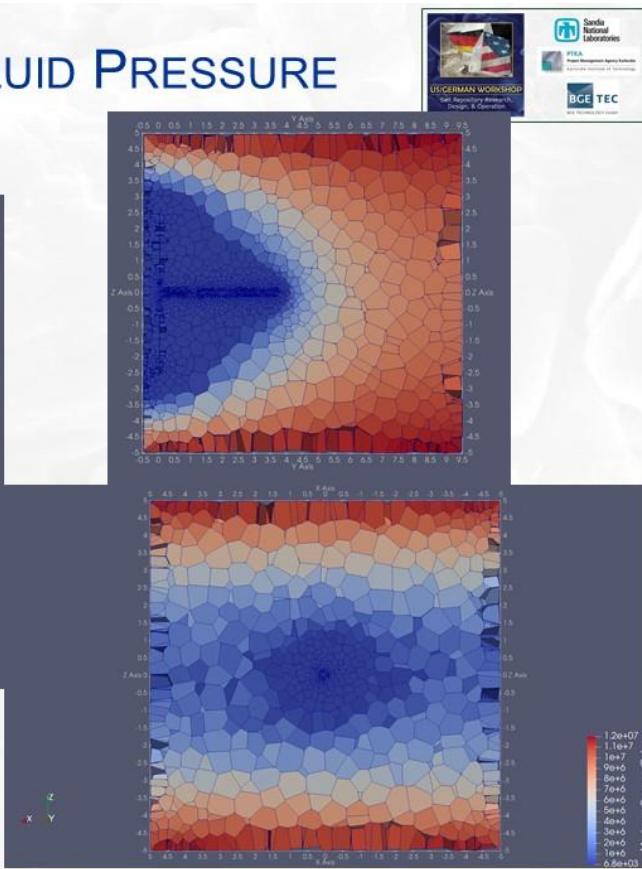
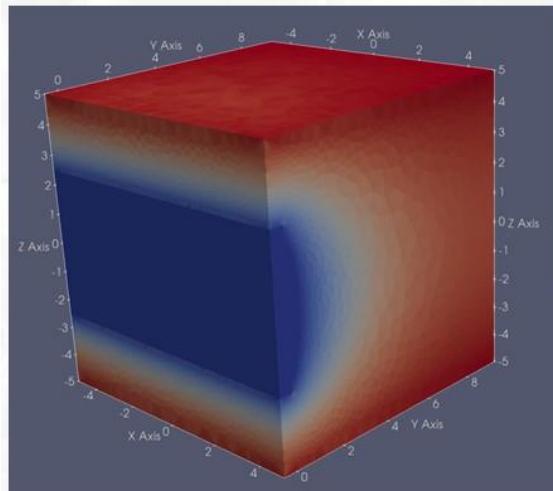
## BUILDING COMPLEXITY - UTILIZING 3-D MODELS TO MATCH FIELD TEST

- 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



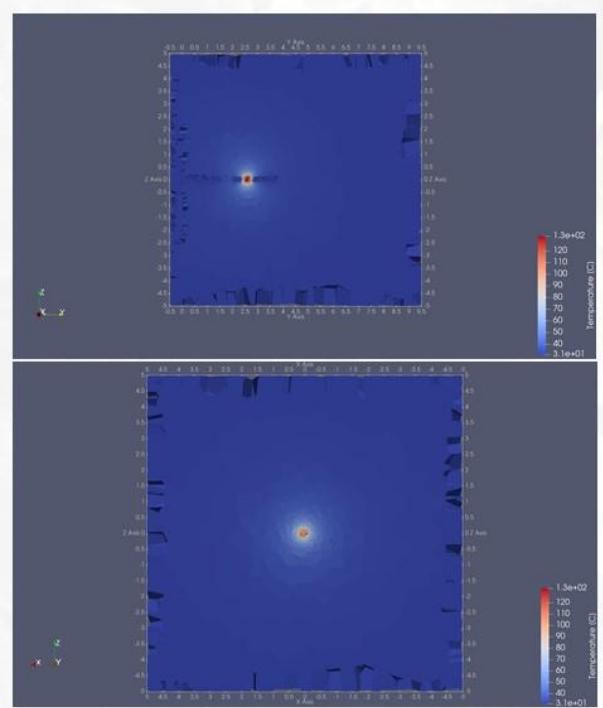
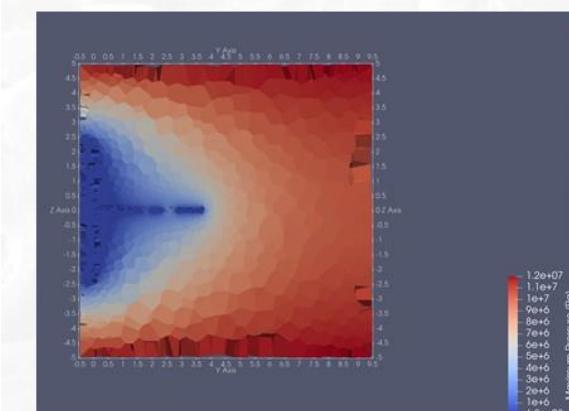
10

## INITIAL CONDITIONS - FLUID PRESSURE

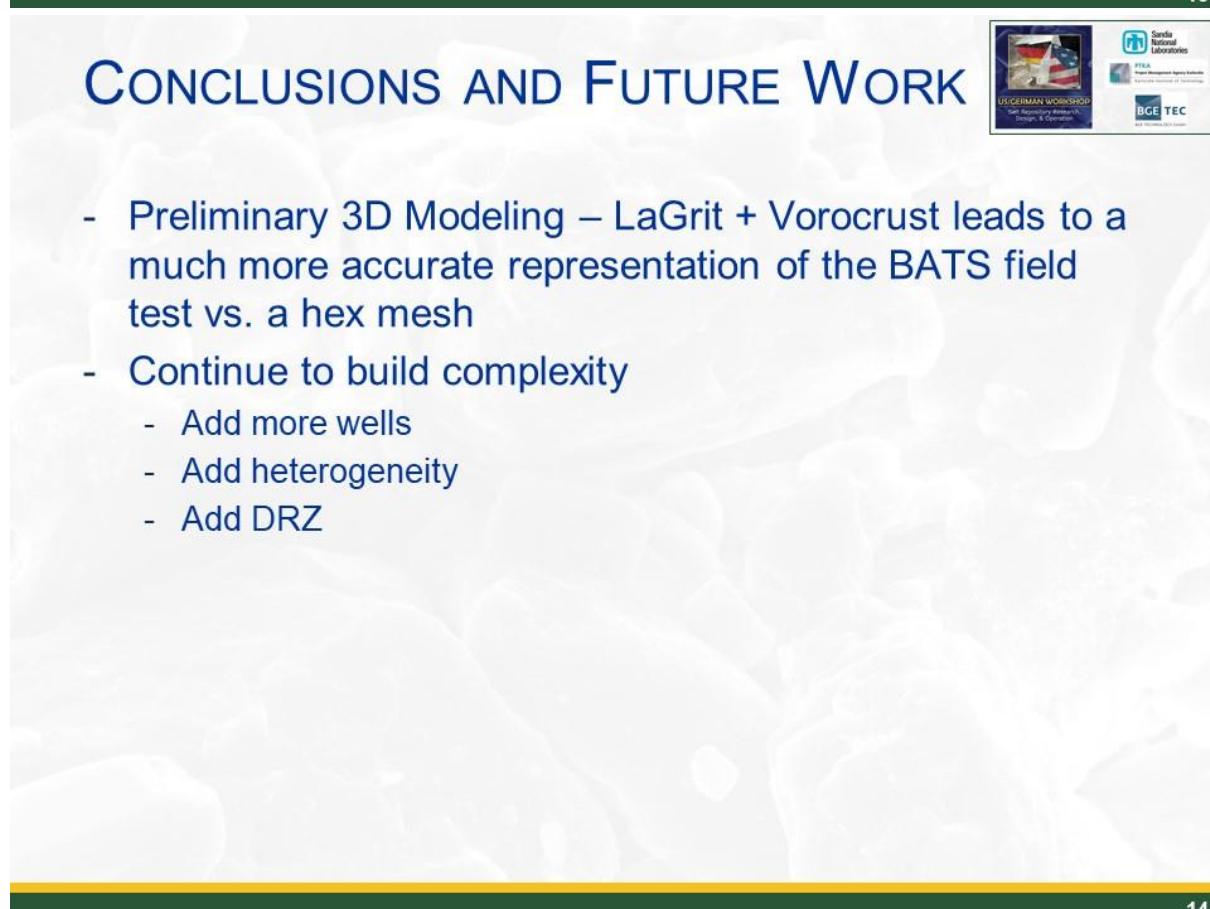
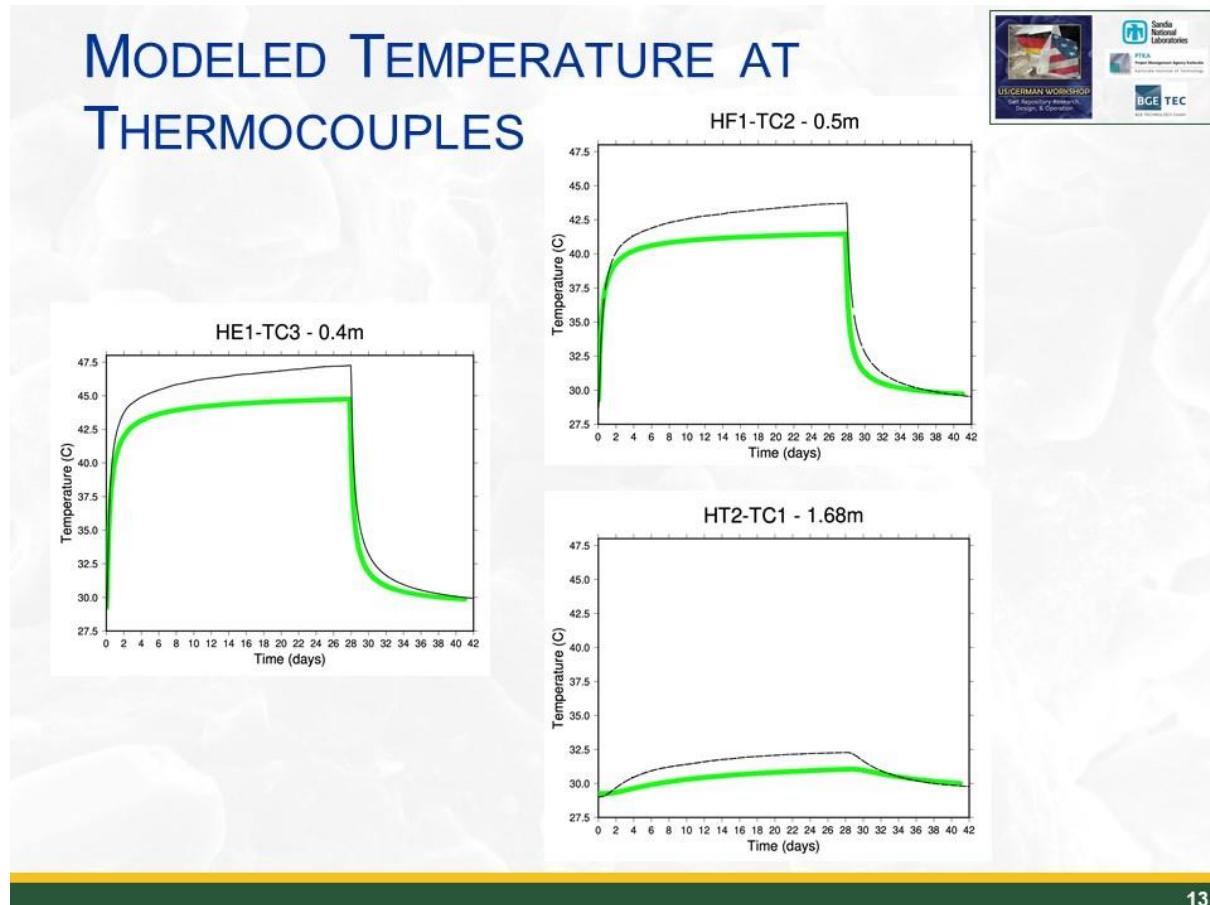


11

## TEMPERATURE AND FLUID PRESSURE AT THE END OF HEATING



12







## BATS Field Test and Related Modeling



Eric Guiltinan<sup>1</sup>, Thomas Rahn<sup>1</sup>, Shawn Otto<sup>1</sup>, Melissa Mills<sup>2</sup>, Kristopher Kuhlman<sup>2</sup>, and Phil Stauffer<sup>1</sup>

<sup>1</sup>Los Alamos National Laboratory

<sup>2</sup>Sandi National Laboratories

LA-UR-21-28810

Part 4 of the online workshop

September 9th, 2021

## 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.

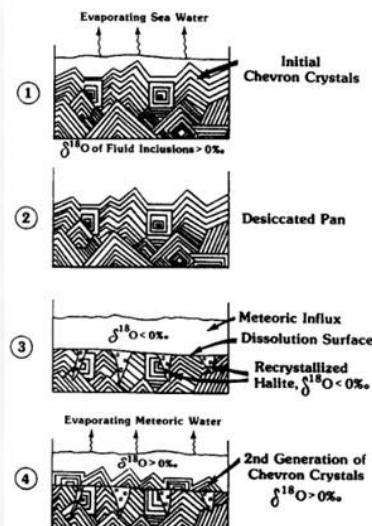


FIG. 10. Relationship between textures in halite and isotopic composition of fluid inclusions. Diagrams after SHEARMAN (1978).

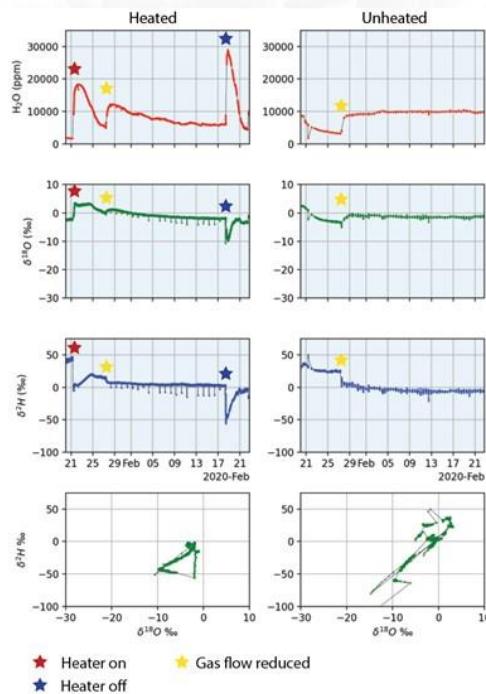
From Knauth & Beeanus, 1985

## Phase 1a Isotopes

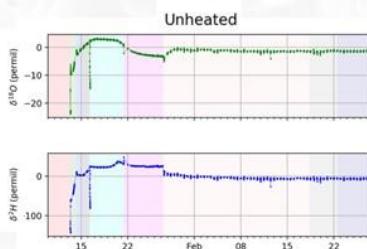


$\text{H}_2\text{O}$  vapor concentration as well as  $\text{d}^{18}\text{O}$  and  $\text{d}^2\text{H}$  in the heated and unheated boreholes as a function of time.

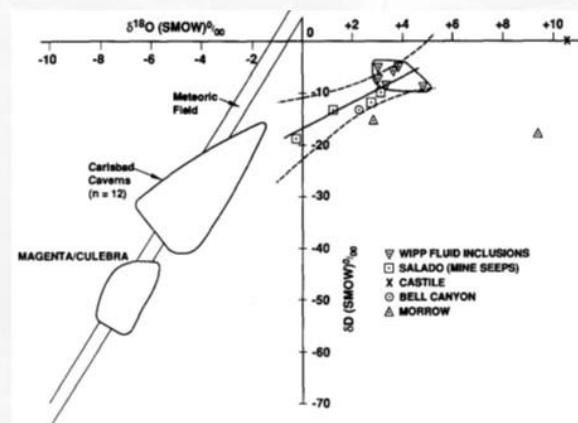
Jan-21-2020: heat on  
 Jan-27-2020: gas reduced (H:50, U:25)  
 Feb-18-2020: heat off (leak)  
 Feb-22-2020: gas spent, leak stops



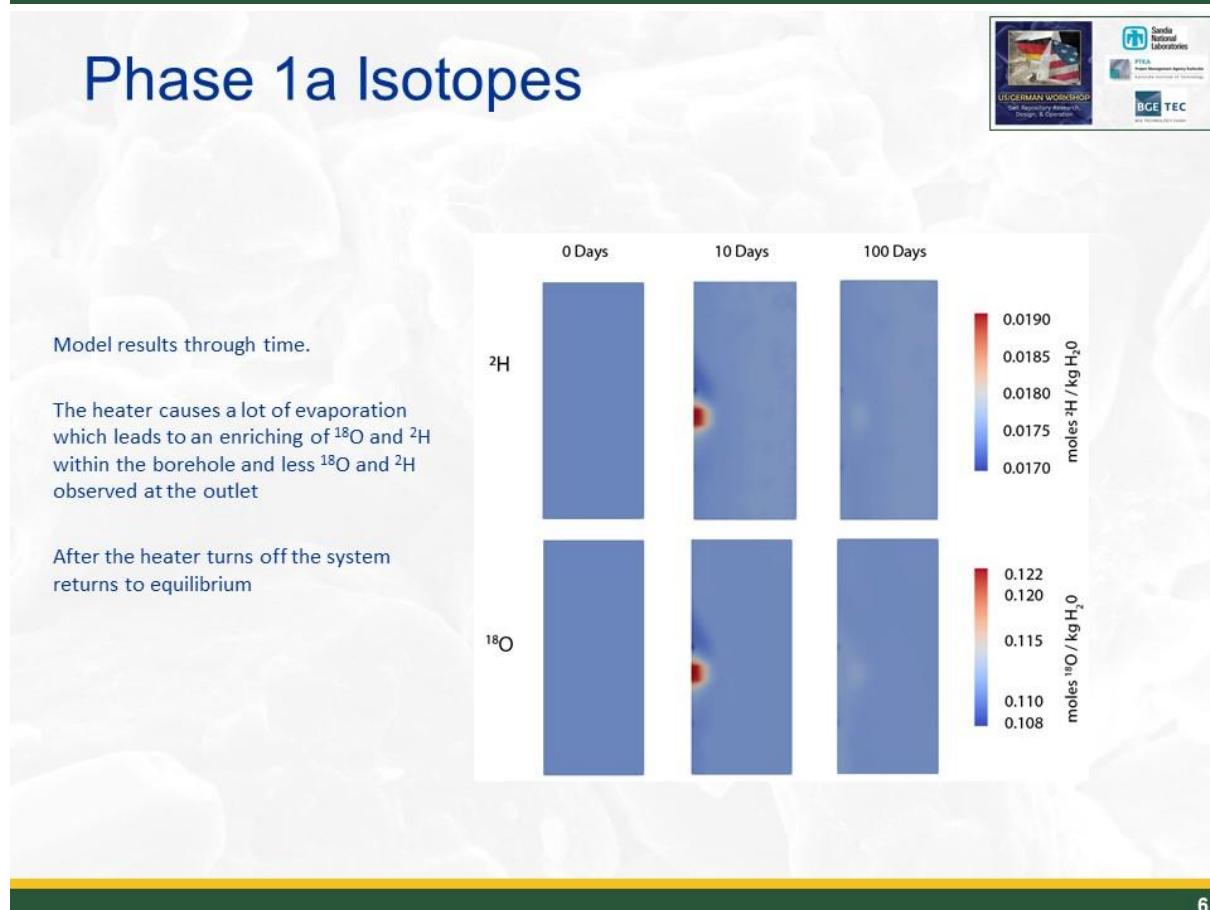
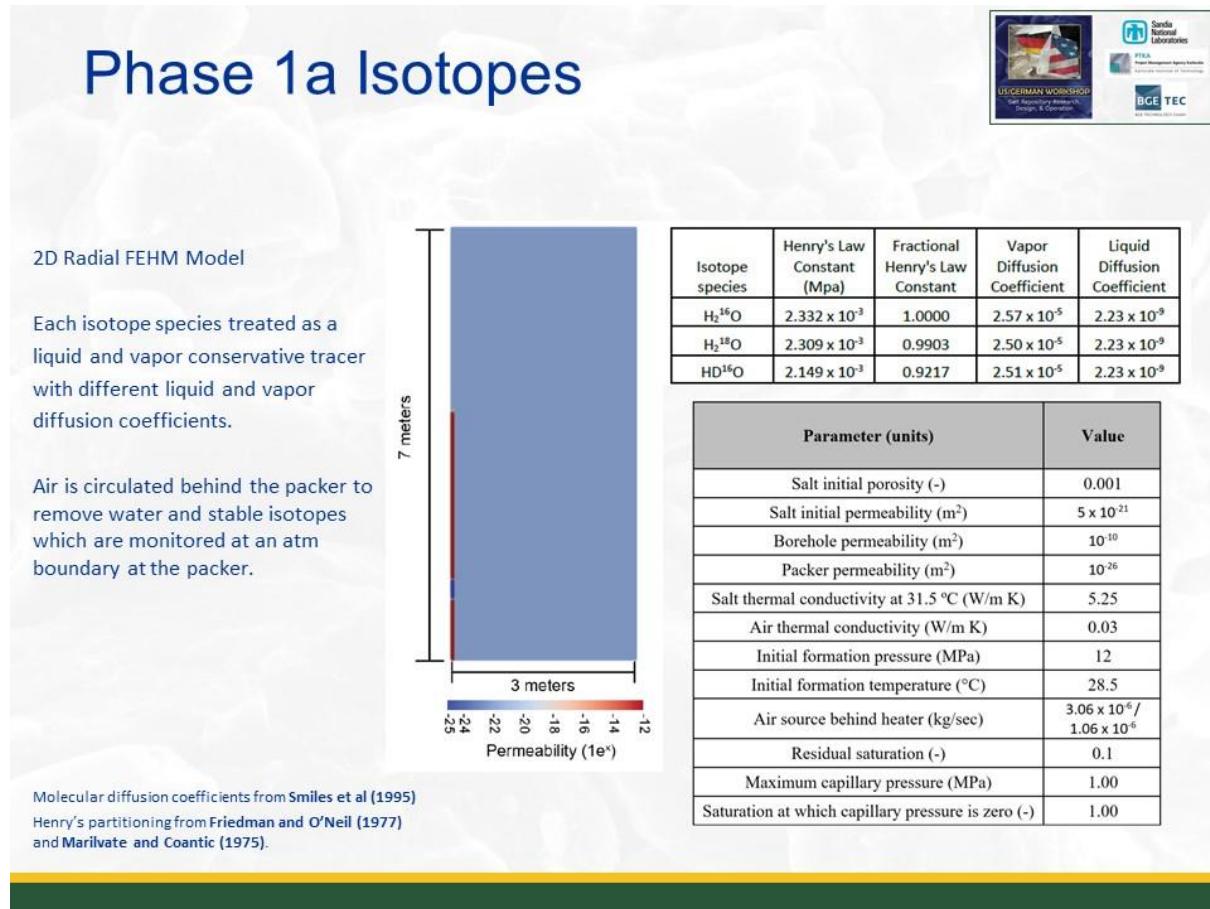
## Phase 1a Isotopes



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



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



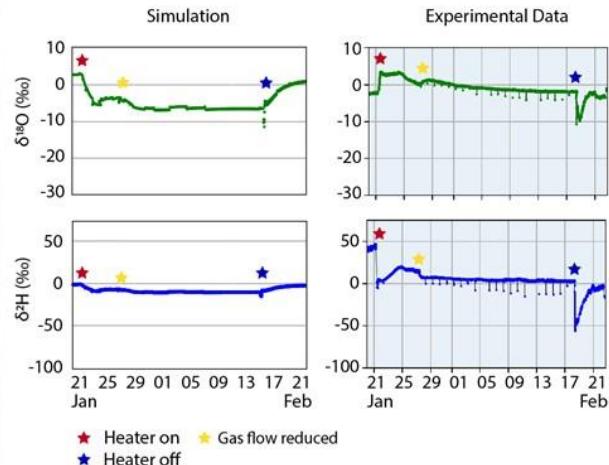
# Phase 1a Isotopes



## $d^{18}\text{O}$ and $d^2\text{H}$ behavior:

- Heater on – Water concentration rises and  $d^2\text{H}$  and  $d^{18}\text{O}$  equilibrate
- Air reduced –  $d^2\text{H}$  falls /  $d^{18}\text{O}$  rises
- Heater off -  $d^2\text{H}/d^{18}\text{O}$  fall sharply and then recover to new background
- FEHM model generally follows the  $d^{18}\text{O}$  response but returns to background after heater off.

Different behavior between  $^2\text{H}$  and  $^{18}\text{O}$  is difficult to explain. Are we seeing a contribution of different sources?



7

# 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.

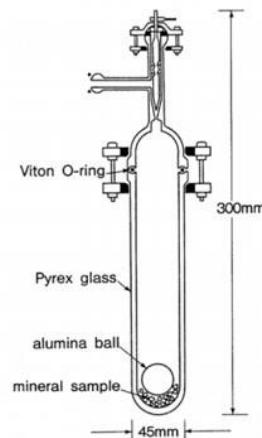
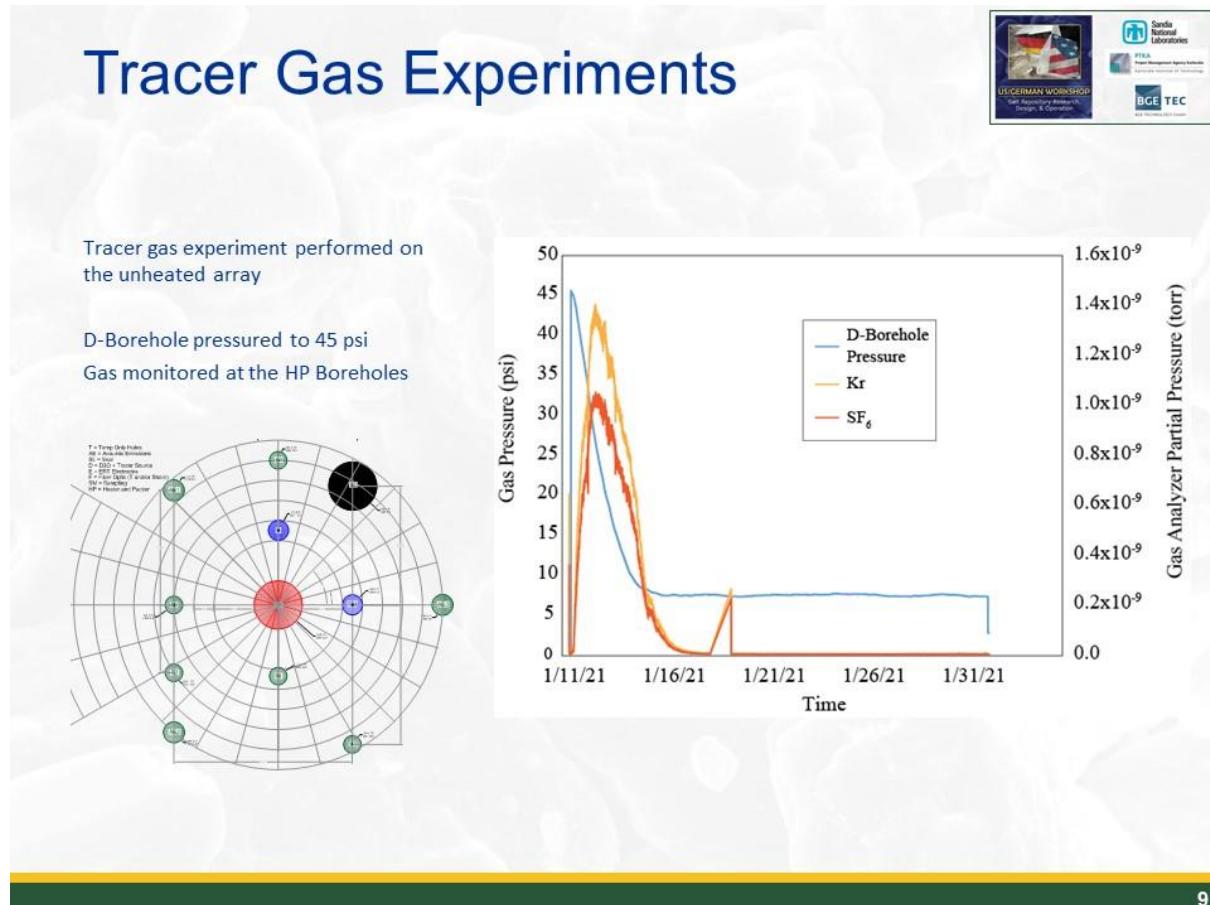
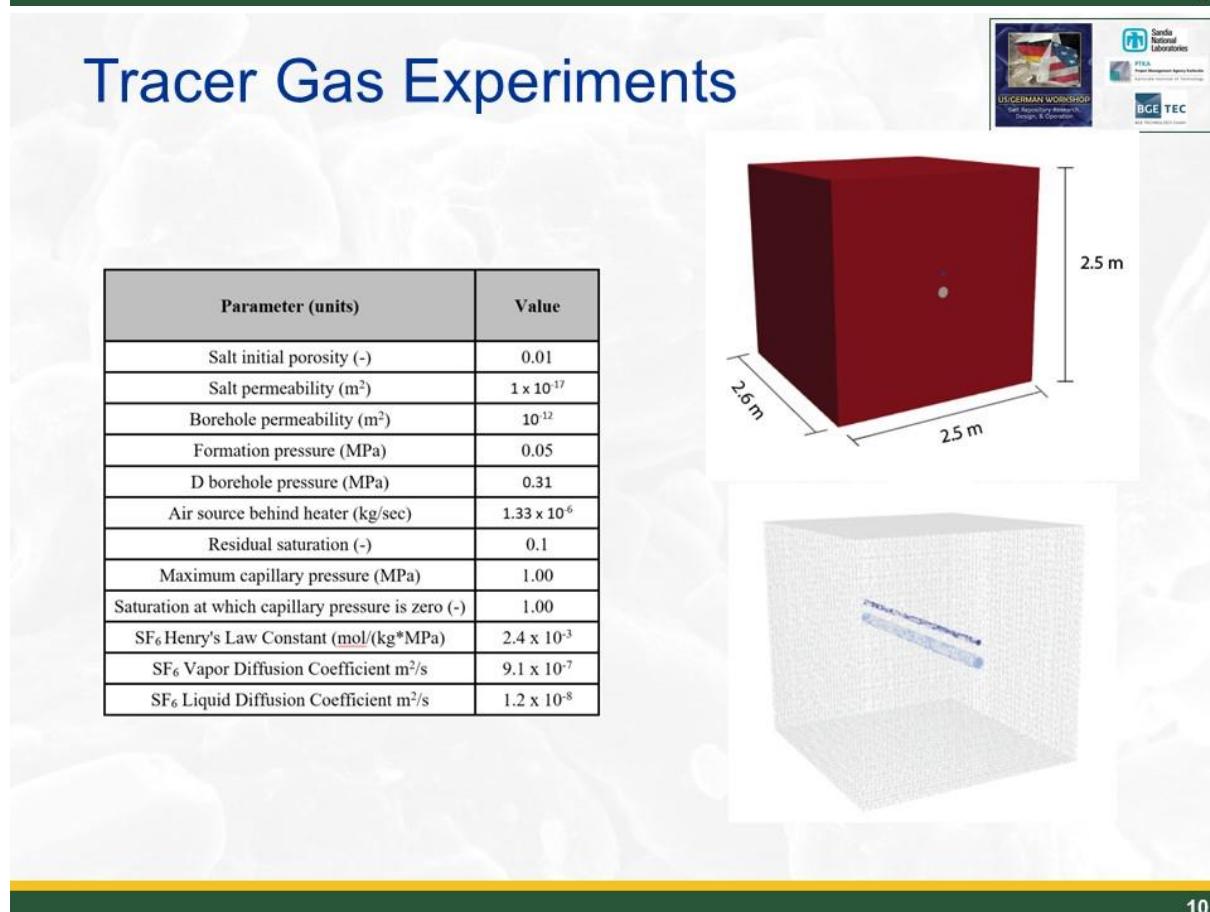


Fig. 1. Ball-mill made of Pyrex glass used in this study

From Horita, 1986



9



10

# Tracer Gas Experiments

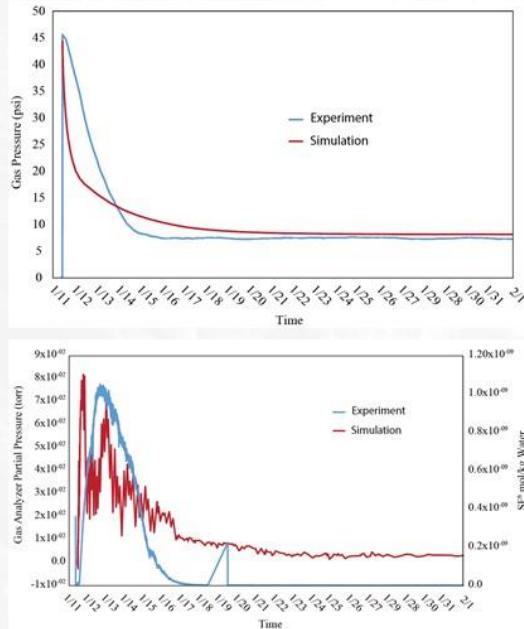


Results are still fairly preliminary.

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.



11

## 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

12



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