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# *Proceedings of the 13th US/German Workshop on Salt Repository Research, Design, and Operation*

## Spent Fuel and Waste Disposition

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# EXECUTIVE SUMMARY

This report summarizes the proceedings of the 13th US/German Workshop on Salt Repository Research, Design, and Operation hosted by Sandia National Laboratories on June 20-23, 2023, in Santa Fe, New Mexico, USA. Over 60 participants attended, representing Germany, United States, the Netherlands, Australia, and the United Kingdom, along with the IAEA. The purpose of the US/German Workshop is to foster in-person collaboration and dialogue amongst salt repository researchers and nuclear waste disposal implementers across international organizations. The workshop included five sessions of topical presentations and two breakout sessions to promote additional discussion on compelling topics. Volunteer authors from attendees provided summaries to capture details of each session and are titled as follows:

- Session 1: Developments in National Programs
- Session 2: Modeling
- Session 3: Breakout- Uncertainties in Modeling and Verification
- Session 4: Special Topics
- Session 5 Engineered Barrier Systems (EBS) - Materials and Backfills
- Session 6: Breakout- EBS Closure Concepts and Material Combinations
- Session 7: Insights on Operating Facilities

The appendix of these proceedings is a compilation of all given presentations during the workshop, to fully retain the shared knowledge and research.

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# ACRONYMS

| | |
|---|---|
| BASE | Federal Office for the Safety of Nuclear Waste Management (English translation of German acronym) |
| BATS | brine availability test in salt |
| BGE | Bundesgesellschaft für Endlangerung (Federal Company for Radioactive Waste Disposal) |
| BGR | Bundesanstalt für Geowissenschaften und Rohstoffe |
| C(A)SH | calcium (alumo)silicate hydrates |
| CCO | criticality control overpack |
| CFR | Codes of Federal Regulations |
| COVRA | Central Organization of Radioactive Waste (The Netherlands) |
| CRP | coordinated research project |
| CSIRO | Commonwealth Scientific and Industrial Research Organization (Australia) |
| DBD | deep borehole disposal |
| DECOVALEX | Development of Coupled models and their Validation against Experiments |
| DGR | deep geologic repository |
| DQO | Data Quality Objective |
| DOE | Department of Energy |
| DOE-EM | DOE Office of Environmental Management |
| DOE-NE | DOE Office of Nuclear Energy |
| DSRS | disused sealed radioactive sources |
| EBS | engineered barrier system |
| EDRAM | International Association for Environmental Safe Disposal of Radioactive Materials |
| EPA | Environmental Protection Agency |
| FGE | fissile gram equivalents |
| FHA | future actions of humans |
| GDF | geological disposal facility |
| GRS | Gesellschaft für Anlagen- und Reaktorsicherheit |
| HI | human intrusion |
| HIDRA | Human Intrusions in the Context of Disposal of Radioactive Waste |
| HLW | high-level waste |
| IAEA | International Atomic Energy Association |
| IfG | Institut für Gebirgsmechanik GmbH |
| IHI | inadvertent human intrusions |
| ILW | intermediate-level waste |

| | |
|---|---|
| IWM | Integrated Waste Management |
| KOMPASS | Compaction of Crushed Salt for Safe Enclosure (English translation of German acronym) |
| LANL | Los Alamos National Laboratory |
| LBNL | Lawrence Berkeley National Laboratory |
| LLW | low-level waste |
| LWA | land withdrawal act |
| MEASURES | Multi-scale experimental and numerical analysis of crushed salt material used as engineered backfill for a nuclear waste repository in rock salt |
| NEA | Nuclear Energy Agency |
| NWS | Nuclear Waste Services |
| POP | pipe overpack |
| PTKA | Project Management Agency Karlsruhe |
| RANGERS | Entwicklung eines Leitfadens zur Auslegung und zum Nachweis von geo-technischen Barrieren für ein HAW Endlager in Salzformationen Design |
| rvSU | representative preliminary safety analysis |
| RWMC | Radioactive Waste Management Committee |
| R&D | Research and Development |
| SAVER | Entwicklung eines Salzgrusbasierten Versatzkonzepts unter der Option Rückholbarkeit |
| SFWD | Spent Fuel and Waste Disposition |
| SFWST | Spent Fuel and Waste Science & Technology |
| SNF | spent nuclear fuel |
| SNL | Sandia National Laboratories |
| THM | thermo-hydro-mechanical |
| TRU | transuranic |
| TUBAF | Technical Bergakademie Freiberg |
| TUC | Technische Universität Clausthal |
| UK | United Kingdom |
| US | United States |
| WIPP | Waste Isolation Pilot Plant (DOE-EM site) |

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# 1. Introduction

The US/German Workshop on Salt Repository Research, Design & Operation has been a focal point for exchanging the latest work conducted in disposal research programs in the United States, Germany, the United Kingdom, the Netherlands, and Australia. Despite its name, which harkens back to the re-invigoration of collaborative ties between salt researchers in the US and Germany in 2010, the meeting has come to have broad international reach and impact. This growth reflects on the importance of the collaboration, and its ongoing relevance across multiple disposal research programs and several institutional changes.

The workshop focuses on salt applications in radioactive waste disposal, but improving our understanding of the engineering and physics relevant to salt formations is also important for other applications, including salt and potash mining, oil/gas exploration, and cavern development for gas or liquid storage. Work emanating from the salt repository research community is of interest to those in allied fields in salt, as well as to repository research in other geological media (e.g., crystalline and argillaceous rock, and deep borehole).

After pausing in-person meetings briefly during the COVID-19 pandemic, there is a consensus among meeting attendees that the quality of interactions and level of engagement at in-person workshops is worth the effort required to preserve it. The application of repository science in a salt host rock also brings together a diverse set of attendees, including: geomechanical experimentalists, mining experts, mechanical, civil, and nuclear engineers, hydrologists, chemists, geologists, numerical modelers, safety case specialists, national regulators, repository implementers, and observers, among others. The US/German Workshop has been fortunate to draw a broad cross-section of specialists who are interested in learning about, and discussing deeper, a range of technical and applied topics. The workshop organizers have sought to foster the workshop to be a time for engagement, questions, and discussion, rather than a purely one-directional dissemination of information from presenter to audience.

These proceedings, like those from previous years, serve to capture the state-of-the-art in salt repository research, to document the areas of interest across multiple programs, and serve as a resource for years to come.  This series of international workshops were reinitiated in 2010 to address salt repository applications, building on collaborations that started decades earlier. At the first meeting of the US/German Workshop, a proposal was raised to start the Nuclear Energy Agency (NEA) Salt Club, which continues and itself has become an important collaboration vehicle. Both these activities have led to several ongoing international investigations and studies.

Since 2010, workshop participants have discussed increasingly advanced tools for the salt repository science and engineering problem. Both more advanced laboratory methods, and increasingly sophisticated numerical methods, as well as reaching out to practical mining and engineering experience from related fields. While advancing the state-of-the-art, the attendees of the meeting also keep in mind that everyone's goal is the eventual safe and permanent disposal of radioactive waste, rather than simply research for its own sake. Possibly, this practicality is one of the most unique aspects of the meeting that helps to keep it relevant and meaningful, to better solve a challenging international problem faced by many countries around the world.

In the following sections, we present summaries of the research presented during the meeting, with each section authored by a different volunteer. The slides presented at the meeting are collated in an appendix, which serves to preserve the breadth and depth of materials presented at the workshop.

# 2. Developments in National Programs

Author(s): *Melissa Mills (SNL)*

The first session of the workshop provides an update and current status of the various national programs, from several representatives, currently investigating or utilizing salt as a repository host rock. There was a total of five countries contributing to this session along with the IAEA.

Dr. Florian Panitz (BGE-Federal Company for Radioactive Waste Disposal) summarized and reviewed the current process of the German site selection procedure. Germany's current waste inventory, to be disposed of, includes low-, intermediate-, and high-level radioactive waste. The licensed Konrad repository (former iron-ore mine) will host low- and intermediate-level waste (LLW and ILW), up to 303,000 $m^3$ of volume. The site selection to host high-level waste (HLW) is still underway, governed by the Repository Site Selection Act (Stand AG). The future site has a current safety period of 1 million years, and must have retrievability during the operating phase and 500 years after closure. They are reviewing multiple host rocks (crystalline, claystone, and salt) and are in Step 2 of Phase 1 (out of 3): Identification of siting regions for surface exploration. Florian gave an overview of the representative preliminary safety analysis (rvSU) with ongoing work and challenges. The rvSU includes four assessment steps to evaluate suitability of any sub-areas identified, and aims for the process to be transparent and document all details. The methodological development for the rvSU is still in progress, delivering challenges for assigning evaluation criteria that encompass the variety and complexity within each host rock type. Examples given were: prediction of internal structures for rock salt diapirs, assessment of exclusion criteria or minimum requirements (such as formation thickness for rock salt stratiform, fault networks and safety margins around faults) for crystalline rock, and prediction of lateral variation from wireline logs for claystone. Current rock salt research activities mentioned was evaluation of internal complexity of salt diapir structures (i.e., size, morphology, halotectonic evolution, and paleogeographic position). Additional work is ongoing to perform 3D geodynamic numerical modelling to determine influence of glaciations on salt structure stability, incorporating internal heterogeneities, parameter sensitivity, and effect of pressure solution creep.

Ingo Kock, Head of Division of Research on Safety Analysis and Methodology (BASE- Federal Office for the Safety of Nuclear Waste Management), presented on the regulators perspective for disposal. BASE is currently working on a decree for long-term documentation, and in 2022 developed the guideline "Calculation basis for dose assessment for the final disposal of high-level radioactive waste", after public involvement. Ingo gave an overview of the three current disposal projects, Asse II, Morsleben, and Konrad, along with each associated entity. He outlined the site selection procedure for HLW, which began in 2017 and is in Phase I: Identification of Subareas and Siting Regions. Within this phase, an interim report and conference on subareas has been completed, where the implementers proposal for surface exploration followed by a federal act for the determination of regions for subsurface exploration remain. The timeline for completion of all phases for the site selection procedure was changed from 2031 to between 2046 and 2068 based on initial identification of 90 subareas (54% of Germany). Ingo spoke about the need for interim storage, but that it must only be temporarily licensed, with renewal temporary as well. This is to promote progress on the site selection procedure and need for final disposal for long-term safety. The potential subareas and sites identified require protection against other uses (i.e., mining, hydrocarbons, geothermal, etc.), which require additional permits along with an agreement between the federal state and BASE. Furthermore, Ingo addressed that the knowledge necessary for handling HLW is dwindling, and the social acceptance and political interest is declining, which poses risks. It is also unclear where the LLW and ILW will go that is not destined for Konrad. The ongoing research at BASE to address the permanent disposal of HLW is externally funded at ~3 million euros/year, with about 20 scientists for a variety of projects. They include nuclear safety, pre-disposal and interim disposal, operational and long-term safety, safeguards, socio-technical systems, record keeping, and knowledge management.

Tim Gunter, Program Manager for Disposal Research and Development (DOE), gave an overview on the status of U.S. spent fuel and HLW disposition. Nuclear energy is about 20% of the U.S.'s electricity, but accounts for half of all emissions-free energy, and the US has a goal to have net-zero emissions by 2050. Spent fuel and HLW storage sites span across the country, mainly at reactor sites, and it is the responsibility of the US-DOE to manage and find sites for storage and disposal. Currently, the Spent Fuel and Waste Disposition (SFWD) program within DOE Office of Nuclear Energy focuses on storage, transportation, and disposal research (Office of Spent Fuel and Waste Science and Technology-SFWST), as well as cross-cutting initiatives and consent-based siting (Office of Integrated Waste Management-IWM). SFWST research initiatives include investigation of various geologies and developing non-site specific disposal concepts, along with analyzing spent fuel integrity, advanced reactor waste forms, and collaboration with international programs. Tim spoke further on advanced reactor research, noting the widening range of designs (varying in size, power levels, and fuel forms) and the US-DOE supporting 10 for additional development and technology demonstration. These new reactors use different fuels from existing inventory, which may need alternative handling or disposal options, and are currently being evaluated by SFWD. The US participation with international programs include the IAEA, the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee (RWMC), the International Association for Environmental Safe Disposal of Radioactive Materials (EDRAM), amongst many other multinational projects (underground research laboratories, transportation research, etc.). Within IWM, focus has been on generic design of facilities, consent-based siting, and transportation planning. The consent-based siting program, concentrated on prioritizing communities and people, recently funded 12 awardees, comprised of various organizations across the US, to facilitate inclusive community engagement and elicit public feedback on storage and disposal of spent fuel.

Karina Lange and Stefan Mayer, from the Nuclear Fuel Cylce and Waste Technology section under the International Atomic Energy Agency (IAEA), presented on the current activities on HLW disposal. A primary focus is developing technical series documents on deep geologic repositories (DGR) to provide basic knowledge and guidance on implementation (i.e., program components and phases, facility design, site investigation management, society engagement, cost, etc.). The IAEA detailed an in-progress guide on site selection criteria, launched in March 2023, which gives an overview of current international practices and lessons learned while providing case studies to present generic guidance. Another document under development is on stakeholder involvement, to help clarify respective roles in decision process, effective engagement, and catalogues experiences from about 20 national disposal programs. This led to a new Global Partnership on municipalities with nuclear facilities to create a global dialogue and share information. A third document described by the presenters was a practical handbook for planning to move from surface-based activities to underground excavation, and incorporating past experiences, both successful and unsuccessful. Finally, a coordinated research project (CRP) on deep borehole disposal (DBD) was announced to enhance the international knowledge basis, providing technical documents on conducting cost estimates for DBD concepts and elements of planning DBD field tests, as well as hosting workshops. An update was given to the CRP for borehole disposal for disused sealed radioactive sources (DSRS) where Nuclear Malaysia has conditioned DSRS inventory into 43 disposal containers and is providing the borehole disposal facility for disposal operations to begin September 2023 in a small diameter borehole.

Dr. Dirk Mallants (Commonwealth Scientific and Industrial Research Organization - CSIRO) provided a status of Australia's R&D program on ILW disposal in salt formations. Australia's current waste inventory requiring disposal is mainly vitrified waste from processed spent fuel and Mo-99 production, which has a higher radiotoxicity level for longer durations compared to waste inventory of some other countries. Potential concepts for current disposal consist of shallow-depth silo/shaft or deep borehole (up to 1.6 km for 26” diameter or 2.7 km for 16” diameter). Dirk presented on areas of salt formations within Australia as a function of depth, where most are located in central and western areas of the country, highlighting the Amadeus Basin deposit aging back to early Neoproterozoic (~800 Ma). An overview of preliminary post-closure safety assessment for modeling radionuclide migration from a deep borehole in rock salt was given. The disposal concept is comprised of three canisters within each overpack in a borehole at ~200 m depth, backfilled with crushed salt, and simplified into a 1D radial model with assumptions of no vertical transport and homogeneity in the salt. Some processes included in the model (simulated with TOUGH-REACT for 10 million years) are diffusion, linear sorption, radioactive decay, degradation of glass, and finite life of stainless steel and overpack. Advection/convection, heat transport, and heat generation are excluded. Dirk detailed 4 different scenarios for modeling, which differ by type of barriers surrounding waste and dissolution times of the glass matrix, and two sets of varying parameters: longevity of engineered barriers and diffusion in salt. Some conclusions from the preliminary simulations show that engineered barriers affect the timing of peak dose rates; effective diffusion coefficients are poorly constrained; and salt is a very effective natural barrier, yet engineered barriers should not be discounted for building confidence in long-term safety. Additionally, Dirk spoke on some ongoing salt geomechanics lab testing to better understand the behavior of the rock salt after drilling a deep borehole. They are doing multi-stage triaxial tests (4 stages with creep and permeability evaluation) on cores from the Frome Formation (~1000m deep) with post-test petrophysical and microstructural characterization. Comparison of strength, stability, and creep response between homogeneous and heterogenous salt samples was conducted, where the clean or homogenous samples are mechanically stiffer and heterogeneous salt creeps 5 times faster. The goal is to use creep rates in numerical simulations for short-term borehole closer and long-term deformation.

Dr. Jeroen Bartol (Central Organization of Radioactive Waste - COVRA) presented on the current status of The Netherlands disposal program. COPERA is a research program (funded by COVRA) underway and will last until at least 2130, when the country plans to have an operational repository, in either rock salt or clay. Even though this is a later date than other countries, the Dutch need to collect funds for a repository, aim to learn and collaborate with other active programs, and pursue a dual track policy. Their goal is to have a continuous research program to avoid periods of possible knowledge loss. Every 5 years, for the next 30, the program is updated based on the studied safety cases, which incorporates various R&D efforts (i.e., waste form, waste package, barriers, host rock, etc.). Recently, the waste inventory for disposal was updated to include the opening of the Pallas research reactor; however, the government is considering opening two new nuclear power plants and extending the operation of the current one, which will alter waste volumes. Jeroen detailed a considered disposal concept in a salt dome with two levels, one for HLW and the other for L-ILW, where containers are placed in drift floors backfilled by crushed salt. For HLW, the proposed disposal containers (CSD-V and ECN) are designed with a single steel hull sealed by electron beam welding, ensuring retrievability during operation. Drums will be used for L-ILW and emplacement by stacking with a conventional fork lift. Additional research on uplift and erosion rates for four salt domes in the northern part of the country were estimated by salt balance. The Dutch geological survey has collected thermal, hydrological, and chemical data for multiple salt formations, with plans to expand the database further to help with modeling. COVRA plans to include convection, diffusion, decay, compaction, and solubility limits in their preliminary safety assessment model and publish a rock salt safety case in 2024.

Dr. Simon Norris (Nuclear Waste Services - NWS) presented (virtually) an update on the United Kingdom’s (UK) implementation of a geological disposal facility (GDF). The UK is currently looking for willing communities to come forward to jointly explore the implications and benefits of a GDF. At the time of the presentation, four communities had come forward, with three of the communities related to offshore deposits of the Mercia Mudstone Group, an interbedded mudstone and evaporite sequence. Simon presented some of the material on the Mercia Mudstone Group, which is a lithologically complex and laterally variable formation, that includes halite, but the repository itself would not be in the halite portions of the formation. The fourth community is located near the mudstone/siltstone formation (Ancholme Group), which does not have significant evaporitic content. Simon’s presentation then continued to highlight NWS research and development on halite, relevant to the current group of willing communities. This work includes literature reviews on backfilling in salt repostiories in Germany, reviews of options related to salt cement and sorel cement sealing materials for sealing evaporite areas in shafts or boreholes, studies on bentonite swelling behavior in saline formations, and modeling studies of gas migration in evaporites.

Each meeting of the US/German workshop begins with a session on national programs, to provide an update and keep in our mind the overall mission of our work, the safe and permanent disposal of radioactive waste. The presentations given on national programs at this year’s workshop included a range of programs from around the world, including countries working to consider sites for deep geological disposal and countries that have many years to go in the site selection and development process.

# 3. Modeling

Author(s): *Richard Jayne (SNL)*

The modeling technical session of the 13th US/German workshop included different aspects of modeling related to salt repositories. The modeling session spanned implementing salt related constitutive models to criticality control overpack (CCO) compaction and criticality analysis. The modeling presented here included (i) container compaction, (ii) salt creep models in OpenGeoSys, (iii) crushed salt modeling and calibration, (iv) shaft seal integrity, (v) thermal-hydrological-mechanical modeling, and (vi) CCO compaction.

Dr. Benjamin Reedlunn from SNL presented on a new geomechanical model used to simulate container compaction; investigating both roof fall and gradual compaction for three different container types: 6-inch pipe overpack (POP), 12-inch POP, and CCO containers. The driving motivation for this work is based on two commonly used models, where Park and Hansen (2005) results in POP compaction being too stiff and Salor and Scaglione (2018) has assumptions that are too compliant for CCO compaction. The geomechanical model presented roof fall compaction results where the block of fallen rock simply settled on top of the containers causing almost negligible deformation or clustering. As for the gradual compaction results, the ceiling and floor severely compacted the containers in the middle of the room which leads to a bow tie shaped envelope of containers. When comparing these results to previous geomechanical models, pipe centers were 1.4x more concentrated than Park and Hansen (2005) and roughly 5 times less concentrated than Saylor and Scaglione (2018).

Dr. Thomas Nagel from TUBAF, next introduced implementing salt creep models into the numerical modeling code OpenGeoSys. Multiple constitutive models for salt were presented which included: stationary creep, non-linear solid rheology, rock salt, and multiple crushed salt models. Additionally, time stepping and code optimization implementations were discussed to aide convergence with the addition of these constitutive models. Large-scale simulations were utilized to investigate the effects of these salt models, which resulted in improvements in stability and post-processing. Dilatancy-driven gas transport: secondary HM coupling were added along with stress field-dependent percolation. Significant improvements have been added to OpenGeoSys including extension of material models, extension of finite strains, and thermo-hydro-mechanical (THM) coupling.

Dr. Jabril Coulibaly from SNL presented results on crushed salt modeling capabilities and developments at Sandia National Labs. The Callahan model for granular salt reconsolidation was discussed along with it's formulation; the Callahan model was found to be difficult to work with. Parameter fitting of consolidation data suggests that equivalent model responses can be obtained with different sets of parameters. Dr. Coulibaly presented a study investigating two sets of parameters and their calibration against the KOMPASS test: TUC-V2. Further verification attempts were also presented against the TUC-V2 test prior to the compaction test and TUC-V4. The calibration and verification attempts resulted in a discussion of the strengths and limitations of the Callahan model. Where the strengths of the model are within 3D tensor form with pressure solution and dislocation creep mechanisms, transition from porous to intact salt behavior, and satisfactory calibration against complex experimental test TUC-V2. In contrast, the limitations include equivalent stress measure, multi-mechanism formalism, inadequate identification and separation of mechanism contributions, and fragile calibration of the model. Looking forward, significant improvements have been made but the question remains what could realistic goals for improvements be?

Paola Léon-Vargas, from BGE, presented on the RANGERS project and the integrity of shaft seals. The RANGERS project is a joint project between SNL and BGE with the main goal of compiling existing knowledge and experience to design salt-relevant EBS for design and performance assessment of geotechnical barriers in a HLW repository in salt formations. Paola discussed RANGERS methodology and relevant scenarios for EBS with a hypothetical repository site within a bedded salt formation. The Reference Scenario described must retain EBS integrity over 50,000 years with three different cases: (1) water from overburden flows into shaft and disposal zones, (2) gas production within the repository is caused by canister corrosion, and (3) water flows into repository from intact salt via inter- and intra-granular brine. Preliminary results were presented for the three main variants of the reference case as well as two alternative scenarios. This research illustrates temperature differences don't show a significant impact on the shaft's near field and that the influence of competent layers within the shaft seal have a substantial effect on the system's tension environment. Future work includes investigating interface elements to simulate more realistic behavior in the contact zone between the seal materials within the shaft and evaluating the safety/integrity criteria for the sealing body, contact zone, and host rock.

Dr. Hafssa Tounsi from LBNL next introduced THM modeling of the salt block heating experiment. The goal is to quantitatively predict the brine flow in a nuclear waste repository in salt rock as a result of excavating, heating/cooling and damage. The methods presented here utilize the TOUGH-FLAC simulator to model experimental data to verify, validate, and build confidence in the THM coupled simulations. Dr. Tounsi presented modeling results that matched the Salt Block II experiment (Hohlfelder and Hadley, 1979), Avery Island (Krause, 1983), Asse mine (Rothfuchs, 1999) and the Brine Availability Test in Salt (BATS) 1a experiment at the Waste Isolation Pilot Plant (WIPP) (Kuhlman, 2020). Results presented here give confidence in the methodology presented by simulating salt block multistage heating and cooling experiments to evaluate the predictive capabilities of the TOUGH-FLAC simulator. Additionally, Dr. Tounsi highlighted the significance of accounting for thermally activated salt damage and permeability alteration during dilation, both in compression and tension, to interpret brine inflow observations, particularly during cooling. Furthermore, the importance of constraining uncertainty in material parameters particularly with respect to the Biot coefficient were discussed.

Dr. Rob Rechard from SNL presented on the use of CCO compaction simulations in post-closure criticality screening. Results from geomechanical modeling of room closure from salt creep predicts the spacing of CCOs and scale neutron modeling were used to determine subcriticality of CCO spacing. The criticality model utilized in this study implemented three material regions: (1) $^{239}$Pu, water, and plastic, (2) Mixture of MgO and WIPP salt, and (3) 10 m of WIPP salt. A massive number of CCO simulations are run and a generic analysis applies to all potential waste streams in CCOs. From these results a low probability argument is developed that room closure cannot sufficiently assemble a critical arrangement of CCO, provided hydrogenous material is limited and/or $B_4C$ is included in the CCO. Approaches discussed here improved geomechanical modeling and updated criticality safety analysis to demonstrate that post-closure nuclear criticality events are improbable. The methodology presented here also supports packaging of contact-handled transuranic (TRU) waste materials in CCOs with up to 380 fissile gram equivalents (FGE) with no additional constraints on WIPP operations.

The modeling session of the workshop illustrated the diverse range of ongoing modeling programs and highlighted the collaborative nature of much of this work. The numerical modeling experiments presented are often iterative, with previous models informing future models with different assumptions, constitutive models, or analyses producing more complex and/or coupled models. With the large number of parameters required to populate these THM models there remains uncertainty in constraining some of these parameters which often requires experimental data. It is important to couple together experimental and numerical modeling studies because often one informs the other which can help reveal complexities or deficiencies that are less obvious when considering only experiments or modeling results individually.

# 4. Uncertainties in Modeling and Verification

Author(s): *Tuanny Cajuhi, Larissa Friedenberg, Oliver Czaikowski (GRS)*

Mathematical and numerical models are essential in the field of salt repository science and engineering as they play an important role in understanding the subsurface, mimicking and predicting repository behavior, and enabling safety analyses. These models need to accurately capture complex geological and THM processes over large time and space scales. The session "Uncertainties in Modeling and Verification" explored technical and philosophical aspects of model reliability; questioning when a model is "true enough." Using philosophical concepts as basis for the discussion and connecting them to examples from numerical modeling, the session seeks to challenge the participants to reconsider the foundations of confidence in building scientific models.

The session introduced some technical aspects of the project "Benchmarking for Validation and Verification of THM Simulators with Special Regard to Fluid Dynamic Processes in Repository Systems (BenVaSim)". This project focuses on examining fundamental processes that are part of most THM-coupled simulations, starting from simple analytical solutions and gradually moving to more complex THM problems (Czaikowski and Friedenberg, 2020; Lux et al. 2021). This step-by-step increase in complexity helps improve understanding of the simulation codes, the processes they model, and how these processes interact as well as identifying code implementation and numerical challenges.

An impulse presentation on philosophical aspects looked at scientific models as simplified versions of reality, limited by their conceptual assumptions. How can the model limitations be identified, i.e. how much does a model deviate from reality? Can all physical processes and observations be taken into account and be reproduced? Testing the reproducibility of a computer simulation is an important step towards model reliability. According to Volodina and Challenor (2021) running and re-running a deterministic code should lead to the same output, while different outputs are obtained if the input values are slightly changed. The authors state that such a variability is important to estimate the modelers' confidence on their results and, consequently, evaluate the differences between the model response and observations. The variability of a computational model does not imply that it is "more" or "less" trustworthy. It points out that it can only deliver what it has been asked for and that not all aspects have been considered during the model setup. The latter is intrinsically related to the definition of "model", i.e. a partial representation of the reality that, consequently, cannot take into account all possible aspects, as the model of a tree that allows to identify selected features of a real tree as shown in Figure 1.

Figure 1: Partial representation model of a tree that allows to identify selected features of a real tree.

This is not a model weakness, but its strength. Through this intrinsic selective nature where determined aspects are neglected, we are able to identify features that would, otherwise, not be identified (Elgin, 2014).

The talk suggested that models are designed for specific purposes, making them "true enough" for those uses. The concept of “true enough” models is proposed and extensively discussed in the work of (Elgin, 2014). Playing with the model input values can provide useful information with respect to its limitations and, since these variations might result in different outputs further understanding on the process can be obtained from computer simulations. During a sensitivity analysis, new scenarios are created for the system in study. A further discussed point is related to the model conception itself. When choosing a model, it’s objectives are pre-set, for example, if a modeler aims to obtain information on the temperature evolution of a cementitious mixture during hydration at the macroscale, they could choose a model that is able to deliver information on, at least, a main variable, e.g. the temperature. Such a model might not be able to address directly the changes in the microstructure of the cementitious material, but to mimic the resulting general hydration behavior, for example the increase of the degree of hydration and consequently of the elastic modulus, among others. When referring to in-situ processes, such as those related to the backfilling of mine cavities with cement-based materials, it is not feasible to explicitly model the processes happening at very small scales such as those at the microscale, but to evaluate, based on observations and general laws, how the backfilled cavity will behave in general and how it would affect the salt repository (Cajuhi et al., 2022). Such a simplification is necessary to tackle complex problems that would otherwise not be understood. It is important to note, however, that complex and detailed models are also relevant to identify particular phenomena, for example modeling the hydration at reaction level to understand the ranges of this process and their main scale of influence.

The discussion then turned to the different types of uncertainties in modeling; dividing them into technical, numerical, human-related, and philosophical categories. Technical uncertainties included challenges in creating detailed models and the ongoing issue of not having enough data. Numerical uncertainties were examined; especially the impact of how models divide time and space and its setup and the suitability of the software used. The human aspect was looked at critically; acknowledging the potential for mistakes in data entry, personal biases, and the lack of collaboration across different fields, points that could affect the outcomes of models, for example, if complex models are prepared following a single point of view. Philosophically, the session considered the fundamental role of modeling in understanding and predicting phenomena despite the inherent uncertainties.

In conclusion, the session called for a more comprehensive approach to modeling that acknowledges the full range of uncertainties, from data variability to process understanding. It highlighted the need for more collaboration across disciplines and a deeper dive into the philosophical underpinnings of scientific modeling.

# 5. Special Topics

Author(s): *Kristopher Kuhlman (SNL)*

The session on "Special Topics" included presentations spanning the breadth of salt topics in repository science, including: site characterization, concepts from long-term assessment modeling, microbiology, actinide brine chemistry, lab testing and modeling of granular salt reconsolidation, borehole heater testing and modeling, and anisotropy in bedded salt. The wide range of talks illustrates the breadth of topics that are currently of interest in repository science.

Philipp Herold (BGE) showed a framework for comparing the behavior of different sealing systems. For example, to weigh the differences between the expected performance of a shaft seal and a ramp seal. A shaft is the shortest connection from the repository to the surface (straight up), while a ramp is longer because it is inclined. While there are many different factors that impact why one would be preferred over another (e.g., depth, geology, operating time, size of waste packages), the presentation focused on the impact that sealing the different types of designs would have on long-term performance. The method compares the time-to-failure via Darcy flow for various configurations of sealing components, considering the possibility of failure for each of the components. Finally, a comparison of different designs or configurations can be made, to assess the robustness of each design. For the example shown in the presentation, the ramp is less susceptible to damage from failure of components (i.e., the ramp is more robust than the shaft design), mostly because the ramp is longer. The presented framework allows a more apples-to-apples comparison of the expected long-term performance of different designs.

Julie Swanson (Los Alamos National Laboratory-LANL) delivered an update on microbiology research in salt, being done at the WIPP. Julie first showed summaries of growth assays for Halobacterium, which indicated there is a positive correlation of growth with NaCl concentration, and a negative correlation of growth with $MgCl_2$ concentration, with less of a correlation with water activity. Secondly, a "habitability index" was developed to explore the impact water activity and pH have on the viability of microbes in a salt environment. Different samples of relevant brines from WIPP and Asse were compared with synthetic brines, illustrating the region of habitability for halophilic microbes. Synthetic WIPP brines fall within the region of habitability but some natural brines from WIPP and Asse fall outside it. Next, some bio-association studies were conducted to show how microbes (haloarchea and bacteria) can impact Nd in solution (Nd is an analog for actinides in a +3-oxidation state). The results showed the impact to be largest in pure NaCl solutions, with moderate influence on Nd solubility in synthetic ERDA brine, and little to no influence on Nd solubility in GWB brine, which is indicative of a reduced biological influence at higher magnesium ion concentrations (> 0.5 M). Finally, some preliminary evidence for biologically-inducted precipitation of Nd (requiring further evidence) and entrapment within extracellular polymeric substance (EPS) was shown. As an analog to the laboratory studies, a 3,100 year-old wooden set of stairs in a bronze-age salt mine were used to illustrate microbial activity under salt-repository relevant conditions.

Marcus Altmaier (Karlsruhe Institute of Technology) gave an update on the seventh Actinide and Brine Chemistry (ABC-Salt) workshop, which also met in Santa Fe the week before the US/German Workshop. The meeting has been organized under the Nuclear Energy Agency (NEA) Salt Club since 2010, with meetings every 2 years (with an extended gap from 2019 to 2023 due to the COVID-19 pandemic). The meeting attracted 38 participants from 15 groups, across the US, Germany, and Spain. The ABC-Salt workshop scope includes: actinide and radionuclide chemistry in brines, brine chemistry and brine evolution, iron chemistry and corrosion, microbial effects in brines, and modeling/thermodynamic database studies. The main observations from ABC-Salt VII were: 1) an excellent round of technical presentations were given on a broad range of relevant topics, 2) there was active discussion and networking, 3) there is mutual interest in more cooperation, and 4) actinide-brine chemistry is an active and important research field. The next ABC-Salt meeting is tentatively planned to be in Germany in 2025.

Svetlana Lerche (TU Clausthal) gave a summary of laboratory and modeling work performed as part of the KOMPASS II project. The presentation started with a long-term strategy and recent history of experimental investigations into compaction of granular salt between the KOMPASS partners (IfG, BGR, TUC, Utrect, GRS, and Sandia) and related projects for field demonstration (i.e., SAVER). The TUC testing has focused on a systematic laboratory testing program centered around long-duration compaction experiments. The long-term compaction test TUC-V2 is 750 days long, comprised of five phases with different influencing factors. The compaction test TUC-V4 is 190 days long, comprised of two phases. The presentation then showed the results of multiple modeling results to match the strains observed in the TUC-V2 compaction test. Different aspects of the complex laboratory tests were matched more or less by different teams, illustrating the shortcomings of the numerical and conceptual models. The presentation ended with plans for the proposed next phase of the KOMPASS II project (MEASURES), which seeks to conduct laboratory compaction tests and modeling exercises to better investigate the effects of various processes on overall compaction.

Richard Jayne (Sandia National Laboratories-SNL) discussed ongoing activities at the Waste Isolation Pilot Plant (WIPP) related to the Brine Availability Test in Salt (BATS) experiment. He presented background and motivational material for BATS testing, which seeks to better understand the excavation damaged zone (EDZ) around drifts, and how this is impacted by temperature and drift closure. BATS has had two phases, with the first phase in 2020-2021 and the second phase ongoing since summer 2022. Data from BATS phase 1 was used in DECOVALEX Task E to validate numerical modeling of the brine release after heating in salt. Some preliminary BATS 2 data was presented, showing some differences to BATS 1 have been observed, while other observations in BATS 1 have been confirmed. The interaction between numerical modelers and the experiments ongoing at WIPP has improved both the models and the experiments.

Jürgen Hesser (BGR) presented on anisotropy in bedded salt. He showed the results of laboratory tests on six samples of bedded salt collected from boreholes, with half coming from horizontal boreholes in the drift face, and half coming from horizontal boreholes in the side wall. Additional tests were done to conduct dilatometer observations in situ in the different orientation horizontal boreholes. Samples for lab testing were grouped into three types: 1) samples with no clear bedding, 2) samples with assumed bedding, and 3) samples with clear bedding. True three-dimensional (i.e., polyaxial) compression tests were conducted to measure several mechanical properties of the salt (bulk modulus, Young’s modulus, shear modulus, cubic strength, strain deformation, onset of dilatancy, and acoustic emissions). In situ borehole testing was conducted with an inflatable packer tool in boreholes with multiple orientations. The laboratory tests did not show any significant direction dependency on strength or deformation behavior, while the borehole dilatometer data showed directional dependency – greater Young’s modulus in horizontal directions than in the vertical direction. The results of the study show that mechanical anisotropy cannot be excluded for bedded salt deposits, while further investigations are planned for permeability testing of boreholes.

While the topics of this session span the breadth of areas of interest in salt repository science, there were a couple themes that arose multiple times during the session. The talks could be grouped into modeling exercises or experimentation exercises, with a few touching on both. The cooperation between numerical modelers and experimentalists (both laboratory and field experiments) has been a fruitful area to explore. Modelers learn from the exercise of fitting their models to real-world data, and experimentalists often learn from modelers about the types of experiments that are easiest or most meaningful to simulate. There are wide ranges of numerical models, from simple Darcy’s law studies on seal performance to geochemical models, to coupled thermo-hydro-mechanical models of recompaction or brine migration. All these types of models have different assumptions, but the process of fitting models to data is usually insightful, and something to strive for in the future.

# 6. Engineer Barrier Systems: Materials and Backfill

Author(s): *Till Popp (IfG)*

The long-term confinement of radionuclides and thus the prevention of their transfer into the biosphere is the goal of the disposal of radioactive waste in deep geological repositories. For rock salt repositories, this goal is achieved, on the one hand, through the impermeable, undisturbed part of the surrounding host rock formation rock salt and, on the other hand, through a system of geotechnical barriers consisting of special designed shaft and drift seals, accompanied by backfill measures of the remaining underground openings. Thus, sealing of salt repositories and backfilling of the respective underground openings has been a topic of interest for US/German collaborators for many years.

Crushed salt is one of the main investigation topics, not only related to room backfilling but for installing long-term seals, because the material will be compacted with time due to convergence. However, although there is no doubt, that this process will act in the post-closure phase of a salt repository, there are some deficits regarding demonstration of the required tightness and a reliable prognosis which needs to be solved, e.g. in the framework of the KOMPASS-project. On the other hand, besides the classic sealing materials, like Bentonite or Asphalt, sorel or salt concrete are considered as the most suitable building materials for construction of fast-acting seals for closure of drifts or shafts in the host rock salt. Conveniently, they can be used, both for the construction of sealing and load-bearing elements to their favourable HM-properties, e.g. tightness and strength. However, geochemical stability of both building materials is the prerequisite for long-term functionality. This is fulfilled if the phase composition (binder phases, aggregates) of the building material is in thermodynamic solubility equilibrium with a possible access/contact solution, whose composition depends on the mineralogy of the host rock. Otherwise, the sealing elements made of salt concrete or Sorel concrete can be affected by significant changes in the phase composition and thus in their hydraulic and mechanical properties when brine penetrates into the repository.

Salt concrete is made from cement and saturated sodium chloride solution. The sand/gravel aggregate that is conventional in normal concrete is replaced by crushed salt. Depending on the specific recipe, additives such as fly ash, lime, etc. may also be included. The exothermic setting reaction creates a solidified structure with the formation of calcium (alumo)silicate hydrates (C(A)SH phases), the binder phases. Sorel concrete is made from caustic magnesium oxide (MgO) and a concentrated $MgCl_2$-solution as a mixing solution. The exothermic setting reaction produces basic magnesium chloride hydrates, $xMg(OH)_2 \cdot yMgCl_2 \cdot zH_20$ (Sorel phases), the binder phases, which crystallize into a solidified structure. Crushed salt aggregates or silicate hard rock grit (sand/gravel) are used as additives.

Thorsten Meyer provided an overview about the current state of investigation of T-H-M-C processes on different concrete sealing systems in rock salt at GRS. The investigations are directly related to the closure of the Morsleben repository (ERAM), where several drift sealing measures are required in order to contribute to long-term safety of the repository. During the safety analysis the corrosion process turned out to be one of the most relevant processes regarding seals functionality in the long-term.

While initially drift seals at the Morsleben site were planned based on salt concrete M2, geochemical analyses demonstrated that at the drift seals locations in the ERAM, $MgCl_2$-rich brine is expected whose $MgCl_2$ concentration guarantees stability of MgO-phases but may corrode cement phases. Thus, the current planning is focused on MgO-based building materials (comparable to the A1-recipe, as already used in the Asse salt mine) as a basis for the construction of qualified drift seals. However, already, in the past extensive backfilling measures were performed in the repository using salt concrete of the type M4. Thus, the investigation program is related to property changes of these three different building material mixtures, i.e. M2, M4 and the MgO-concrete, exposed to different types of salt solutions. The investigations consist of two work topics:

(1) Hydraulic measurements with various permeability test setups and different sample arrangements, e.g. monolithic concrete samples or combined test specimens (salt cylinders with a central borehole filled with concrete, i.e. small scale test for simulation of a salt drift)
(2) Chemical-hydraulic behavior of the various concrete types with various short- and long-term experiments, each accompanied by analysis of fluid compositions (ICP-OES/MS) and the solid (e.g. XRD), following two methods:
    a. Batch experiments, using different types of salt solution (NaCl(sat.), IP21-, Q-brine, Q-TEC 4.0) with experimental reaction times from 1 to 360 days; and
    b. Cascade experiments for a better understanding of the reaction path between concrete and corrosive solution (experimental reaction time: 4-90 days)

The preliminary results document that depending on the experimental conditions (e.g. temperature, confinement, solution composition), permeability of the various concrete may change (increase or decrease). However, due to the limited time scale and the sample scale, reliable conclusions are not fully possible. Thus, further investigations in the future are needed to assess the impact of possible corrosion processes in such sealing systems.

Cement seals in salt are also the topic of the joint presentation of Melissa Mills and Kris Kuhlman (SNL), which is motivated by the ongoing uncertainties in long-term performance of geologic repositories for nuclear waste disposal related to construction and temporal evolution of geotechnical barriers. Most of the results she presented are related to the ongoing field tests in the framework of the “Brine Availability Test in Salt” (BATS). In the test BATS 2.0, two mixtures of modified salt and MgO concrete are used as borehole seal, to ensure isolated conditions for the heater-test. During the tests the materials were subjected to numerous heating and cooling cycles, whereby internal strains in the plug were measured related to temperature and humidity. The experiments will be continued, and the plug material will be recovered for mineralogical/chemical investigations for characterization, e.g. of the phase composition.

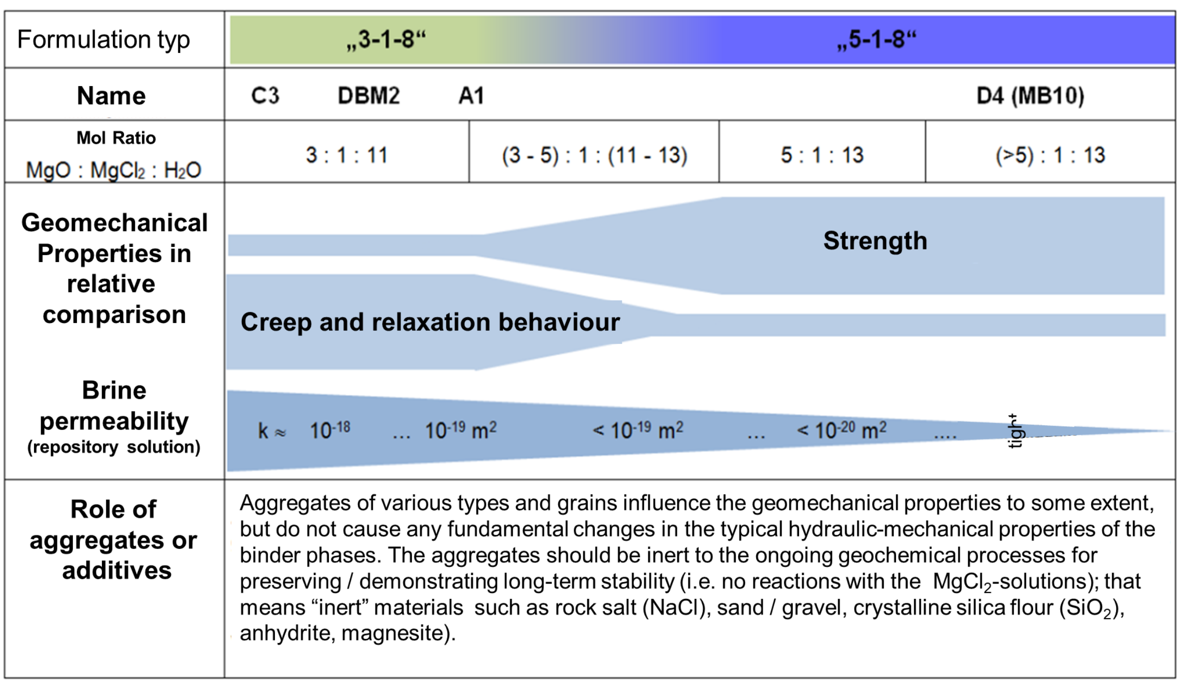


Figure 2: Toolbox of MgO-concrete formulations related to the binder phases 3-1-8 and 5-1-8.

Iris Paschke from Freiberg University (Germany) summarized the achieved level of S&T, based on results from many years of use as well as from R&D projects of the last decade. She focused on the two main MgO-concrete formulations (according to 3-1-8 and 5-1-8 binder phases) and the basic properties of different concrete types in connection with the technological implementation for underground sealing measures (Figure 2). The various mixtures are related to different hydro-mechanical properties due to the individual phase composition, which offers a variety of different mixtures corresponding to site-specific requirements (e.g. weak or stiff dam sealing element).

As she said, the 3-1-8 binder phase, which is often present in the hardened building material, is in chemical equilibrium with $MgCl_2$ solutions as well as with NaCl-saturated solutions, which contain low $MgCl_2$ contents (>0.5 molal at 25°C; >1 molal at 40°C) (Pannach et al. 2017 and 2023). There is also a solubility equilibrium with complex solutions of the hexary system of oceanic salts, such as Q or R solution, IP 21, IP 19, etc.

The other possible binder phase 5-1-8 (binder phase formation depending on the building material recipe) is a none equilibrium phase and converts into the 3-1-8 phase (possibly and/or $Mg(OH)_2$) upon contact with the solution. However, this is not an exclusion criterion for proving the long-term stability of buildings with this binder phase. The phase transformation takes place in the surface contact area, combined with an increase in solid phase in the pore space that is primarily accessible to solution, which reduces the inflow of further solution. The integrity of the building is thus preserved. Proof of long-term stability can therefore also be provided via proof of integrity.

As already mentioned above, 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. With time, it is compacted by convergence to low porosity and permeability, making it an important sealing function in the long term. When a sufficiently high hydraulic resistance is achieved, brine entry into the emplacement areas of the repository is avoided.

However, as pointed out by Larissa Friedenberg (GRS), a reliable prediction of crushed salt compaction is difficult, due to missing hydro-mechanical data in the low porosity range (< 5%). In addition, suitable constitutive models are currently not available to describe the mechanical/hydraulic property changes during the requested time schedule.

Aiming on a reduction of these deficits, the KOMPASS project was initiated by a consortium of German partners that consist of BGE TECHNOLOGY GmbH, BGR, GRSgGmbH (coordinator), IfG, and TUC together with international associative partners from Sandia and Utrecht University and COVRA. To fulfil the objective a combination of experimental investigations, microstructural examinations, and numerical strategies was conducted. 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 finished in the middle of 2023. She summarized the outcome of the last three years documenting a significant progress in knowledge but highlighted also the remaining deficits, which shall be solved in the forthcoming project: MEASURES.

In addition, she pointed out that there is close cooperation with the SAVER project, in which, among other things, internally-stabilized crushed salt material (GESAV-approach) is investigated during lab and field tests (as presented by L. Schaarschmidt, next chapter).

In summary, it can be said that in the last decade continuous work progress has been achieved, particularly with MgO- and salt-concrete, which justifies that these building materials can now be used to build real seals in salt formations, which is necessary not only for radioactive waste repositories (e.g. at the Morsleben site) but also in conventional mines or underground repositories for chemical-toxic waste (e.g. for the Teutschenthal mine). Nevertheless, there are still options to further optimize the existing building material recipes and, at the same time, the large-scale application, including in-situ concrete or shotcrete technology, still represents a challenge in detail.

That is why two large-scale (1:1 drift seal) underground tests are currently being carried out in Germany to demonstrate the technical feasibility of dam seals in salt for the closure of the ERAM: (1) MgO concrete dam (3-1-8 phase) as site concrete construction in rock salt in the Sondershausen mine (D): the MASTRIS demonstration project; and (2) a dam using shotcrete technology with a 5-1-8 recipe in anhydrite in the Grube Bernburg (D): the DeSpriBi research and development project. Both projects will be finished at the end of 2025.

Regarding the understanding of crushed salt compaction and the modeling of the hydro-mechanical processes that take place, it should be noted that the level of understanding which exists for the mechanical behavior of rock salt, e.g. as a result of the WEIMOS project, has not yet been reached. It is therefore important that this work is continued with the MEASURES research project.

# 7. Closure Concepts and Material Combinations for Engineered Barrier Systems

Author(s): Jörg Melzer (PTKA)

Developing sealing concepts of shafts and tracks in salt mines is a long-known challenge, especially for repositories for hazardous waste. This part's range of experiences and development lasts from the late eighties to now. The sealing concepts were adopted, further developed, and specialized for the use of Engineered Barrier Systems (EBS) in repositories for nuclear waste.

The former session, titled "EBS-Material and Backfill" presented some of the already done research and investigation, about the properties and use of the material itself as well as the connected modeling for different uses in repositories. To point out the international interest in these concepts for EBS, as an example, two projects should be mentioned which have many associated international partners KOMPASS (investigation of crushed salt behavior) and RANGERS (Guideline to prove EBS).

The key question for the open discussion was "Are we already done or what could be the next steps in the investigation?"

The conclusion of the following discussion showed that many studies of EBS-Material on a laboratory scale have already been done. The results lead to the realization that laboratory experiments cannot depict the complete properties in interaction with the host rock and the environment in the repository. However, experiments in the laboratory are still indispensable for understanding individual processes and material parameters but it is essential to have more in-situ investigation to complete the database.

The discussion came to several results:

1. Starting an "International State of The Art Report" to summarize the known results and bring them in context to each other is needed to see where the open points for further investigation are.
2. Developing a Roadmap for having a concept for future investigation perhaps with the following sequence
    a. Focus on open questions of already known materials
    b. extend to research and investigation of new materials
3. The most important point was, that more in-situ investigation is needed. For that, cooperation with states having underground research laboratories (URL) in salt mines is required or the building of a URL, e. g. in Germany, must be considered.

# 8. Insights on Operating Facilities

Author(s): Neel Gupta (RESPEC)

Globally, nuclear power plants produce 10% of electricity generation; in advanced economies, it's rising up to 20%. One of the biggest challenges that nuclear power plants currently face is the interim waste storage at sub-surface storage waste facilities, while the availability of long-term disposal is still pending. It is internationally accepted that the best approach to manage long-lived intermediate and high-level radioactive waste safely is through disposal in a deep geological repository (DGR). Most countries are planning the DGRs at a depth of between 250 and 1,000 meters to provide a substantial natural barrier. According to the Nuclear Energy Agency (NEA), rock salt is one of the candidate rocks to host a DGR for HLW because of its favorable characteristics of extremely low permeability, viscoplastic behavior that closes all void spaces, etc. In Germany, nuclear repository sites, such as Morsleben, Gorelben, and Schacht Asse II, are in the salt dome, while in the United States, the Waste Isolation Pilot Plant (WIPP) is located in a deep layer of bedded salt. In both countries, experts are making continuous advancements in storing nuclear waste at active sites and monitoring the performance of active repository sites for the safety and security of the general public.

Andreas Reichert from BGE presented the retrieval plan and current status at ASSE. ASSE II was an evaporite mine used to produce potash and rock salt, later used as a deep geological repository for radioactive waste disposal. Between 1967 and 1978, approximately 126,000 drums containing 47,000 $m^3$ of low intermediate-level radioactive waste were placed in formed mining chambers, primarily in the Southern flank of the mine. At the ASSE II mine, the high extraction ratio around the Southern flank and no backfilling for more than 75 years has caused geomechanical instability in the overlying strata and created a channel for brine influx into the mine, approximately at the rate of 12 $m^3$ per day from 1980. To prevent the risk to humans and the environment, the German government decided to recover the radioactive waste from the mine and decommission it.

In the short-term, to prevent the contact of brine coming into the mine with radioactive waste, brine is collected at point 3/658 and then it is disposed. However, the rock's continued movement is causing sealing foil deformation at point 3/658 and forming a sinkhole where brine is accumulated. For emergency conditions, the erection of the flow barriers and backfilling and stabilization of brine cavities are ongoing. However, urgent emergency preparations are needed in case of uncontrollable water inflow. Experts plan to recover the radioactive waste via a new retrieval mine, including the development of a retrieval shaft (shaft 5), surface facilities, and waste treatment plant/interim storage. So far, the salt structure to the east of the existing mine has been explored; necessary contracts have been signed for the retrieval mine, and operational areas for the retrieval mine have been acquired. The regional planning and nuclear licensing procedures have already started, and the drilling site is under construction to confirm the location of the retrieval shaft. As shown in Figure 3, experts plan to recover the radioactive waste from the emplacement chambers, perform intermediate packaging in the airlock area between the mine and chamber, transport it from underground to the surface through Shaft 5, and transport the intermediate package of recovered waste to a waste treatment plant where it will be characterized, conditioned, and placed into the interim storage facility. During this process of waste retrieval, specific incidents are possible, such as additional radioactive discharge during the opening of the chambers where waste has been emplaced, incidents within the emplacement chamber during retrieval from the movement of the rock, and incident of open radioactivity in the airlock between chamber and mine or the waste treatment facility. Therefore, appropriate retrieval procedures and technology are needed to mitigate the probable incidents. According to the experts, the retrieval may begin in 2033 and continue through 2050, with the projected cost of preparing to commence at 3.35 billion Euros plus another 400 million Euros for administration.

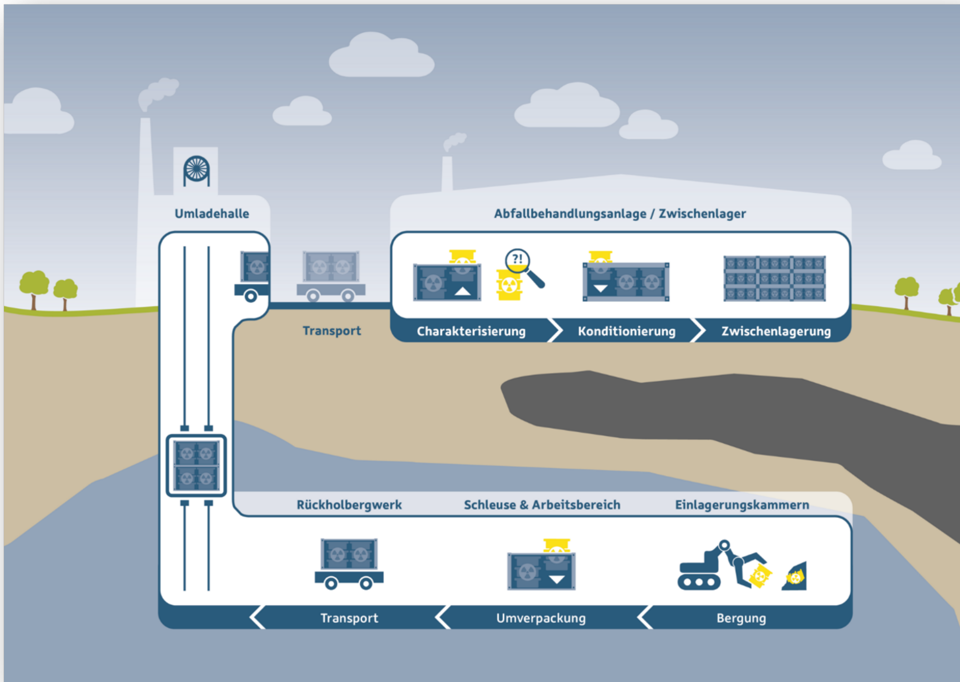


Figure 3: Process of Waste Retrieval

Jens Wolf from GRS presented the human intrusion scenarios. According to the National Energy Administration (NEA, 1995), the future actions of humans (FHA) can't be anticipated in the long time frame, and inadvertent human intrusions (IHI) may potentially disturb the radioactive waste disposal system with radiological consequences. Since it is a plausible scenario that the FHA may impair the performance of the disposal system, but because of their unpredictability, stylized assumptions, and corresponding treatments need to be formulated through regulations. Appropriate site selection, deep disposal of radioactive waste, or even use of markers may compensate for the absence of regulatory limits in case of human intrusion (HI). Global Research Alliance (GRA, 2009) provided some guidelines to developers or operators of near-surface disposal facilities for solid radioactive waste. According to GRA, developers/operators should assume that HI is highly unlikely to occur after the authorization period and consider implementing practical measures to reduce this likelihood further. If HI, developers/operators should also assess the possible consequences after the authorization period. Since FHA can't be predicted, the HI scenario should be based on human actions similar to the historical or current human practices in comparable geological and geographical settings anywhere in the world. Repository Safety Requirements Ordinance (EndlSiAnfV) by Germany defined four classes of scenarios, e.g., expected evolutions, deviating (alternating) evolutions, hypothetical evolutions, and evolutions based on FHA to optimize the disposal system and test its robustness. The selection of a DGR to dispose of HLW over permanent storage at or near the Earth's surface is an effective measure to reduce the impact of FHA on the repository. However, if FHA is carried out with the knowledge of the existing repository, in that case, future living people who plan and carry out activities that knowingly affect the repository are entirely responsible. In the United States, Codes of Federal Regulations (CFR) has recommended the direct incorporation of HI into Waste Isolation Pilot Plant (WIPP) compliance calculations and provides the scope of performance assessment of a disposal system (40 CFR 194.32) and definitions of stylized scenarios (10 CFR 63.322). Also, member states of the International Atomic Energy Agency (IAEA) conducted the Human Intrusions in the Context of Disposal of Radioactive Waste (HIDRA) project.

The project focused on developing an approach for identifying HI scenarios to be assessed and protective measures to reduce the potential for and consequence of IHI. The project was conducted in two phases. In the First Phase (between 2013 and 2015), the focus was on potential scenarios, societal factors, and protective measures, while in the Second Phase (between 2016 and 2018), the focus was on practical implementation of the HIDRA approach and documentation of the country. Recently, in 2023, an online workshop was organized regarding the HI in Salt Repositories, which was attended by 40 participants from Australia, Germany, The Netherlands, Switzerland, the UK, and the US. The workshop summarized that the stylized scenario of HI is a disruptive event, such as drilling a borehole into a displacement area, in line with 10 CFR 63.322 (a). An in-depth consideration of HI is essential in building confidence in safety cases and its communication with different stakeholders.

Andy Ward from US-DOE, Carlsbad Field Office, presented the lessons learned at WIPP, primarily on Compliance (Re)Certification Applications. WIPP, short for Waste Isolation Pilot Plant in Carlsbad, NM, is the repository in bedded salt (Permian Salado Formation) for the disposal of defense-generated transuranic (TRU) and TRU mixed radioactive waste from Department of Energy (DOE) sites around the US. In the WIPP Land Withdrawal Act (LWA), Congress required the Environmental Protection Agency (EPA) to certify that the US DOE's WIPP complies with waste disposal regulations at 40 CFR Part 191, Subparts B and C, as well as WIPP Compliance Criteria at 40 CFR Part 194. Congress also required EPA to recertify the facility every five years following the initial receipt of TRU waste until the end of its operational activities. EPA initially certified WIPP in 1998, and WIPP first received TRU waste in 1999. Since then, DOE has submitted the Compliance Recertification Application (CRA) in 2004, 2009, 2014, and 2019.

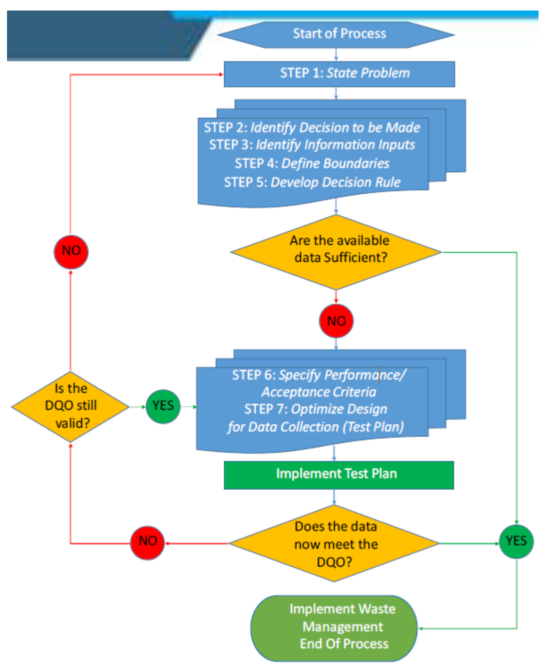


Figure 4: Flow Diagram of Data Quality Objective (DOQ) Process

After the initial receipt of CRA in 2019, EPA recertified DOE's WIPP facility in 2022. During the evaluation, EPA raised approximately 200 questions and concerns about geochemistry, actinide chemistry, etc. At WIPP, redox reactions are vital to its geochemistry, affecting actinide's gas generation, pH, and solubility. EPA raised concerns about the influence of radiolysis on the performance of spent nuclear fuel (SNF). The ionizing radiation particles from nuclear waste, e.g., α particle, can cause radiolysis of water, which generates Hydrogen gas ($H_2$) as one of the radiolytic byproducts, and hydroxyl ion (OH) that may lead to iron oxidation if it encounters ferrous ion ($Fe^{2+}$). To ensure that all DOE radioactive waste is managed to protect workers, public health and safety, and the environment, DOE issues Radioactive Waste Management Manual (DOE O 435.1). DOE also adopted the Data Quality Objective (DQO) process, which is a systematic planning process for generating data that will be sufficient for their intended use. It's a seven-step process, as shown in Figure 4, with multiple feedback loops that become the basis for balancing uncertainty with available resources and defining appropriate types of data to collect and quality requirements to support decisions. DQO must start with high-quality, focused questions and end with the most effective investigative design that will make good use of time and money to generate helpful information in making decisions.

Andreas Reichert from BGE presented the lessons learned on BGE facilities. BGE is the federal company for radioactive waste disposal in Germany. BGE shared their insights on the valuable lessons learned while working on the Konrad and Morsleben repository. According to BGE, in Germany, the approval procedures are the most time-critical processes, so the duration should be planned realistically. An effective licensing strategy should be developed, such as involving licensing authorities from the early stage through the entire process, building trust with licensing authorities, and fostering commitment between the applicant, licensing authorities, experts, and the public.

The application documents must be prepared by experts familiar with the requirements of nuclear licensing procedures. Applicants should coordinate with authorities regarding structure, scope, and depth in advance and should not make application documents more detailed than required. Applicants should specifically classify equipment, systems, and components in the application documents. Complexity and the longer duration of the project may lead to mistakes. The operating organization should consider comparable processes as a basis to determine the realistic duration of a proposed process and shouldn't plan all operations from the beginning; instead, they should schedule their planning. Digitization, such as building information modeling (Figure 5), can provide a unique opportunity to optimize cooperation, communication, and costs. In long-duration projects, planning of the intermediate construction stages is also helpful. For instance, at the Konrad geologic repository, BGE planned the shaft development at multiple stages to determine the realistic timeframe for its completion. Standard solutions with equipment, systems, and components should be adopted wherever possible, e.g., selecting a standard heavy-duty forklift over a heavy-duty forklift at the Konrad facility.

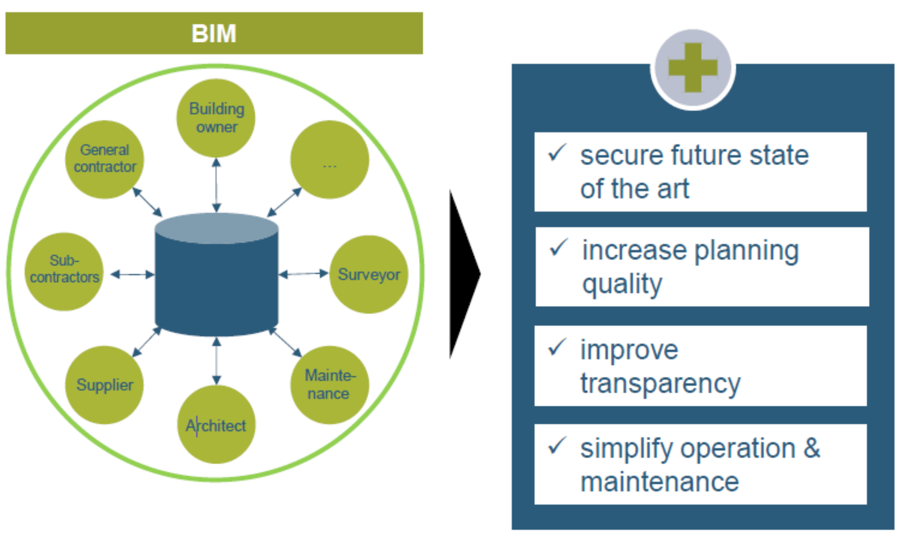


Figure 5: Example of Building Information Modeling (BIM).

The presented work in this session provided valuable insight into the licensing, planning, and construction of selected nuclear waste disposal sites. To comply with federal regulations and environmental guidelines, researchers are anticipating the scenarios within nuclear repositories or future human actions including inadvertent human intrusion that may compromise the isolation of nuclear waste and expose the radionuclide into the biosphere. Experts are utilizing systematic planning tools to collect the correct data to decide within desired confidence limits and digitize to optimize cooperation, communication, and costs. Also, for searching and constructing new repository sites for the disposal of nuclear waste, experts are continuously monitoring the performance of existing disposal sites, evaluating the associated risk, and planning to either decommission or retrieve the nuclear waste from repositories.

# 9. Concluding Remarks and Future

The proceedings of this workshop documents ongoing collaborations and key activities in salt disposal research within several countries. The Workshop has been a focal point for exchanging the latest work conducted in disposal research programs in the United States, Germany, the United Kingdom, the Netherlands, and Australia. The format of the meeting (a single track of presentations with breakout discussions and ample breaks) is designed to encourage interaction and dialog between attendees. Despite its name, the meeting has achieved broad international reach and impact beyond the US and Germany. While presenting on the state-of-the-art, the attendees of the meeting also keep in mind that the overall goal is eventual safe and permanent disposal of radioactive waste.

The sessions from the meeting spanned a range of topics. The meeting format, as previous years, begins with with progress reports from represented countries and the International Atomic Energy Agency. This is both informative and helps keep everyone aware of the ultimate goal of all our research programs. The workshop continued with presentations and discussion on ongoing numerical modeling efforts, and benchmarking exercises being conducted to better understand the limitations and applicability of numerical models. The breakout session on BenVaSim was an important chance to think more philosophically about what it means to create, calibrate, and use numerical models. The session on special topics included a diverse cross-section through the salt repository research, including microbiology, performance assessment modeling, and laboratory and field experiments. This session illustrates the breadth of topics being investigated in different salt repository programs. Engineered barrier systems (EBS) were featured in both a session of presentations and a breakout session, which reflects the importance of EBS in repository design and optimization. The final session discussed operating facilities, which connects back up with the theme that began the meeting, namely the safe and permanent disposal of radioactive waste.

During the conclusion of the workshop, some questions were put forward to the audience relevant to the future of the workshop series. First question was whether participants preferred in-person or virtual meetings. The overwhelming response was in favor of in-person meetings, with possibly incorporating more displayed posters for further discussions during breaks. Questions were asked about the workshop style format, which was also generally favored, but there was a proposal for two breakout sessions held in parallel to accommodate different focuses with smaller groups. Lastly, a question was asked about a possible call for papers, which was not generally favored.

Finally, the tentative location for the next workshop was announced, June 2024 in Manchester, UK. The participants from National Waste Services in the UK have agreed to assist in the hosting of the next meeting.

# 10. References

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# APPENDIX

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


# 13th US/German Workshop on Salt Repository

M. Bühler, J. Melzer,
P. Herold, M. Mills,
K. Kuhlman

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## Organization Team

Michael Bühler,
Project Management Agency Karlsruhe

Jörg Melzer,
Project Management Agency Karlsruhe

Philipp Herold,
BGE TECHNOLOGY GmbH

Melissa Mills,
Sandia National Laboratories

Kristopher Kuhlman,
Sandia National Laboratories

# US/German Workshop History

| | | |
|---|---|---|
| 1 | 25-27 May 2010 | Mississippi State Univ, Canton, USA |
| 2 | 9-10 Nov. 2011 | Hotel Schönau, Peine, Germany |
| 3 | 8-11 Oct. 2012 | SNL, Albuquerque, USA |
| 4 | 17-18 Sep. 2013 | *Hollywood Media Hotel, Berlin, Germany |
| 5 | 8-10 Sep. 2014 | La Fonda Hotel, Santa Fe, USA |
| 6 | 7-9 Sep. 2015 | Hotel Pullman Dresden Newa, Dresden, Germany |
| 7 | 7-9 Sep. 2016 | *Crystal City Embassy Suites, Washington DC, USA |
| 8 | 5-7 Sep. 2017 | *COVRA, Middelburg, The Netherlands |
| 9 | 10-11 Sep. 2018 | *BGR, Hannover, Germany |
| 10 | 28-30 May 2019 | *SD School of Mines, Rapid City, USA |
| 11 | 2 Feb, 17 Jun., 8-9 Sep. 2021 | Virtual (MS-Teams) |
| 12 | 6-8 Sep 2022 | *Hotel Steigenberger, Braunschweig, Germany |
| **13** | **20-23 Jun 2023** | ***Drury Plaza Hotel, Santa Fe, USA** |

*co-convened with NEA Salt Club

# Sessions

- Introductions / Welcomes
- Session 1: Developments in National Programs

- Session 2: Modelling
- Breakout Session 3: Uncertainties in Modelling and Verification
- Session 4: Special Topics

- Session 5: Engineered Barrier Systems (EBS) – Materials and Backfills
- Breakout Session 6: EBS Closure Concepts and Material Combinations
- Session 7: Insights on Operating Facilities

## Day 1: Agenda

| | | | |
|---|---|---|---|
| 13:00 | 13:10 | Welcome by the organizers | Organization team |
| 13:10 | 13:20 | Welcome | Sylvia Saltzstein (SNL) |
| 13:20 | 13:30 | Welcome | Sabine Mrugalla (BMUV ) |
| 13:30 | 13:40 | Welcome | Tim Gunter (DOE-NE) |
| **SESSION 1: Developments in National Programs**<br>Chair: Michael Bühler (PTKA) | | | |
| 13:40 | 14:00 | Status of German site selection and on-going work | Florian Panitz (BGE) |
| 14:00 | 14:20 | Germany: regulators perspective | Ingo Kock (BASE) |
| 14:20 | 14:50 | Status of US Program | Tim Gunter (DOE-NE) |
| 14:50 | 15:20 | *Coffee break* | |
| 15:20 | 15:50 | IAEA - Status and new developments (Virtual) | IAEA |
| 15:50 | 16:20 | Australia (Virtual) | Dirk Mallants (CSIRO) |
| 16:20 | 16:50 | Netherlands | Jeroen Bartol (COVRA) |
| ***No evening activity planned*** | | | |

## Proceedings

- Sandia will be compiling a summary report (i.e., proceedings) on the workshop

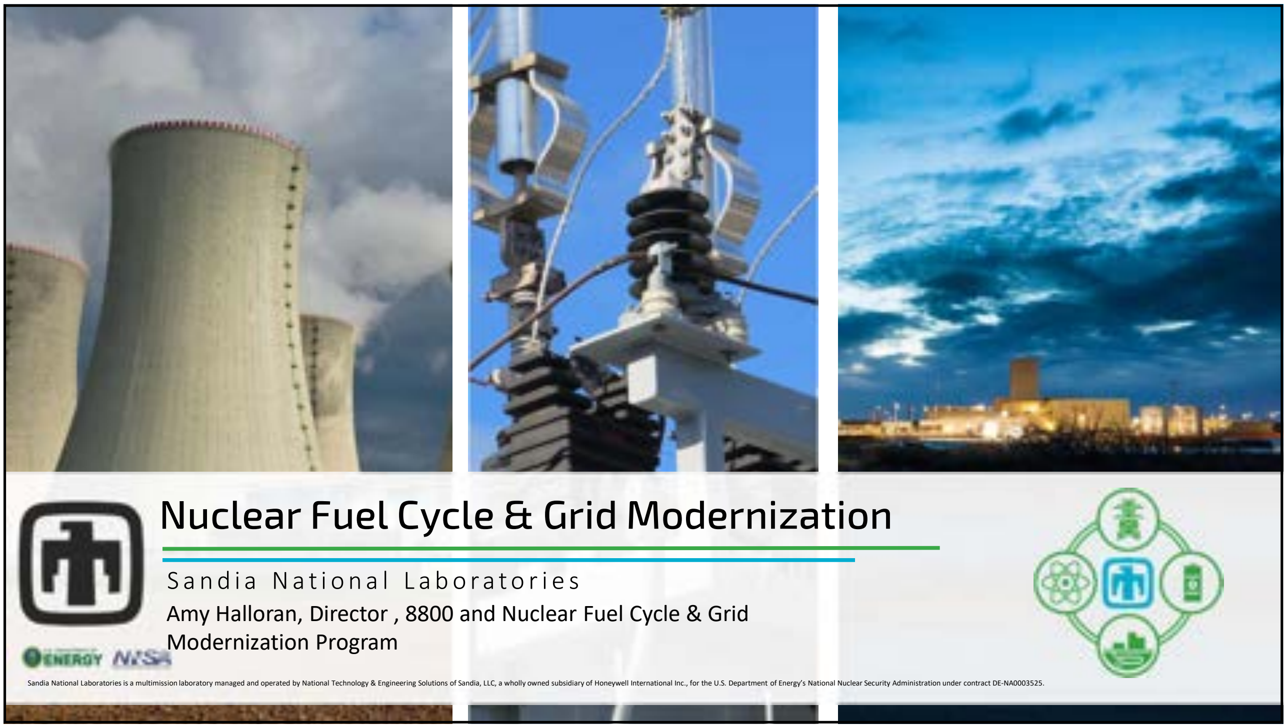
- Seeking volunteers for summarizing individual sessions

# Day 2: Agenda

| | | | | |
|---|---|---|---|---|
| DAY 2 | **SESSION 2: Modelling** Chair: Kris Kuhlman (SNL) | | | |
| | 08:00 | 08:30 | Simulations of Container Compaction to Support Nuclear Criticality Assessments | Ben Reedlun (SNL) |
| | 08:30 | 09:00 | Implementation of salt creep models in OpenGeoSys | Thomas Nagel (TUBAF) |
| | 09:00 | 09:30 | Crushed Salt Modeling and Calibration | Jibril Coulibaly (SNL) |
| | 09:30 | 10:00 | RANGERS: Integrity of shaft seals | Paola León-Vargas (BGE TEC) |
| | *10:00* | *10:30* | *Coffee break* | |
| | 10:30 | 11:00 | THM Modeling of the Salt Block Heater Experiment | Hafssa Tounsi (LBNL) |
| | 11:00 | 11:30 | Use of CCO Compaction Simulations in WIPP Post-Closure Criticality Screening Analysis | Rob Rechard (SNL) |
| | 11:30 | 12:30 | **SESSION 3: BREAKOUT** Uncertainties in Modelling and Verification (BenVaSim 2) Chair: Oliver Czaikowski (GRS) | |
| | *12:30* | *13:30* | *Lunch Break* | |
| | **SESSION 4: Special Topics** Chair: Jörg Melzer (PTKA) | | | |
| | 13:30 | 14:00 | National Program Update: United Kingdom (Virtual) | Simon Norris (NWS) |
| | 14:00 | 14:30 | LARYSSA Project | Philipp Herold (BGE TEC) |
| | 14:30 | 15:00 | Microbes in Salt Repositories | Julie Swanson (LANL) |
| | 15:00 | 15:30 | Geochemistry and ABC Salt into Summary of the ABC-Salt VII Workshop | Marcus Altmaier (KIT) |
| | *15:30* | *16:00* | *Coffee break* | |
| | 16:00 | 16:30 | Laboratory testing for KOMPASS 2 | Uwe Düsterloh (TUC) |
| | 16:30 | 17:00 | Ongoing Brine Availability Test in Salt (BATS) at WIPP | Rick Jayne (SNL) |
| | 17:00 | 17:30 | Anisotropy - An Issue for Bedded Salt | Jürgen Hesser (BGR) |
| | ***19:00*** | | ***Organized (self pay) Conference Dinner at Restaurant in Santa Fe Plaza*** | |

# Day 3 Agenda

| | | | | |
|---|---|---|---|---|
| DAY 3 | **SESSION 5: EBS - Materials and Backfill** Chair: Philipp Herold (BGE TEC) | | | |
| | 08:00 | 08:30 | THYMECZ: Investigation of T-H-M-C processes on sealing systems in rock salt | Thorsten Meyer (GRS) |
| | 08:30 | 09:00 | Cement Seals in Salt | Melissa Mills (SNL) |
| | 09:00 | 09:30 | Overview of MgO Concrete types | Iris Paschke (TUBAF) |
| | 09:30 | 10:00 | KOMPASS Summary & Outlook MEASURES | Larissa Friedenberg (GRS) |
| | *10:00* | *10:30* | *Coffee break* | |
| | 10:30 | 11:00 | Big Scale In-Situ Application of Matrix-stabilized vs. Conventional Backfill With Improved Backfilling Method | Louis Schaarschmidt (TUBAF) |
| | 11:00 | 11:30 | RANGERS - Summary of State-of-the-Art in EBS materials | Ed Matteo (SNL) |
| | 11:30 | 12:00 | MgO concrete C3: New building material for long-term & fast-acting closure elements | Till Popp (IfG) |
| | *12:00* | *13:00* | *Lunch Break* | |
| | 13:00 | 14:00 | **SESSION 6: BREAKOUT** EBS Closure Concepts and Material Combinations Chair: Jörg Melzer (PTKA) | |
| | **SESSION 7: Insights on Operating Facilities** Chair: Melissa Mills (SNL) | | | |
| | 14:00 | 14:30 | Asse - Retrieval plan and current status | Andreas Reichert (BGE) |
| | *14:30* | *15:00* | *Coffee break* | |
| | 15:00 | 15:30 | Human Intrusion Scenarios | Jens Wolf (GRS) |
| | 15:30 | 16:00 | WIPP Lessons Learned | Anderson Ward (DOE-EM) |
| | 16:00 | 16:30 | Operation Lessons Learned on BGE Facilities | Andreas Reichert (BGE) |
| | 16:30 | 17:00 | US/German Workshop 2024 Outlook | Organization team |
| | | | ***End*** | |


Nuclear Fuel Cycle & Grid Modernization
Sandia National Laboratories
Amy Halloran, Director , 8800 and Nuclear Fuel Cycle & Grid Modernization Program
ENERGY
NNSA
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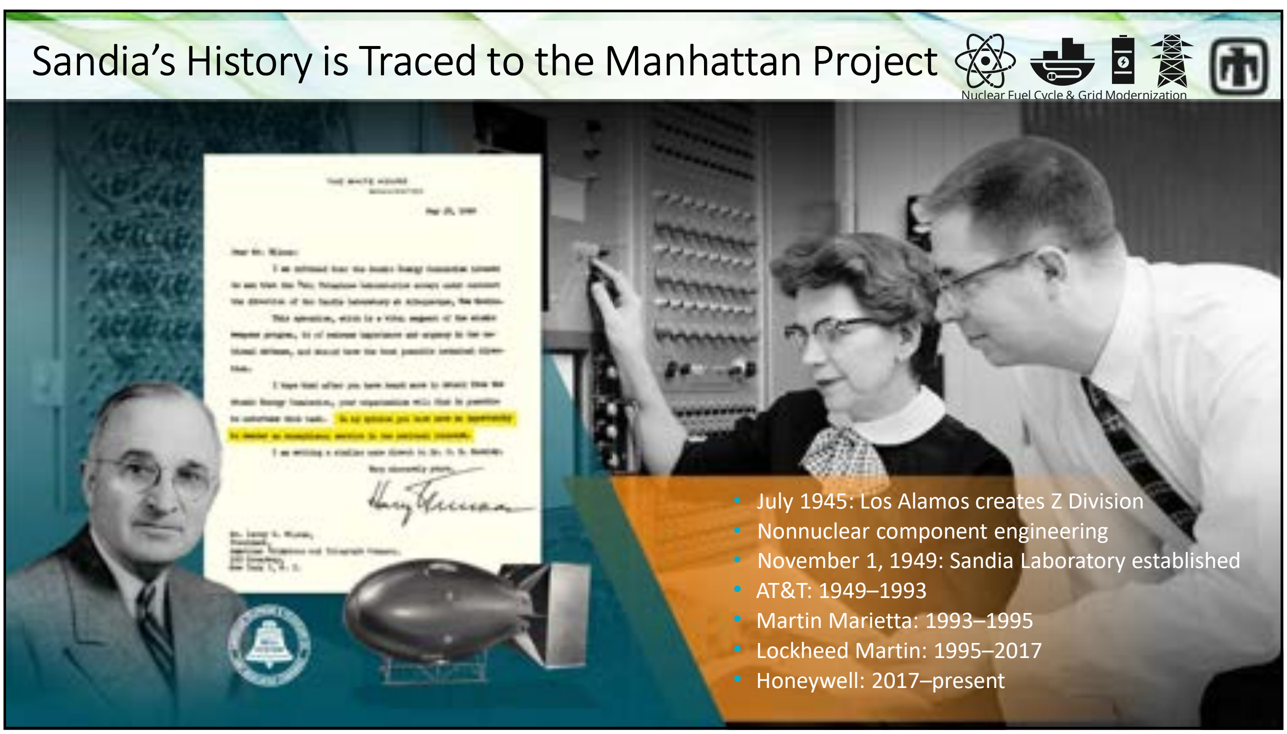
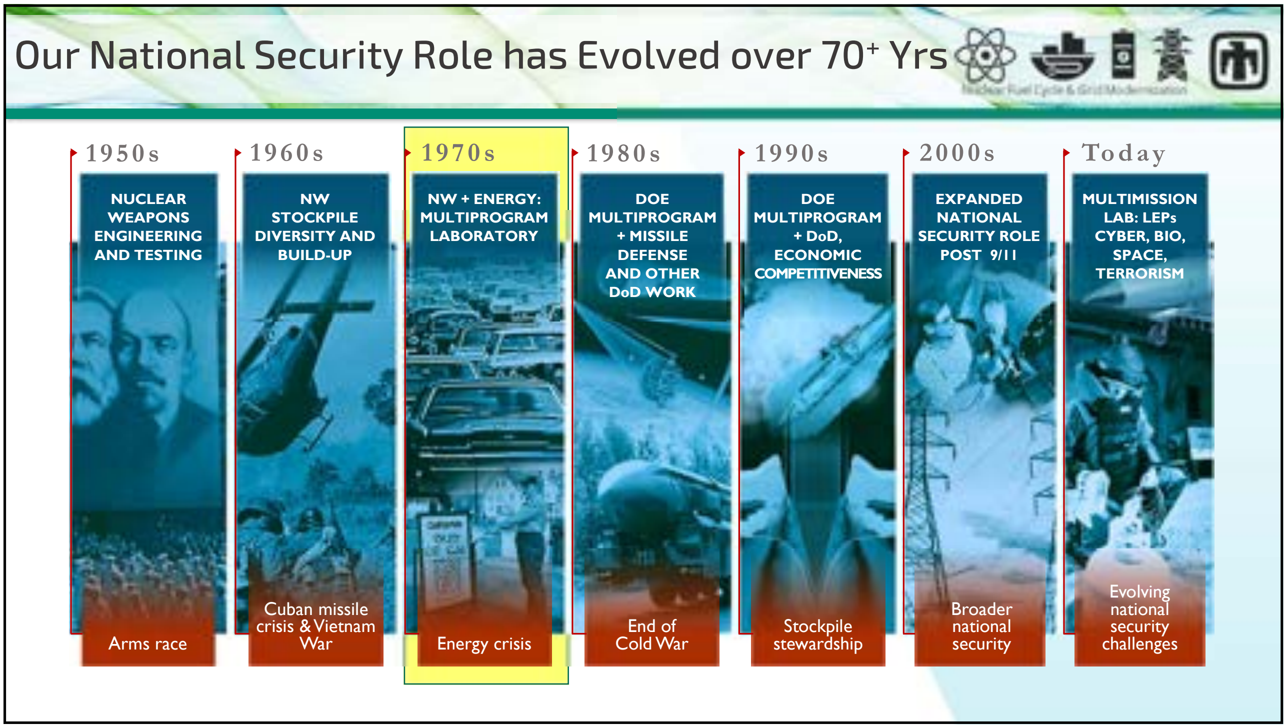

Sandia's History is Traced to the Manhattan Project
Nuclear Fuel Cycle & Grid Modernization
• July 1945: Los Alamos creates Z Division
• Nonnuclear component engineering
• November 1, 1949: Sandia Laboratory established
• AT&T: 1949–1993
• Martin Marietta: 1993–1995
• Lockheed Martin: 1995–2017
• Honeywell: 2017–present

2


Our National Security Role has Evolved over 70+ Yrs
1950s
NUCLEAR WEAPONS ENGINEERING AND TESTING
Arms race
1960s
NW STOCKPILE DIVERSITY AND BUILD-UP
Cuban missile crisis & Vietnam War
1970s
NW + ENERGY: MULTIPROGRAM LABORATORY
Energy crisis
1980s
DOE MULTIPROGRAM + MISSILE DEFENSE AND OTHER DoD WORK
End of Cold War
1990s
DOE MULTIPROGRAM + DoD, ECONOMIC COMPETITIVENESS
Stockpile stewardship
2000s
EXPANDED NATIONAL SECURITY ROLE POST 9/11
Broader national security
Today
MULTIMISSION LAB: LEPs CYBER, BIO, SPACE, TERRORISM
Evolving national security challenges

3


Capabilities Housed Across the Nation
Nuclear Fuel Cycle & Grid Modernization
Activity locations
Kauai, HI
Waste Isolation Pilot Plant, Carlsbad, NM
Pantex, Amarillo, TX
Tonopah, NV
Utqiagvik (Barrow), AK
Lubbock, TX
Main sites
Albuquerque, New Mexico
Livermore, California

4

# NFCGM Program

Nuclear Fuel Cycle & Grid Modernization

**Nuclear Fuel Cycle & Grid Modernization**
**Amy Halloran**

- Grid Modernization & Energy Storage — **Charles Hanley/8810**
- Advanced Nuclear Energy Program — **Sylvia Saltzstein/8840**
- Nuclear Energy Safety Technology — **Richard Griffith/8850**
- Defense Waste Management Programs — **Paul Shoemaker/8800**

**300+ Research Staff:**
LTEs, Post Docs & Students
Working in 25 states

**13 Research Facilities:**
Including the Distributed Energy Technologies Laboratory, Energy Storage Test Lab, Geochemistry Facility, Nuclear Energy Work Complex, and the Transportation Lab

**A unique set of Modeling, High Performance Computing, Experimental, Engineering, & Testing capabilities**



# Our Work at Sandia

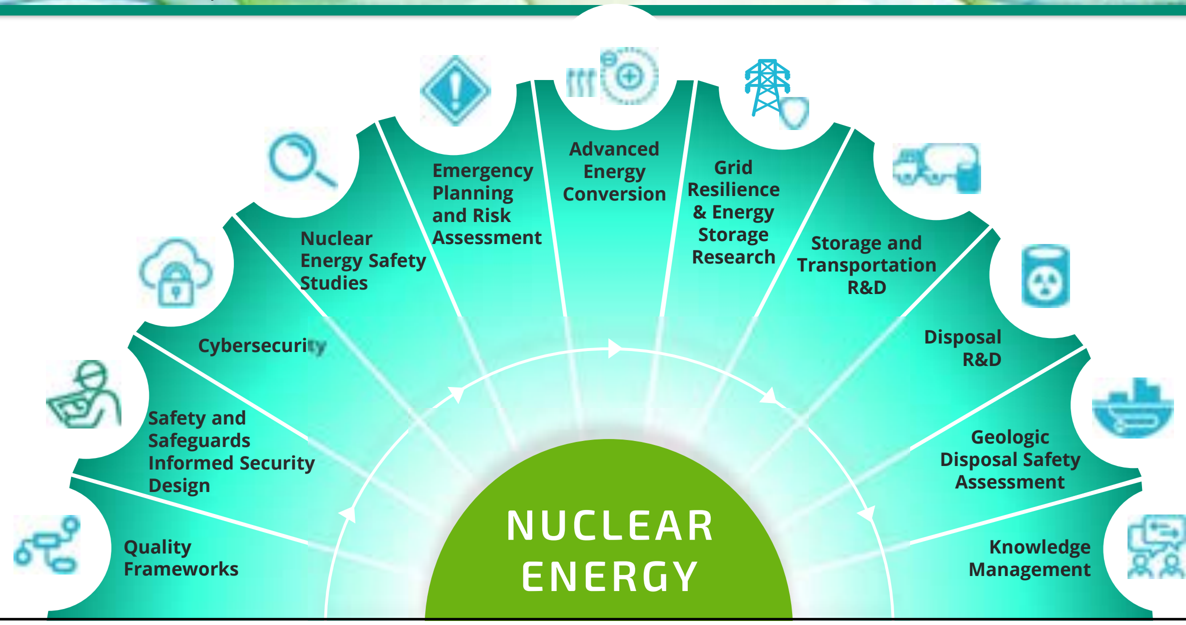
Nuclear Fuel Cycle & Grid Modernization

OUR PROJECTS ARE…

- Developing an advanced Electric Grid with Reliable Resources and Storage
- Enhancing the safety, security, safeguards and economical viability of Nuclear Energy
- Advancing the science and engineering of Nuclear Waste Management

# R&D to Ensure Nuclear Energy is Safe, Sustainable, & Secure

Nuclear Fuel Cycle & Grid Modernization




7

Nuclear Fuel Cycle & Grid Modernization


8

# Our Workforce

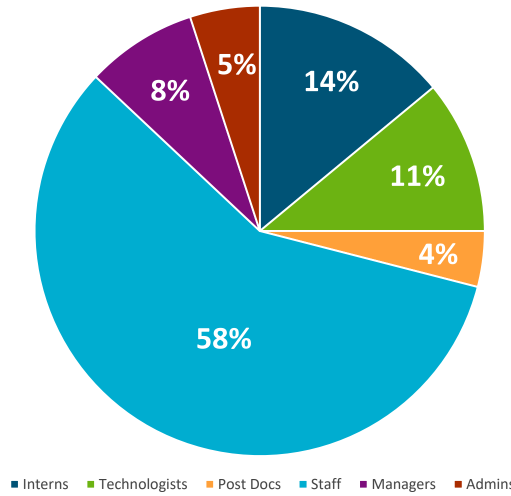
Nuclear Fuel Cycle & Grid Modernization

R & D ORGANIZATION
Higher percentage of PhDs than Sandia overall

RELATIVELY YOUNG
Median <6 years with Sandia
<12 years since B.S.

Diverse Backgrounds

- 50% Engineers
  - Aeronautical, Agricultural, Architectural, Chemical, Civil, Computer, Electrical, Energy, Environmental, Industrial, Manufacturing, Materials, Mechanical, Metallurgical, Nuclear, Petroleum, Structural, and Systems
- 10% Earth Sciences
- Many Others
  - Biology, Chemistry, Computer Science, Environmental Science, Health, Math, Physics, etc.






# We Steward Unique Large-Scale Test Facilities and Labs

# Critical Partners



Academic

Industry

Govt/ National Labs



# Accomplishments

Nuclear Fuel Cycle & Grid Modernization

**Secretary's Achievement Award for Nuclear Waste Management (NWM) Cloud**

In 2022, awarded a DOE Secretary's Achievement Award for developing an **easily accessible, turnkey IT solution for Nuclear Quality Assurance-1/NRC-regulated NWM disposal, storage, or transportation projects.**

**The Advanced Power Electronic Conversion Systems**

Sandia successfully went from concept → design/build → implementation of a power converter (patent pending) that provides integrated control of multiple energy sources on a single grid. **This capability allows rapid development of new power conversion systems**.

**Multi-Modal Transportation Test**

Sandia and PNNL **quantitively demonstrated that spent nuclear fuel can be transported by ship, train, or truck with little risk of damaging the fuel.** NRC used this in NUREG-2224 "Dry Storage and Transportation of High Burnup Spent Nuclear Fuel", simplifying licensing for transporting high burnup SNF.

**MELCOR**

Sandia developed the MELCOR software to analyze nuclear power reactor accidents that could lead to release of radiation to the environment. The software **enables comprehensive assessment of potential for consequences to public health and safety**.

**Puerto Rico Energy Resilience**

Sandia has **provided tools to ensure that Hurricane Maria recovery enables energy resilience** and provides critical services by engaging community leaders in our microgrid design workshops. This approach can be applied in other communities, e.g. SMRs in remote or Arctic areas, to ensure local participation, buy-in, and ensure resilience for those loads that are most important to the communities.

**Secretary's Achievement Award for Mars 2020 Perseverance Rover Radioisotope Power Systems**

The Mars 2020 Perseverance Rover Radioisotope Power Systems Team was awarded the Secretary of Energy's Achievement Award for **using Sandia's state-of-the-art supercomputers and experimental data to assess the various risks posed by the rover's radioisotope thermoelectric generator during launch**.


Sandia
National
Laboratories
Exceptional service in the national interest

# SESSION 1: Developments in National Programs

Chair: Michael Bühler

# Status of German site selection and ongoing work

## US/German Workshop 2023 (Santa Fe, USA)


**Dr. Florian Panitz**
Federal Company for Radioactive Waste Disposal (BGE)
Site Selection Procedure
Safety Assessment

1

# Agenda



2

## TOPIC 1: THE GERMAN SITE SELECTION PROCEDURE



## Radioactive waste in Germany

### High-level radioactive waste

- Forecast: approx. 1,900 castor containers
- Approx. 10,100 tons heavy metal from fuel elements plus waste from reprocessing
- 99 % of radioactivity


### Low- and intermediate-level radioactive waste

- Approx. 303,000 $m^3$ storage capacity in the Konrad repository mainly from NPP[1] decommissioning
- Up to 220,000 $m^3$ from Asse
- Up to 100,000 $m^3$ other
- 1 % of radioactivity


[1]Nuclear power plant

Source: BGE

## Key principles of the procedure


Source: BGE

- Basis: Repository Site Selection Act (StandAG)
- Site located in the Federal Republic of Germany
- Deep geological storage
- Best possible safety for a period of 1 million years
- Retrievability during operating phase of the repository facility
- Recoverability for 500 years after closure of the repository facility
- Participative, science-based, transparent, self-questioning and learning procedure



## Host rocks in Germany

**Crystalline rock**

Heat-conductive, robust, but brittle

**Rock salt**

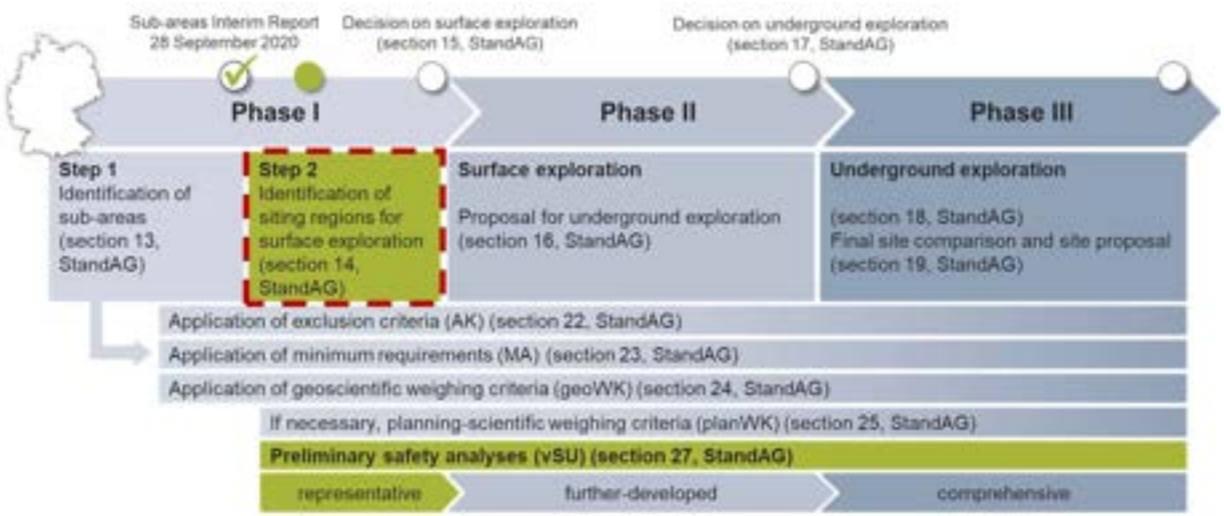
Heat-conductive, ductile and practically impervious, but water-soluble

**Claystone**

Sorptive, low hydraulic conductivity, but thermally vulnerable

Source: BGE

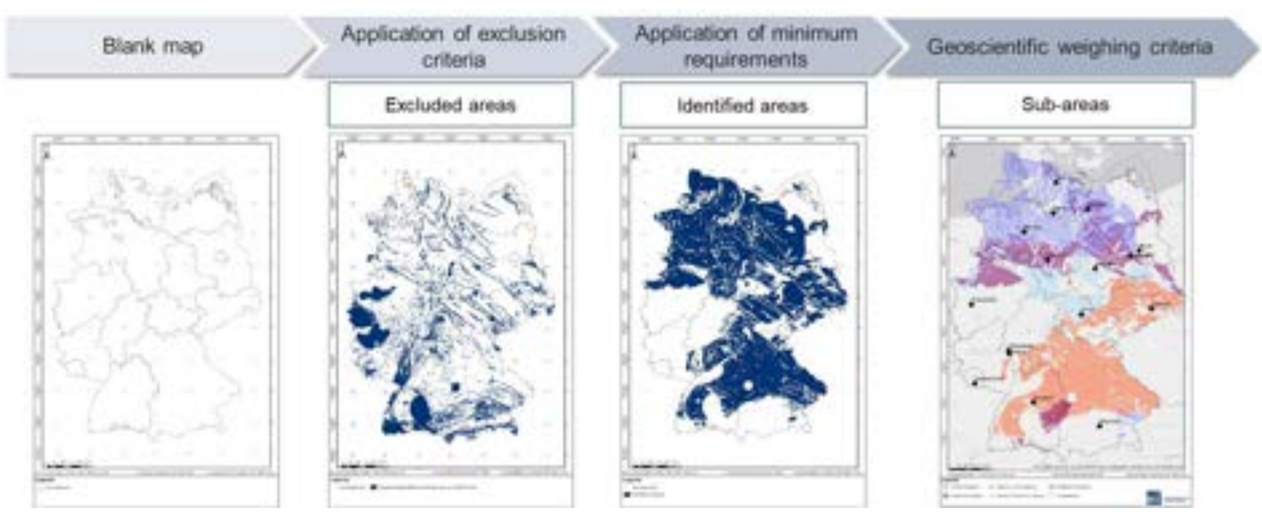
## Sequence of procedure steps




Source: BGE



## Step 1, Phase I: Identification of sub-areas



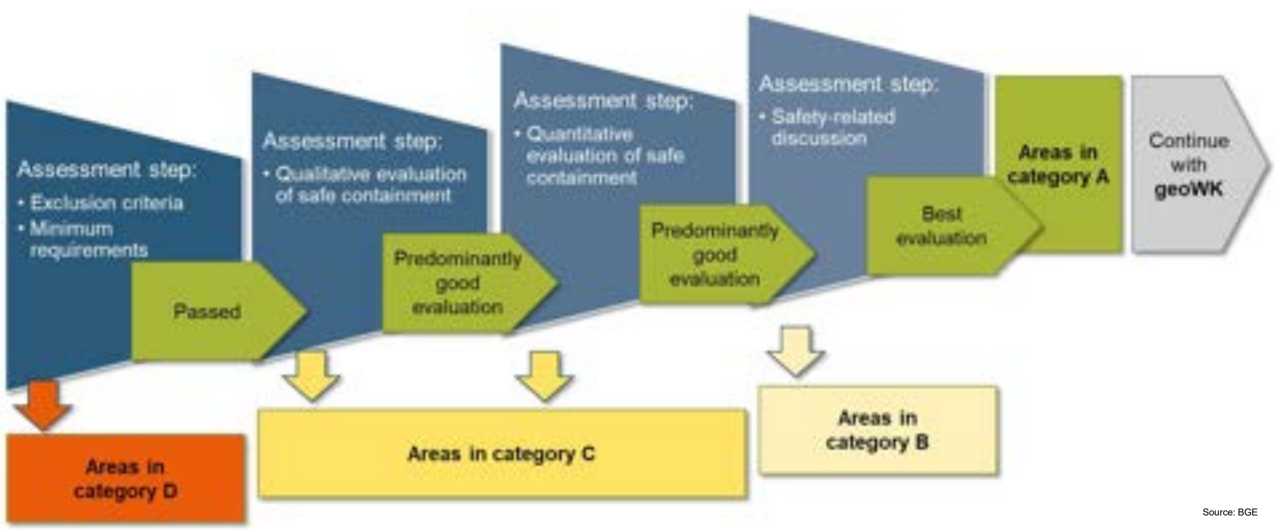

- For further reading see “Sub-areas Interim Report pursuant to Section 13 StandAG” (BGE 2021cj)

Source: BGE

# TOPIC 2: THE REPRESENTATIVE PRELIMINARY SAFETY ANALYSES (rvSU)

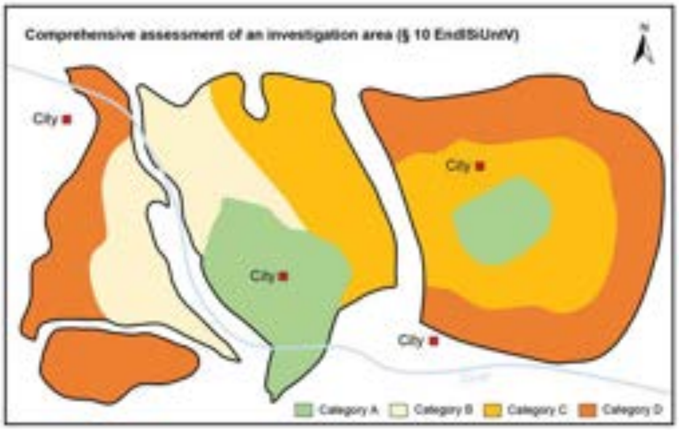


## Procedural flow – the four assessment steps




Source: BGE

## Result of comprehensive evaluation




Source: BGE

- Evaluation of all sections of an investigation area (= sub-area)
- Detailed processing with a focus on particularly suitable areas
- Transparent representation and documentation of suitability assessment for all areas



## TOPIC 3: ONGOING WORK AND CHALLENGES

## Methodological development for the rvSU

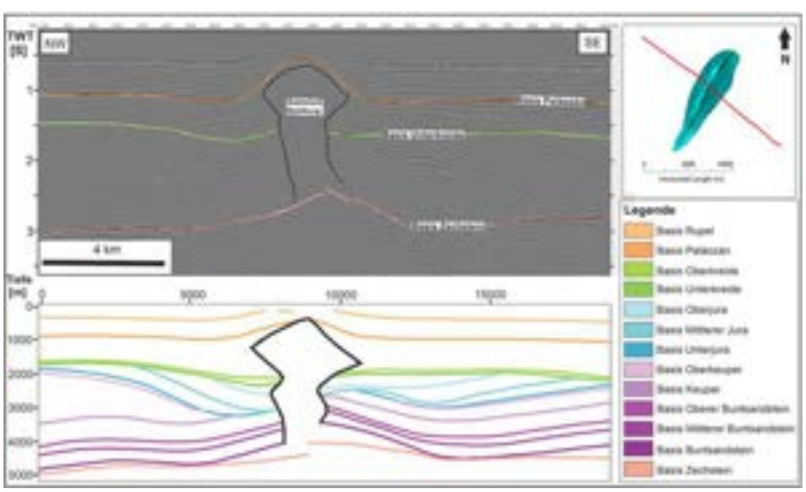
- Publication of a general concept and basic methodological description of the rvSU in March 2022
- Some methodological details still have to be finalised, for example concerning:
  - ➢Assessment step 2 (“Qualitative evaluation of safe containment”)
  - ➢Assessment step 3 (“Quantitative evaluation of safe containment”)
  - ➢Assessment step 4 (“Safety-related discussion”)
  - ➢Uncertainty evaluation
- Developed methods need also to be tested in investigated areas


Source: BGE



## Host rock: Rock salt (diapirs)

**Prediction of the internal structure for rock salt diapirs**




Source: BGE

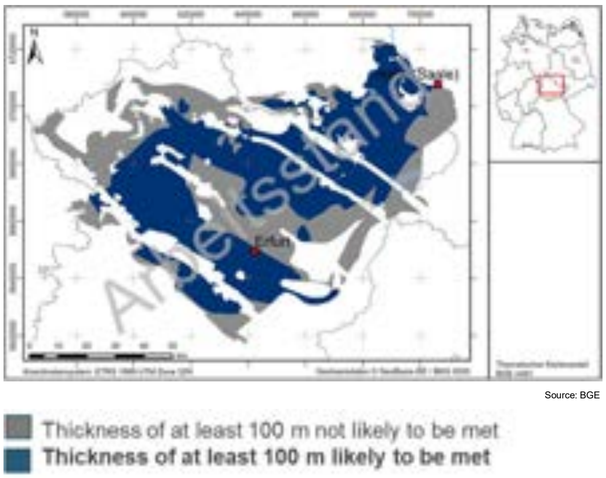
- Example showing the level of detail of salt structures in a 2D model
  - Barely possible to characterise the internal configuration of the salt structure
  - Depiction of the internal salt structure was not the goal of the initial data acquisition

⬇

Development of a method for the prediction of the degree of the internal complexity of salt diapirs

# Host rock: Rock salt (stratiform)

**Assessment of individual exclusion criteria/minimum requirements**




Source: BGE

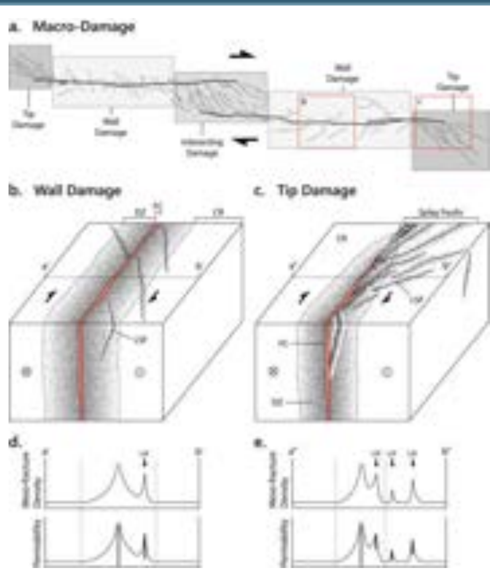
Analysis of available information from:

- Boreholes
- Thickness maps
- Cross sections
- Well logs
- More detailed 3D modelling

Identification of suitable areas in the area for method development “Thüringer Becken” with an expected thickness of at least 100 m



# Host rock: Crystalline Rock

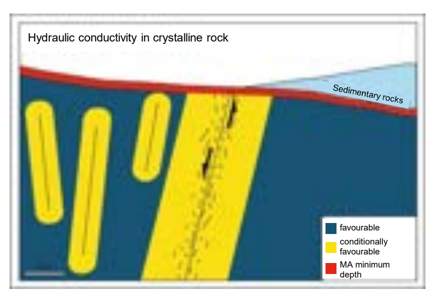



Source: Ostermeijer et al. (2020)

- Assessment of permeability using a robust, data-based approach
- Discrete structures (regional fault zones) are generally considered to be potentially water-conducting
- Fault damage zones are potentially water-conducting, while the fault core and host rock are less permeable

i. **Fault network database** in crystalline rock formations

ii. **Application of safety margins** around known **regional fault zones**

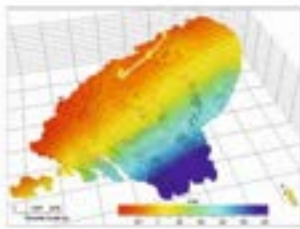


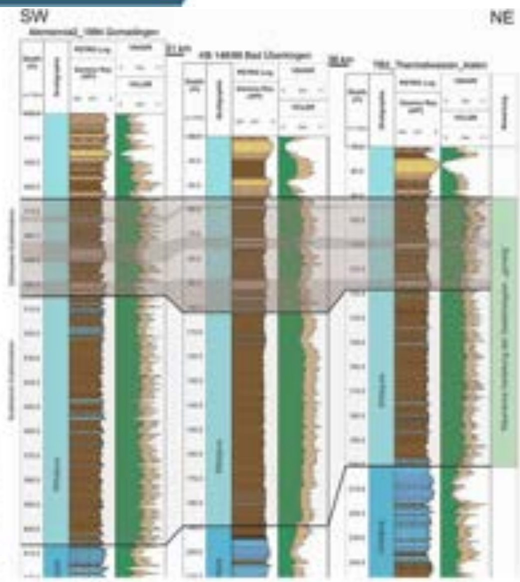

Source: BGE

# Host rock: Claystone

- SW – NE cross section
  - ➢Interpretation of host rock succession using wireline logs from wells
  - ➢Thickening of host rock succession towards SW
  - ➢Upper part of the succession: correlation of silty, carbonate cemented layers possible across the area of investigation

Prediction of lateral variation possible **by interpretation via wireline logs**






Source: BGE



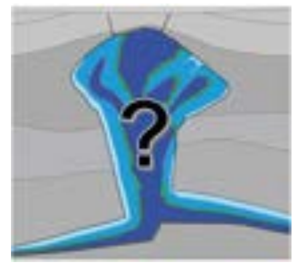
# TOPIC 4: SELECTED RESEARCH ACTIVITIES CONCERNING ROCK SALT

## Diapirs: Degree of internal complexity

**Proxies which might refer to a certain type of internal structures and their complexity**

| Group | Size | Morphology | Halotectonic evolution | Paleogeographic position |
|---|---|---|---|---|
| Proxies | Horizontal section area | Shape in horizontal section | Phases (amount, extension/compression) | Primary thickness of rock salt |
| | Variability in horizontal section | Shape in cross section/ wall configuration | Peripheral sinks | Proportion of non-chloridic components |
| | Thickness < 1,500 m | Overhangs | Maturity | Structure-forming salt formation |
| | | Saltwings | Secondary thickness | |
| | | | Basement faults | |
| | | | Activity of basement faults | |

Source: BGR (edited)



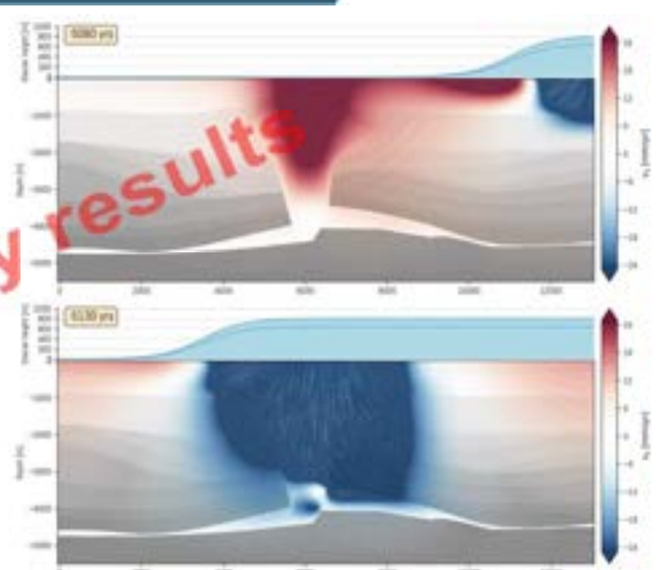
Source: BGE





## Glaciation influence on salt structures

- Evaluation of the influence of glaciations on the stability of salt structures
- 3D geodynamic numerical modelling
- Method takes into account:
  - Internal heterogeneities and faults in the salt and overburden
  - Sensitivity of the results to variations in the material parameters
  - Evaluation of the potentially significant effect of pressure solution creep
- Partners: smartTectonics GmbH and GeoStructures Consultancy


Source: smartTectonics GmbH

## TOPIC 5: SUMMARY AND OUTLOOK



## On-going work and challenges

- Basis of the site selection procedure in Germany is the Repository Site Selection Act (StandAG)
- The procedure is currently in Phase I, Step 2 (out of three phases) and considers three kinds of host rock
- Research and development activities are essential for the site selection procedure ("science-based, learning procedure")
- The main goal in Phase I, Step 2 is the identification of siting regions for surface exploration
  - ➢Therefore:
    - –Finalisation of the methodological development for the rvSU
    - –Full processing of the rvSU for all sub-areas
    - –Further development and subsequent application of the geoscientific weighing criteria
    - –Preparation of a potential application of the planning-scientific weighing criteria

# Thank you for your attention!

## Would you like to read more?

**Information on the Sub-areas Interim Report**

Interactive introduction to compilation of Sub-areas Interim Report and to all criteria and requirements

Sub-areas Interim Report with all documents and annexes

Dedicated page for each sub-area

Interactive map with all sub-areas and excluded areas

**Information on the status of the rvSU methodological development**

Descriptions of areas for methodological development

Event series on YouTube

Overview of representative preliminary safety analyses

Concept for carrying out representative preliminary safety analyses

Description of method for carrying out representative preliminary safety analyses



# Abbreviations

| | |
|---|---|
| **AK** | Exclusion criteria |
| **BGE** | Federal Company for Radioactive Waste Disposal |
| **BGR** | Federal Institute for Geosciences and Natural Resources |
| **geoWK** | Geoscientific weighing criteria |
| **MA** | Minimum requirements |
| **NE** | North-east |
| **NPP** | Nuclear power plant |
| **NW** | North-west |
| **planWK** | Planning-scientific weighing criteria |
| **rvSU** | Representative preliminary safety analyses |
| **SE** | South-east |
| **StandAG** | Repository Site Selection Act |
| **SW** | South-west |
| **vSU** | Preliminary safety analyses |

# References


- BGE (2020cj): Sub-areas Interim Report pursuant to Section 13 StandAG. Peine: Bundesgesellschaft für Endlagerung mbH. https://www.bge.de/fileadmin/user_upload/Standortsuche/Wesentliche_Unterlagen/Zwischenbericht_Teilgebiete/Zwischenbericht_Teilgebiete_-_Englische_Fassung_barrierefrei.pdf

- Ostermeijer, G. A.; Mitchell, T. M.; Aben, F. M.; Dorsey, M. T.; Browning, J.; Rockwell, T. K.; Fletcher, J. M.; Ostermeijer, F. (2020): Damage zone heterogeneity on seismogenic faults in crystalline rock; a field study of the Borrego Fault, Baja California. Journal of Structural Geology, Bd. 137. S. 1–20. ISSN 01918141. DOI: https://doi.org/10.1016/j.jsg.2020.104016

- StandAG: Repository Site Selection Act – Standortauswahlgesetz vom 5. Mai 2017 (BGBl. I S. 1074), das zuletzt durch Artikel 8 des Gesetzes vom 22. März 2023 (BGBl. 2023 I Nr. 88) geändert worden ist

Federal Office
for the Safety of
Nuclear Waste Management

# Germany: regulator´s perspective


**Ingo Kock, Head of Division**
**Research on Safety Analysis and Methodology**



**June 2023: 13th US/German Workshop on Salt Repository Research, Design & Operation**



Federal Office
for the Safety of
Nuclear Waste Management


## Stakeholders in Germany

| | |
|---|---|
| The Parliament: German Bundestag / Bundesrat | Political Responsibility |
| The Ministry: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) | Political Responsibility |
| ↓ The Authority: Federal Office for the Safety of Nuclear Waste Management (BASE) | Supervision, public participation |
| ↓ The Implementor: Federal Company for Radioactive Waste Disposal (BGE) | Implementation |

National Citizens' Oversight Committee (NBG)

# BASE:
# Our Tasks & Responsibilities




# Rules & Regulations

- Currently: Working on decree for long-term documentation
- 2022: Guideline “Calculation basis for dose assessment” finished
  During 2022: public involvement for the Calculation basis
- 2020: Decrees on Safety Requirements and Preliminary Safety Investigations for the Final Disposal of High-Level Radioactive Waste

**Full title: “Calculation basis for dose assessment for the final disposal of high-level radioactive waste”**

Federal Office for the Safety of Nuclear Waste Management

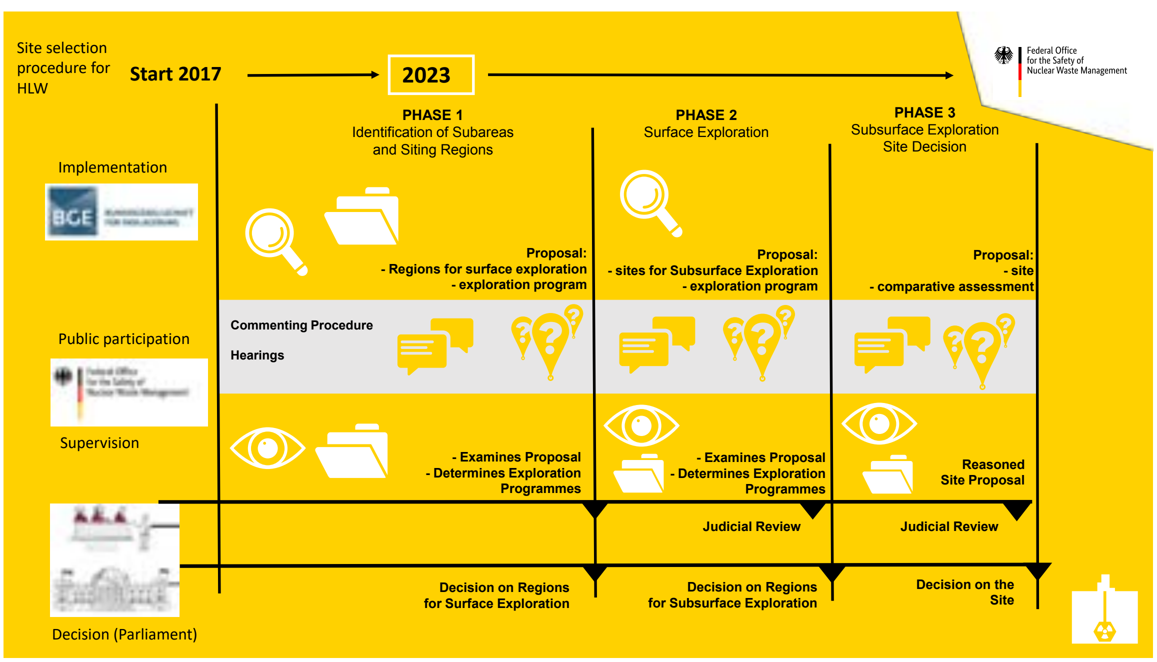
# Existing Disposal projects

- „Schachtanlage Asse II“
- BASE: Nuclear regulatory authority
- BGE licensee / operator of the Asse II mine
- LBEG, Lower Saxony, Mining Authority for the Asse II Mine
- NMU Lower Saxony Ministry for the Environment, … : Licensing Authority for the Asse II Mine

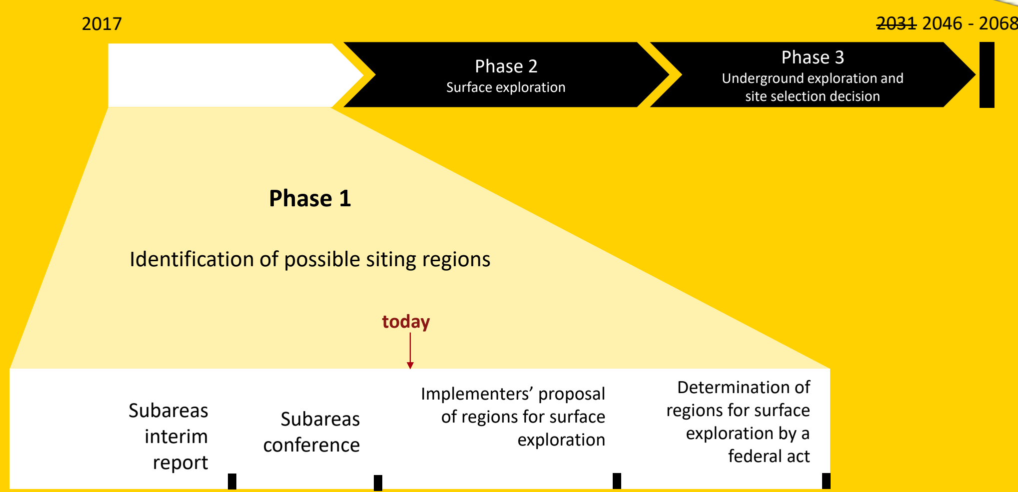
- Repository for radioactive waste Morsleben (ERAM)
- BASE: Nuclear regulatory authority
- BGE: licensee / operator
- LAGB Saxony-Anhalt, Mining Authority for ERAM
- MWU Ministry for the Environment … , Saxony-Anhalt: licensing authority

- Konrad
- BASE: Nuclear and radiation protection regulatory authority
- BGE licensee / operator Konrad
- LBEG, Lower Saxony, Mining Authority, Mining authority for the Konrad repository
- NMU Lower Saxony Ministry for the Environment, …: Licensing Authority
- NLWKN Lower Saxony State Agency for Water Management, … :water-legal licensing authority



## The site selection procedure:






## Delayed Site Selection Procedure

- Site Selection Act: 2031
  Best Case
  Estimated 20-30 subareas
  Ambitious, but not impossible
- 2 BGE scenarios:
  A: 2046
  B: 2068
- ~ 90 subareas, 54% of Germany

➔ Possible Consequences and Risks

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Nuclear Waste Management

## Consequences and Risks: Interim Storage

- HLW radioactive waste is currently stored above ground in interim storage facilities throughout Germany.
- Licensing is (on purpose) temporary only!
- License renewal can only be temporary again.
- License renewal must take into account the current State of the Art in Science and Technology
- License renewal must take public participation appropriately into account.

➔ We need long term safety (final disposal) and we need progress in the site selection procedure.
➔ We need interim storage to be **safe** and **temporary**.



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## Consequences and Risks: site protection

- Currently, 54 % of Germany are subareas and therefore potential sites
- All these sites have to be protected against other use
- For any mining activity (hydrocarbons, geothermal) an additional permit has to be applied for.
- Agreement between a federal state and BASE has to be reached regarding this permit.
- so far there has be no case of denial at BASE – but we have only few information on how many applications are stopped already at the federal states

Source: Wikimedia Commons

## Consequences and Risks

The probability increases that

- the necessary knowledge for handling highly radioactive waste is dwindling
- that social acceptance and political interest in the responsible handling of radioactive waste are declining
- that the disposal of LLW and ILW which is not destined for the Konrad repository will remain unclear for a long period of time



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Nuclear Waste Management

## Evaluation: site selection procedure

- What period of time is possible and justifiable for nuclear safety in Germany when all interactions are weighed up?
- A holistic view and evaluation is required.
- It is the responsibility of the legally defined actors to tackle this evaluation quickly.
- This is laid down in the law itself: the site selection procedure is self-learning and questioning.

# The role of research at BASE

Federal Office for the Safety of Nuclear Waste Management

Basis:
- laid down in the act to establish BASE and
- in site selection act

Implementation:
- External Funding: ~3 Mill €/y
- Projects: ~ 20 scientists



# Our Research

Federal Office for the Safety of Nuclear Waste Management

- **Nuclear Safety (AI, Climate Change ➔ Nuclear Safety (tender coming soon))**
- **Pre-Disposal, Interim Storage (Interaction between extended interim storage and long term safety)**
- **Operational Safety, Long-term Safety (AI, Thermo-Osmotic Flux (tender coming soon))**
- **Safeguards (new technologies, final disposal)**
- **Socio-technical systems (sustainable regional development in siting regions)**
- **Record Keeping / Knowledge Management (durability of paper / electronic storage)**

**➔ Research Agenda Update in Progress!**

Federal Office
for the Safety of
Nuclear Waste Management

Many thanks for your attention !

visit us online: www.base.bund.de

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

# Status of U.S. Spent Fuel and High-Level Waste Disposition


**Timothy C. Gunter**

Program Manager for Disposal Research and Development

**June 21-23, 2023**
**Santa Fe, New Mexico**

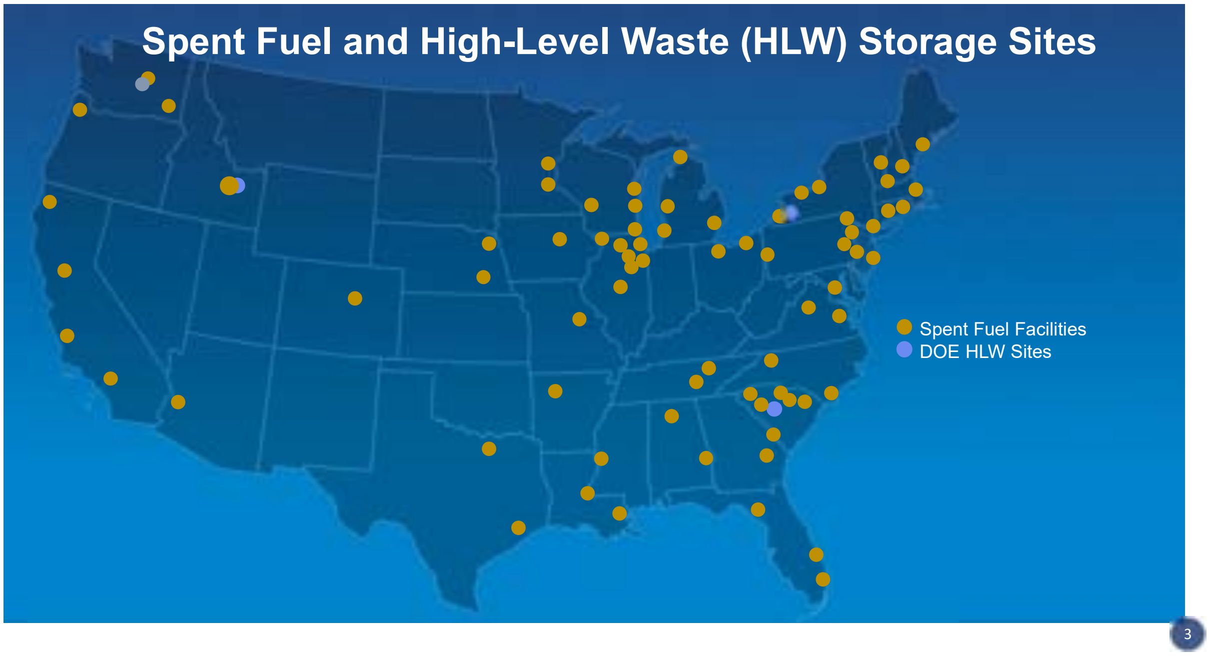
1

## NUCLEAR ENERGY in the U.S....

- ~20% of our nation's electricity
- 50% of our emissions-free energy
- Goal: net-zero emissions by 2050


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

2




3

# Integrated Waste Management

- As we continue to deploy nuclear energy as a solution for decarbonization, increasing access to energy, and tackling climate change, we need to make progress on the back end of the fuel cycle
- The U.S. Department of Energy is responsible for managing the nation's spent nuclear fuel and high-level radioactive waste, including finding sites to store and dispose of the spent nuclear fuel
- While spent nuclear fuel is stored safely all over the country, the communities that have the spent nuclear fuel never agreed to host the material long term

4

## U.S. DOE Spent Fuel and Waste Disposition (SFWD)

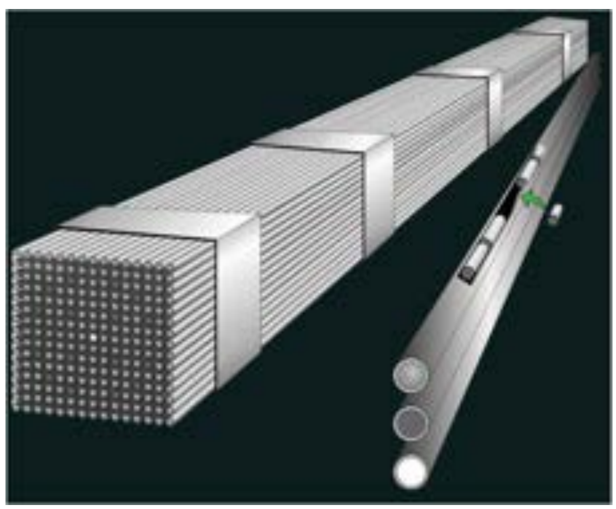
- **Nuclear Energy and Waste Management**
  - **Office of Spent Fuel and Waste Science and Technology (SFWST)**
    - **Disposal Research and Development (R&D)**
    - **Storage and Transportation R&D**
  - **Office of Integrated Waste Management (IWM)**
    - **Cross-Cutting Initiatives**
    - **Consent-Based Siting**



5

## SFWST Research & Development

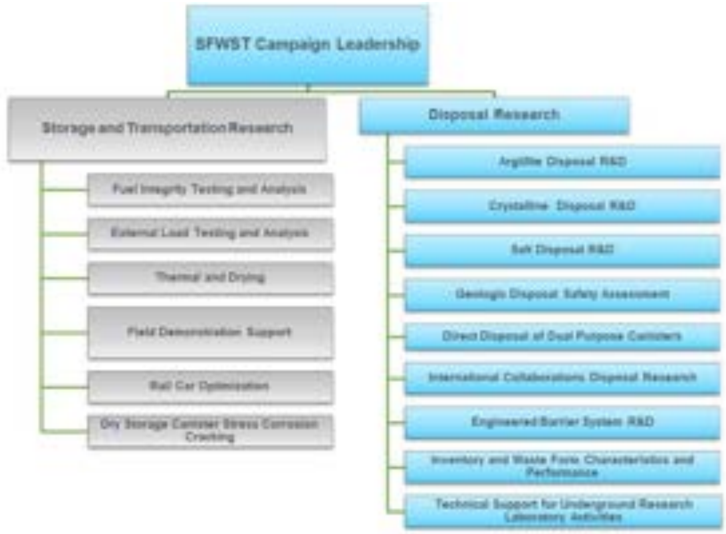
- R&D for eventual geologic disposal, extended storage, and transport of spent nuclear fuel and high-level radioactive waste
- Investigating different geologies and developing non-site specific disposal concepts
- Effects of storage and transportation on spent fuel integrity
- Advanced reactor waste forms
- Leverage international collaboration





6

## SFWST R&D Focus Areas






# Advanced Reactor R&D

- Many different advanced reactor designs are being proposed.
- The U.S. Department of Energy is supporting 10 U.S. advanced reactor designs to help develop and demonstrate their technologies.
- These reactor designs vary in size, power levels, and the forms of fuels they will use.
- These fuels may differ substantially from the existing commercial spent nuclear fuel inventory—and may need different handling, storage, transportation, or disposal options
- These fuels are being evaluated as part of our waste management program.

# International Collaboration

- International Atomic Energy Agency
  - Joint Convention on the Safety of Spent Fuel and on the Safety of Radioactive Waste Management
  - Nuclear fuel Cycle Options and Spent Fuel Management Technical Working Group
  - Various consultancy and technical meetings
- OECD/NEA Radioactive Waste Management Committee (RWMC)
- International Association for Environmentally Safe Disposal of Radioactive Materials (EDRAM)
- Participation in multinational collaboration projects (e.g. underground research laboratories R&D, transportation research, other)
- Bilateral R&D collaborations

Image Source: U.S. Mission to International Organizations in Vienna



# Office of Integrated Waste Management

- Plan for transportation of spent nuclear fuel
- Perform system analysis and integration
- Generic design of facilities
- Consent-based siting

# CONSOLIDATED INTERIM STORAGE

- Removes SNF from current host sites
- Promotes economic opportunities
- Reduces taxpayer liability



# Consent-Based Siting

Consent-based siting is an approach to siting facilities that focuses on the needs and concerns of people and communities.

By prioritizing communities and people, we believe we can find a solution to the decades-long stalemate on managing the nation's spent nuclear.

A consent-based approach, driven by community well-being and community needs, is both the right thing to do and our best chance for success.

## CONSENT-BASED SITING: FUNDING OPPORTUNITY ANNOUNCEMENT

**$26 million in funds; 13 awards; period of performance is 18-24 months**

### Eligible awardees includes:

- Higher-education institutions,
- Tribal, State, and local governments
- Community foundations
- Non-governmental organizations

### Geographically and institutionally diverse awardees

- Across the continental United States

### Builds capacity for future engagement

- Establishes a community of practice
- Strengthens involvement and mutual learning aimed at building trust
- Ensures commitment to environmental justice



# Consent-Based Siting

# PUBLIC FEEDBACK INFORMING NEXT STEPS IN CONSENT-BASED SITING

**1**
Awarding cooperative agreements for interested groups and communities to learn more

**2**
Mutual learning and further updating consent-based siting process

**3**
Clarifying DOE's broader strategy for an integrated waste management system



# Looking Ahead

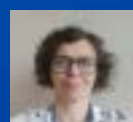
- Consent based siting and addressing societal challenges
- Need for a disposal pathway
- Extended storage research
- Foreseeing waste management from advanced reactors deployment
- Knowledge management


Thank you!
U.S. DEPARTMENT OF ENERGY
Office of NUCLEAR ENERGY

IAEA
International Atomic Energy Agency

# US-German Salt Workshop, June 2023
# IAEA Activities on HLW disposal

Waste Disposal Team
NE Department - NEFW Division – Waste Technology Section


Vaclava Havlova


Shin Horiguchi


**Karina Lange**


Gerry Nieder-Westermann


**Stefan Mayer**

# IAEA activities on HLW disposal

## Nuclear energy technical series documents - DGR

(URF Network )

(Technical cooperation with new and advanced DGR programmes)

## CRP on deep borehole disposal

## Basic knowledge and guidance to implementing a DGR?

- ✓ What are the main DGR programme components and iterative phases?
- ✓ How to start from a generic concept to then design the facility?
- ✓ How to manage the site investigation programme?
- ❖ How to establish and use site selection criteria?
- ✓ How to engage with civil society?
- ❖ What are local stakeholder experiences and expectations?
- ✓ How to estimate overall programme cost and provide funding?
- ❖ How to plan, construct and start operating first underground facilities?
- ❖ What is the historical evolution and current status of knowledge on DGR viability?

… how to plan the RD&D programme?
… are there viable alternate concepts?

❖ IAEA technical guidance under development
✓ IAEA technical guidance available

## Nuclear energy technical series documents - DGR

- Roadmap for implementing a geological disposal programme
- Design Principles and Approaches for Radioactive Waste Repositories
- The management of site investigations for radioactive waste disposal
- Site selection criteria and their application towards informing site selection of a geologic disposal facility*
- Communication and Stakeholder Involvement in Radioactive Waste Disposal
- Local Stakeholder Experiences with Radioactive Waste Management Programmes**
- Costing Methods and Funding Schemes for Radioactive Waste Disposal
- Practical Consideration and Experiences in Going Underground at a potential DGR site*
- URF Compendium**

Preparations ongoing…
… to establish guidance on Planning a research program for DGR
… to launch a cooperation to progress on the deep borehole concept

*Under development **Being finalized

## 1. Site selection criteria - recently launched (March '23)

IAEA

- **Goal:** To develop a technical guide on establishing and using site selection criteria to support the DGR siting process
  - ✓Build on overview of current international practices, experiences, lessons learnt
  - ✓Present generic guidance illustrated by national programme case studies
- **Audience:** Expert staff contributing to emerging or ongoing national DGR programmes
- **Outcome**: Nuclear Energy Series document; Training module
- **Initial Motivation:** by URF network during a 2019 workshop; during March '23 CM, representatives of 8 programmes starting working on the draft
- **Technical meeting** planned 11/27 – 12/01, 2023 (Participants welcomed)

## 2. Stakeholder Involvement with Disposal

IAEA

"Recognizing the situational nature of communication and stakeholder involvement[...]"

Broad principles
Spectrum of involvement
Catalogue of experiences

National
Regional !
Local

Designing a sound process

- ✓ No ambiguity on what decisions will be needed
- ✓ Clarity on respective roles in decision process – national, regional and local entities
- ✓ Agreement on what decisions can be reversed and until when in the process

Sound engagement starts when the decision process is being developed

Initiation → Siting → Construction / Operation / Closure → Institutional Oversight

- Social license → maintaining mutual understanding
- Involvement process → decision process, flexibility
- Political/Regulatory framework → sustained approach
- Resources → basis for sound decisions
- Community support → recognition

"Situational" implies
*No simple recipe*

→ Catalogue of experiences from ~ 20 national disposal programmes

# Focus on local stakeholders

*"[…]developing a deeper understanding of how to engage local stakeholders and enable them to become active, informed participants[…]"*


Synthesis of local stakeholder experiences suggests a suite of good practices

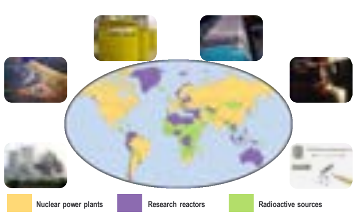
- Tailor stakeholder involvement to the nature of the project
- Prepare organizations for long-term local involvement
- Empower the local level
- Engage broadly – Broaden to region & Reach out to Youth
- Make learning a priority
- Promote long-term community well-being
- Embrace change over disposal programme timelines
- Learn from others – Build local knowledge
- Incorporate the long timeframes into the engagement approach

During a 10/2022 Technical Meeting, we clearly heard that municipalities and elected officials expect to be a significant part of the process.

# Global Partnership of Municipalities

RWM is a global issue and a national responsibility, requiring local solutions.

10/31-11/04, 2022 IAEA Meeting:
Elected representatives from over 25 countries discussed their experiences and expectations as host of a nuclear facility.




- A new Global Partnership on municipalities with nuclear facilities was established:

gmf · Energy Communities Alliance · CANHC Canadian Association of Nuclear Host Communities

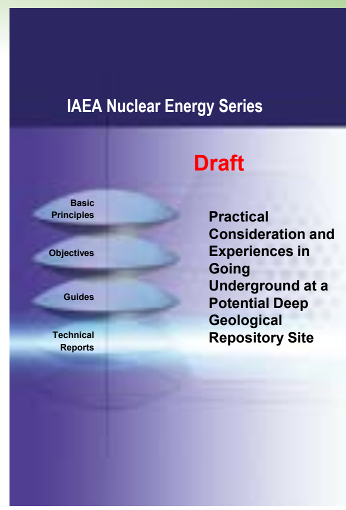
- Launched "a new dialogue among the global coalitions of communities to share information, educate each other, advocate for municipalities in nuclear and work together to assist our communities and other communities hosting or interested in hosting nuclear facilities."

16-20 October 2023:
TM on Local Stakeholder Engagement in RWM

Broaden the global dialogue → Please inform and liaise with local elected officials and representatives of host communities within the national DGR programme you represent.

## 3. Construction – "Going underground"

- Provides a practical handbook on what needs to be considered at the point when a national programme is planning to move from surface-based activities to underground excavation
- Drawing upon past experiences from both successful and unsuccessful attempts to 'go underground'
- General observations are provided for the most studied host rock types argillaceous rocks (clays, mudstones, and marls), crystalline rocks (gneiss, granite) and salt rock formations (principally bedded or dome rock salt)
- Lessons learnt from sinking Gorleben shafts is included




## 4. IAEA CRP #T22003 on Deep Borehole Disposal (2024-2027)


Figure courtesy of Sandia National Labs.

Objectives:

- ✓ To enhance the international knowledge basis available on Deep Borehole Disposal
- ✓ To support Member States strategic decision on whether to pursue DBD as part of their national disposal programme
- ✓ To support preparatory work for one (or two) DBD field demonstrator(s)

Motivation:

- ✓ Request from Member States to provide a cooperation platform
- ✓ Potential to address disposal needs for small(er) or specific challenging wastes
- ✓ Specific plans in several Member States

➢ Open for research proposals: July-September 2023

## Overall Expected Outcome and Results

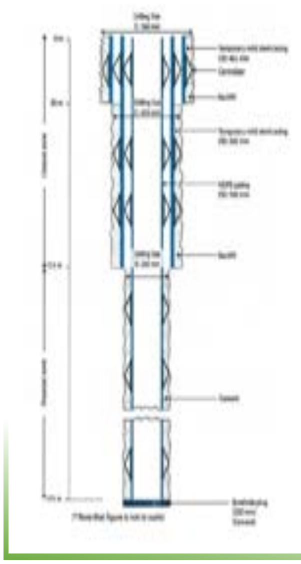
- Technical IAEA document summarizing current state of knowledge on DBD; augmented by main technical progress achieved through CRP developments
(e.g. on TRLs, FEPs, risk analysis, operational and post-closure safety assessments, “library” of sealing materials, viability of drilling approaches in disposal context…)
- Technical IAEA document presenting the steps taken to conduct cost estimate for a range of deep borehole disposal concepts, and the basis used to establish probable cost effectiveness as compared to other viable disposal concepts
- Technical IAEA document presenting elements of planning for a DBD field test as envisioned by CRP participants to provide in-situ verification of laboratory results
- IAEA course/workshop to share current understanding on DBD with a wider audience.
- IAEA workshop to engage with stakeholders sharing an interest in this concept, for example to establish a regulator/implementer dialogue on associated regulatory framework.

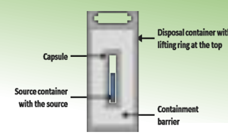
## Main coordination activities (initial assumption)

| Activity | Year 1 | Year 2 | Year 3 | Year 4 |
|---|---|---|---|---|
| 1. Organizing the first RCM, including scoping discussions on potential implications for DBD concept meeting IAEA safeguards req… | ■ | | | |
| 2. Organizing a workshop on focus technical topics, such as establishing a Material Breakdown Structure, Technological Readines… | ■ | | | |
| 3. Organizing a workshop to initiate a dialogue between implementers and regulators on the compatibility of a DBD concept with t… | | ■ | | |
| 4. Organizing the second RCM | | ■ | | |
| 5. Organizing a workshop to focus on the gap analysis for feasibility and safety as main input to draft DBD field demonstrator requi… | | ■ | | |
| 6. Organizing a consultancy meeting to discuss first drafts of publications generated through CRP work and to agree further inputs | | | ■ | |
| 7. Organize a follow-on workshop engaging disposal implementers and regulators on the compatibility of a DBD concept with the t… | | | ■ | |
| 8. Organizing a workshop to elicit feedback on draft publications and training material as CRP outputs | | | ■ | |
| 9. Organize a workshop to transfer knowledge established through CRP outputs | | | | ■ |
| 10. Organizing the third RCM | | | | ■ |
| 11. Organizing a consultancy meeting to verify consistency and quality of CRP Outputs | | | | ■ |
| 12. Organizing a workshop to identify potential implications that safeguards requirements might have on DBD concept requirements | | | ■ | |

DRAFT

# Update - Borehole disposal for DSRS





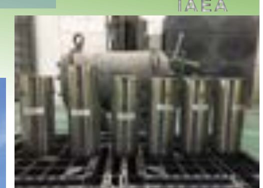

✓CRP – borehole disposal for DSRS – ending in 2023

- Third RCM for the effective implementation of borehole disposal, focus on site characterization (Vienna, Oct 23-27, 2023)

✓Nuclear Malaysia borehole disposal for DSRS inventory – 2023

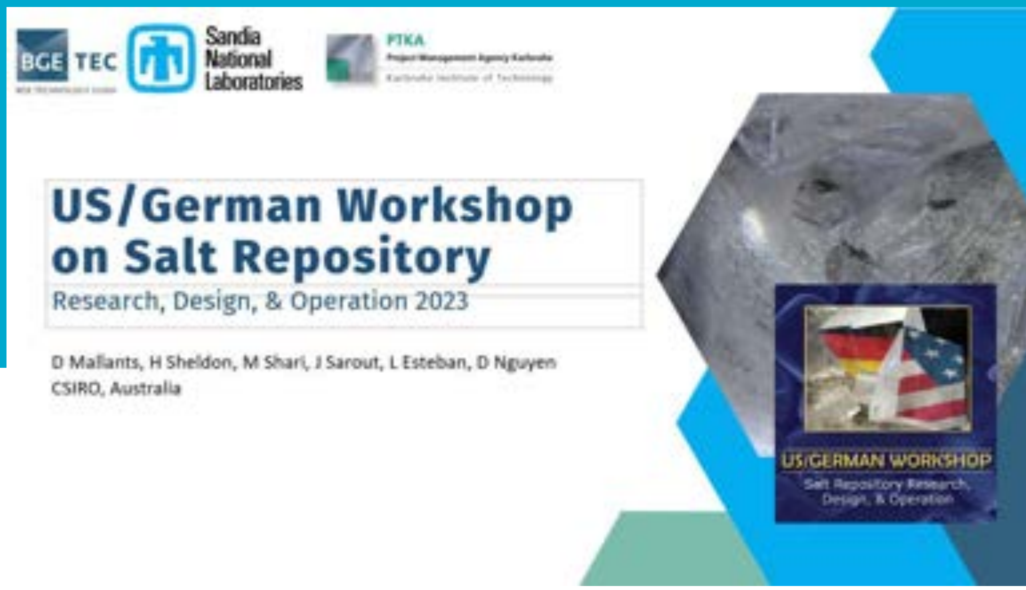
- Conditioning DSRS inventory into 43 disposal containers
- Providing the borehole disposal facility 06-09/2023 (drilling, lining, documenting, verifying…)
- Disposal operations ~ 09-10/2023

# "Small diameter" borehole – construction (a few impressions)



IAEA
International Atomic Energy Agency
Atoms for Peace and Development

*Thank you!*




CSIRO


Australia's National Science Agency



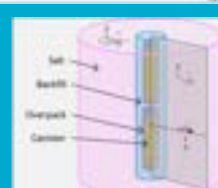
CSIRO

# Status of Australia's RD&D program on ILW Waste Disposal: Focus on Salt Formations

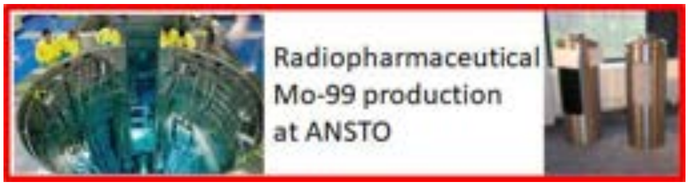
13th US/German workshop on Salt Repository

D Mallants, H Sheldon, M Shari, J Sarout, L Esteban, D Nguyen

20/6/2023




## Australia's inventory requiring geological disposal

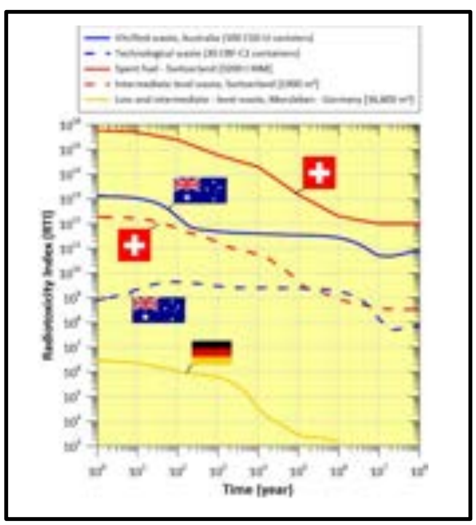



| | Type | Volume ($m^3$) | Activity (TBq) |
|---|---|---|---|
| Long-lived ILW | Processed Spent Fuel (HIFAR & OPAL Research Reactors-LEU) – vitrified waste | 20 (< 1%) | 54000 |
| Long-lived ILW | Synroc (Mo-99) – glassy waste form | 150 (5%) | 1300 |
| | Spent Uranium Filter cups (Mo-99 production) | 10 [20](<1%) | 60 |
| | DSRS (cat I & II) | - | - |



## Radiotoxicity: vitrified & technological waste

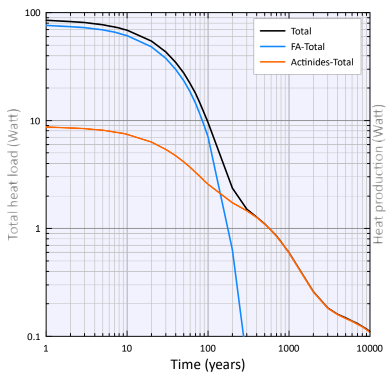
$$RTI(t) = \sum A_j(t)\, F_j / (10^{-4}\mathrm{Sv})$$

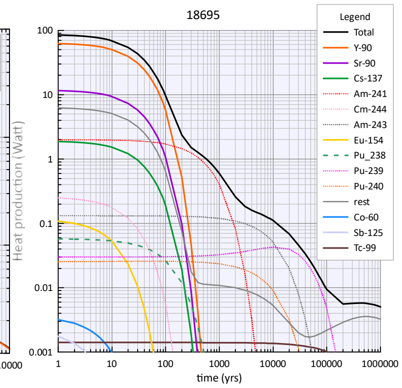


# Heat production of CSD-U waste

- Inventory – based heat calculation
- FISTPAC-II code
- $T = T_0 + 1\ year$: 84.8±0.12 W/container
- $T = T_0 + 20\ years$: 54.4±0.07 W/container

## Single container

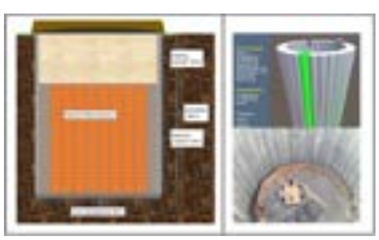


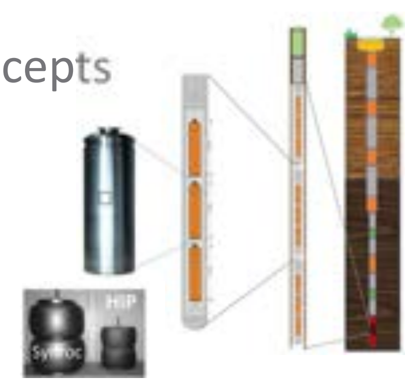




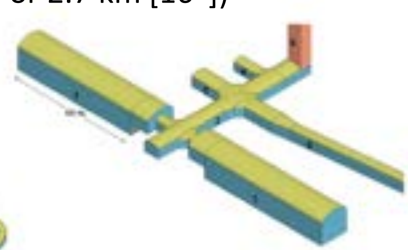

# Potential disposal concepts



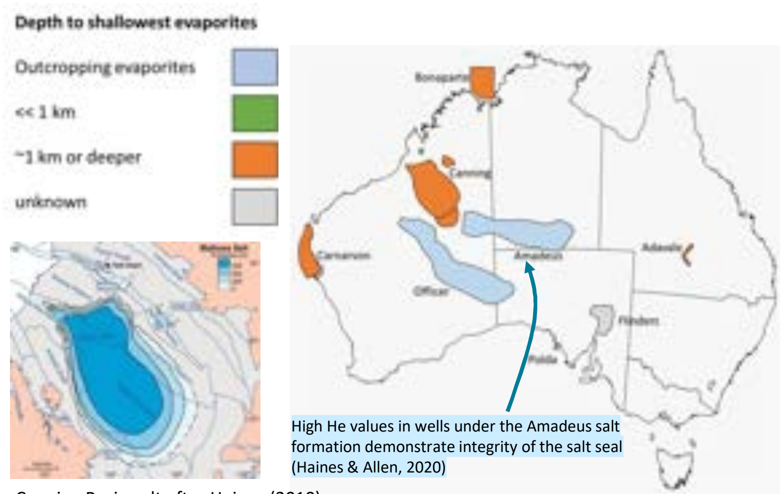
Shallow-depth silo/shaft



Deep borehole (up to 1.6 km [26"] or 2.7 km [16"])



# Occurrence of salt formations in Australia




Canning Basin salt after Haines (2010).

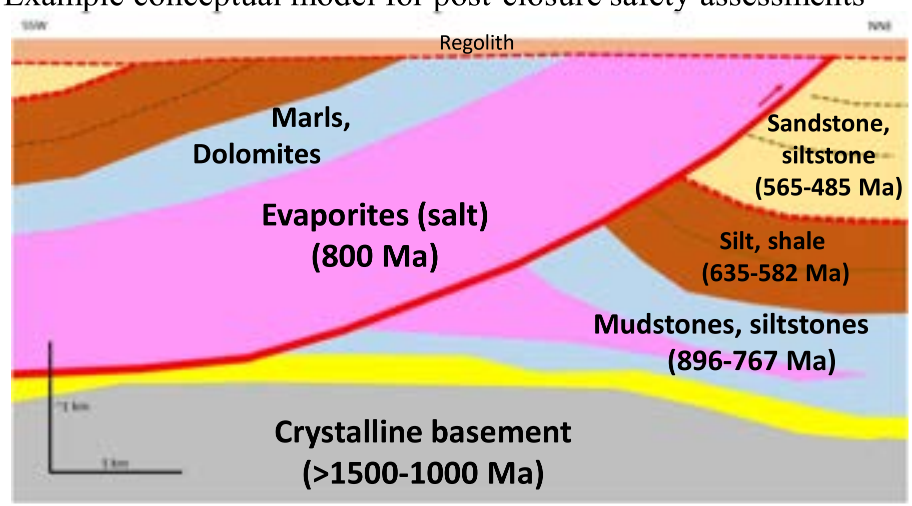
| Property | Evaporite |
|---|---|
| Hydraulic conductivity and fluid flow | Flow is negligible |
| Porosity | 0.02 – 0.04. Undisturbed halite is likely to have a connected porosity of effectively zero, although there may be inclusions of fluid on the micron to mm-scale |
| Solute transport | Any transport is likely to be by diffusion via heterogeneities (e.g. clay or anhydrite interbeds) |
| Mechanical strength and excavation stability | Low to medium mechanical strength, e.g. 12 MPa – 30 MPa Unconfined Compressive Strength. Excavations could be self supporting |
| Deformation behaviour and possibility of self-sealing EDZ | Exhibits rock creep. Any EDZ can be expected to recover by deformation |
| Thermal conductivity and heat tolerance | Relatively high thermal conductivity, 3.5 W $m^{-1}$ $K^{-1}$ – 6 W $m^{-1}$ $K^{-1}$ (4) and high tolerance to heat (e.g. 200 °C temperature limit) |
| Sorption behaviour | Limited potential for sorption to evaporite |
| Gas transport properties | High gas-entry pressure |





# Occurrence of salt formations in Australia

- Amadeus Basin (NT): "oldest regionally extensive salt deposits in the world" (Haines & Allen, 2020) - early Neoproterozoic (~ 800 Ma)
- Example conceptual model for post-closure safety assessments

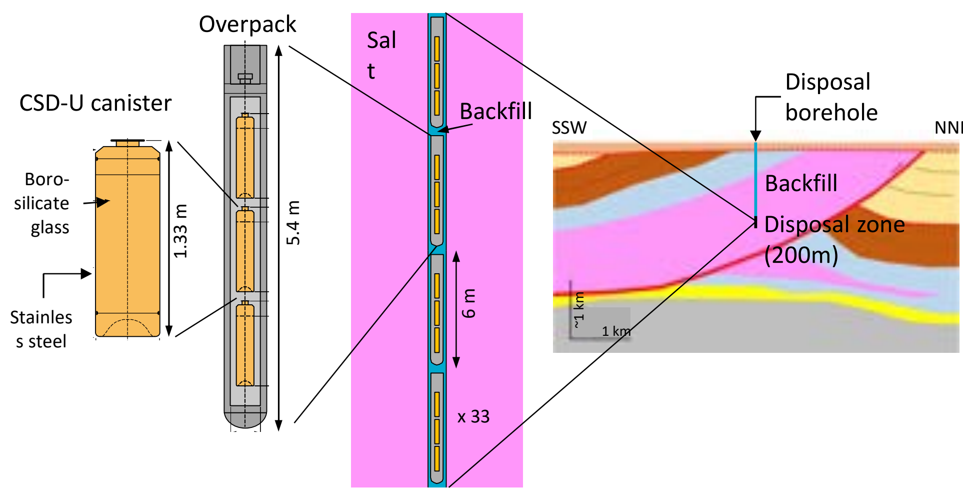


## Preliminary post-closure safety assessment: Modelling radionuclide migration from a deep borehole in rock salt

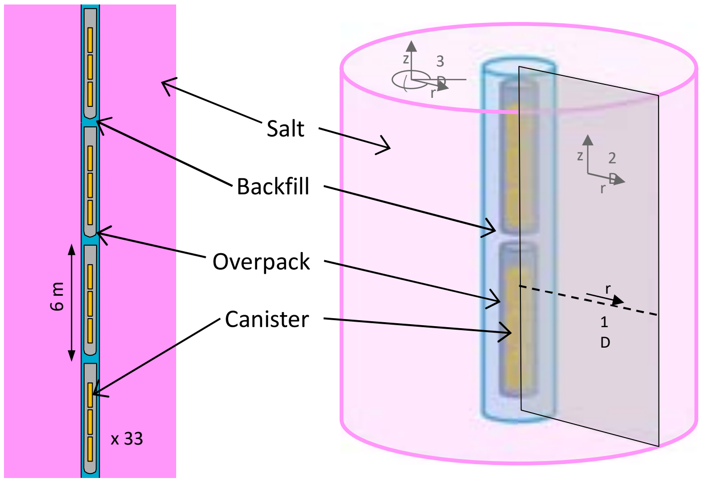




## Disposal concept



# Simplification: 1D radial model



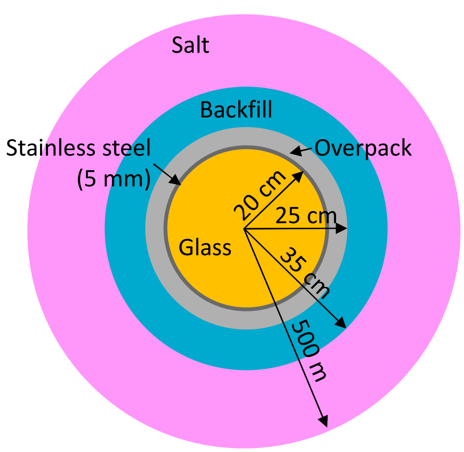

Assumptions:
- No vertical transport
- Homogeneous in z and θ

Fast computation → parameter sensitivity





# Radial geometry




Backfill = crushed salt

# Processes

Included:
- Diffusion
- Linear sorption
- Radioactive decay
- Gradual degradation of glass
- Finite life of stainless steel and overpack

Excluded:
- Advection/convection
- Heat transport
- Heat generation

Simulated using TOUGH-REACT
Simulation time 10 million years



# Inventory and decay chains

Actinides

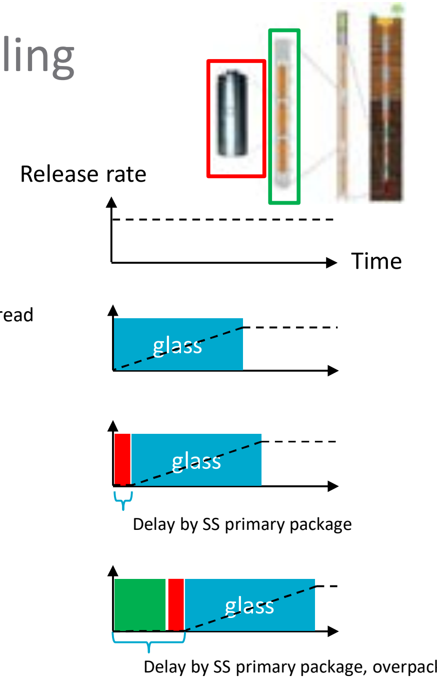
| Radionuclide | Mean activity per canister (Bq) |
|---|---|
| U-234 | 2.11E+07 |
| U-235 | 3.40E+05 |
| U-236 | 8.78E+05 |
| U-238 | 1.13E+07 |
| Pu-238 | 6.41E+10 |
| Pu-239 | 3.58E+10 |
| Pu-240 | 3.03E+10 |
| Pu-241 | 6.67E+11 |
| Pu-242 | 2.03E+07 |
| Np-237 | 4.16E+08 |
| Am-241 | 2.21E+12 |
| Am-243 | 1.51E+11 |
| Cm-244 | 2.62E+11 |
| Cm-245 | 7.03E+06 |


Fission & activation products

| Radionuclide | Mean activity per canister (Bq) |
|---|---|
| Co-60 | 7.69E+09 |
| Se-79 | 1.74E+09 |
| Sr/Y-90 | 4.18E+14 |
| Zr-93 | 9.60E+09 |
| Tc-99 | 1.03E+11 |
| Pd-107 | 3.37E+08 |
| Sb-125 | 2.04E+10 |
| Sn-126 | 2.40E+09 |
| Cs-135 | 3.51E+09 |

# Scenarios for modelling

- Scenario 1 - Base case:
  - What-if scenario – very conservative. Bounding case
  - No engineered barriers: instant release of all activity
- Scenario 2:
  - Gradual dissolution of glass matrix (2E4 or 7E4 y) – spread release
  - No containment by SS primary package or overpack
- Scenario 3:
  - Gradual dissolution of glass matrix (2E4 y)
  - Containment by SS primary package (2500 y)
  - No containment by overpack
- Scenario 4:
  - Gradual dissolution of glass matrix (2E4 y)
  - Containment by SS primary package (2500 y)
  - Containment by overpack (1E4, 1E5, 1E6 y)

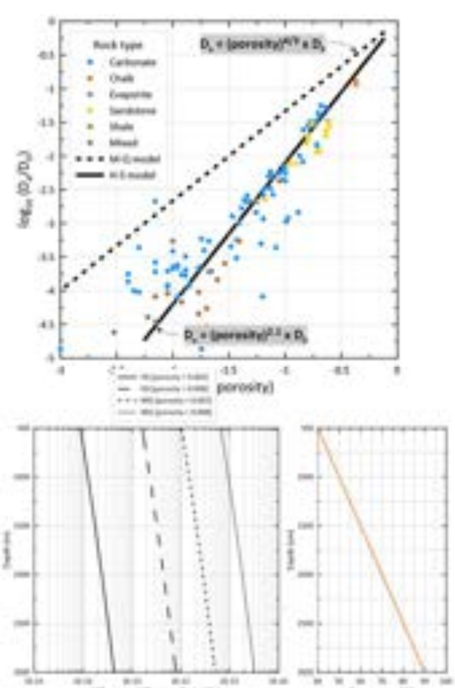





# Parameter sensitivity

2 sets of parameters were varied:

1. Longevity of engineered barriers
   - Glass: 0, 2E4, 7E4 years (gradual dissolution)
   - Stainless steel: 0, 2500 years
   - Overpack: 0, 1E4, 1E5, 1E6 years
2. Diffusion parameters in salt $D_e = \phi^n D_0$
   - Porosity ($\phi$): 0.2 or 0.8%
   - Porosity exponent (n): 2.1 or 1.33 (Millington-Quirk)
   - Depth/temperature ($D_0$): 500, 1000, 3000 m (40, 50, 90 °C)



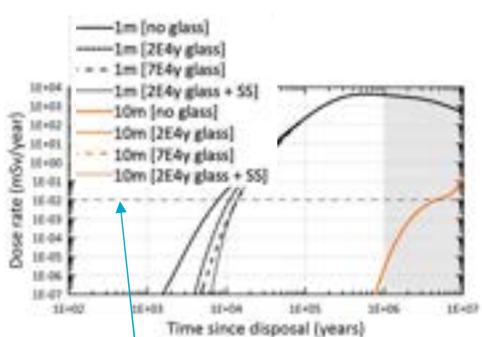
## Performance metrics

- Total dose rate to adult assuming consumption of 730 L of groundwater annually (hypothetical exposure scenario)
- Cumulative radionuclide flux
- Containment factor = inventory / (cumulative flux)



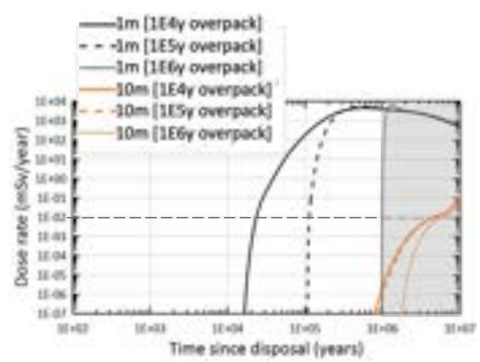
## Effect of engineered barriers

**Glass and stainless steel**




Dose threshold 0.01 mSv/y (IAEA 1996)

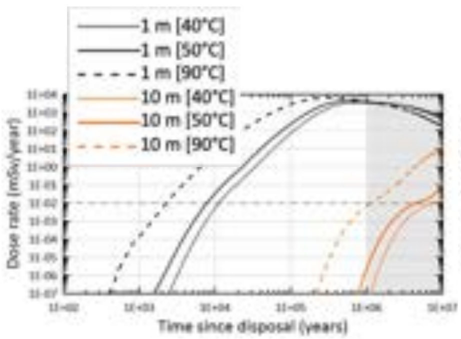
**Overpack**



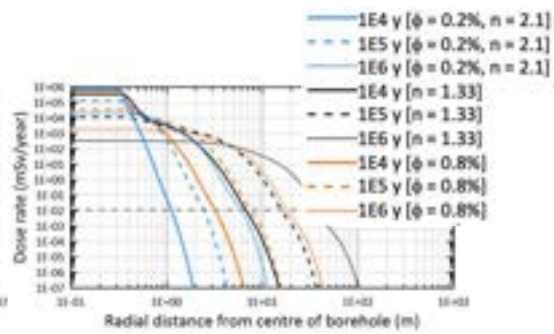

- How influential is glass dissolution & overpack corrosion rate?
- Diffusion into rock salt is rate-limiting step: very effective in spread release
- Consistent with other studies in low-perm rock (Boom Clay, NAGRA, KBS-3,…)

## Sensitivity to diffusion parameters

**Varying temperature (depth)**




**Varying porosity (ϕ) and n**








## Containment factors (end of simulation)

1: no containment

INF: complete containment

| Engineered barriers | Overpack | Backfill | 10 m salt | Overpack | Backfill | 10 m salt |
|---|---|---|---|---|---|---|
| No barriers | 1.0 | 1.1 | 1.3E4 | 1.0 | 3.0 | INF |
| Glass 2E4 y | 1.0 | 1.1 | 1.3E4 | 1.0 | 3.0 | INF |
| Glass 7E4 y | 1.0 | 1.1 | 1.3E4 | 1.0 | 3.0 | INF |
| SS 2500 y | 1.0 | 1.1 | 1.3E4 | 1.0 | 3.0 | INF |
| Overpack 1E4 y | 1.0 | 1.1 | 1.3E4 | 1.0 | 3.0 | INF |
| Overpack 1E5 y | 1.1 | 1.2 | 1.4E4 | 1.0 | 3.1 | INF |
| Overpack 1E6 y | 1.9 | 2.1 | 2.8E4 | 1.6 | 4.7 | INF |

| Diffusion parameters | Se-79 | | | Zr-93 | | |
|---|---|---|---|---|---|---|
| | Overpack | Backfill | 10 m salt | Overpack | Backfill | 10 m salt |
| n = 2.1, 50 °C, ϕ = 0.2% | 1.0 | 1.1 | 1.3E4 | 1.0 | 3.0 | INF |
| n = 1.33 | 1.0 | 1.0 | 1.7 | 1.0 | 1.1 | 1.0E11 |
| 40 °C | 1.0 | 1.2 | 3.4E6 | 1.0 | 4.0 | INF |
| 90 °C | 1.0 | 1.1 | 107 | 1.0 | 2.0 | INF |
| ϕ = 0.8% | 1.0 | 1.0 | 5.5 | 1.0 | 1.4 | INF |

# Conclusions

- Engineered barriers influence timing of peak dose rate, but not magnitude
  - Repository in salt host rock is very robust (limited sensitivity to engineered barriers)
- Effective diffusion coefficient remains a poorly constrained, but influential parameter in tight rocks
  - Importance of conceptual model for effective diffusion estimation
  - Influence of temperature
- Salt is a very effective natural barrier (minimal effect beyond 10 m within 1E6 years)
- *Demonstrating an engineered barrier is not influential does not remove the need for a multi-barrier concept for building confidence in long-term safety*

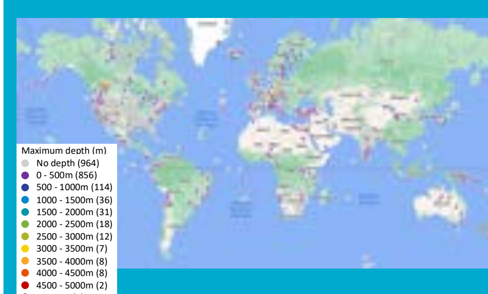


MC0

# Global petrophysical database

- Key parameters for safety assessments
- *K*, *η*, *D*, $\rho_b$, $\rho_m$ …
- Global database
  - ✓6 continents, 74 countries
  - ✓6 pre-existing databases, >700 data sources
  - ✓84,000 entries
- Crystalline, Shale, few salt
- QA/QC (quality ranking)
- Selection by rock type, region, measurement method, rock volume tested, …

| Property | Crystalline | Shale | Salt |
|---|---|---|---|
| Hydraulic conductivity | 8411 | 601 | 1 |
| Thermal conductivity | 4825 | 1109 | 28 |
| Porosity | 3575 | 978 | 53 |
| Density | 3670 | 798 | 8 |
| Permeability | 2657 | 1180 | 181 |
| Heat capacity | 1197 | 138 | |
| Radiogenic heat production | 1113 | 154 | |
| Thermal diffusivity | 975 | 38 | |
| Hydraulic diffusivity | 26 | 359 | |
| Specific surface area | | 137 | 2 |
| Water content | | 114 | |
| Diffusion coefficient | | 79 | 1 |
| Specific storage | | 55 | 1 |
| TOC | | 50 | |
| Coefficient of consolidation | | 32 | |
| Cation exchange capacity | | 11 | |



# Salt geomechanics: Lab tests

- Purpose:
- Understand rock salt geomechanical behaviour during and after drilling of deep borehole

- Testing workflow:
  - Mechanical testing (**multi-stage triaxial tests**)
  - Post-test petrophysical & microstructural characterisation

- Multi-Stage Triaxial Test (4 stages) with *CREEP* and *PERMEABILITY* evaluation at each stage
  - Core sample from Frome Formation (~ 1000 m deep
  - D=38mm x L=80mm

- Typical test duration: 2-3 months






# Mineralogy and structure

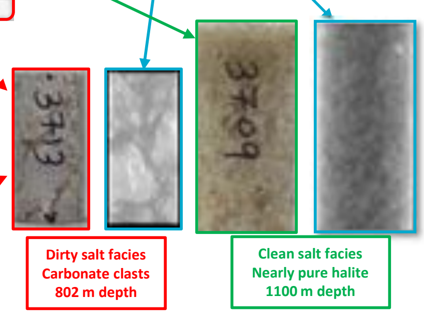
- Mineralogy (XRD)

| Sample | Phase concentration (relative crystalline wt%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Quartz | Halite | Kaolinite | Chlorite | Mica | Dolomite | Anhydrite | Sylvite |
| 3709 | | 98 | | | | 1 | 1 | |
| 3710 | 3 | 84 | | | | 12 | 2 | |
| 3711 | <1 | 97 | | | | 2 | 1 | |
| 3712 | 20 | 36 | | 2 | 5 | 24 | 13 | <1 |
| 3713 | 6 | 40 | <1 | 3 | 4 | 38 | 8 | <1 |

- Cation Exchange Capacity (CEC)

**To measure the salt ability to hold positively charged ions**

| Sample | Corrected MBC (cmolc $kg^{-1}$) (weight loss normalised) | Measurement uncertainty (cmolc $kg^{-1}$) |
|---|---|---|
| 3710 | <0.2 | 0.1 |
| 3712 | <0.5 | 0.3 |
| 3713 | <0.5 | 0.3 |

# Porosity and gas permeability *vs* pressure/depth

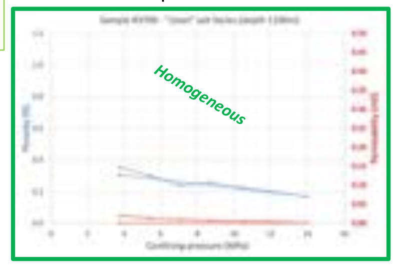
*Gas permeameter / porosimeter*

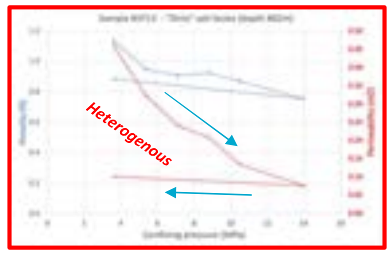
*Homogeneous salt facies (1100m)*

$\phi$ = 0.2 to 0.3%

*k* = 1 to 20 µD

In situ pressure: 25 MPa




In situ pressure: 18 MPa

*Heterogenous salt facies (802m)*

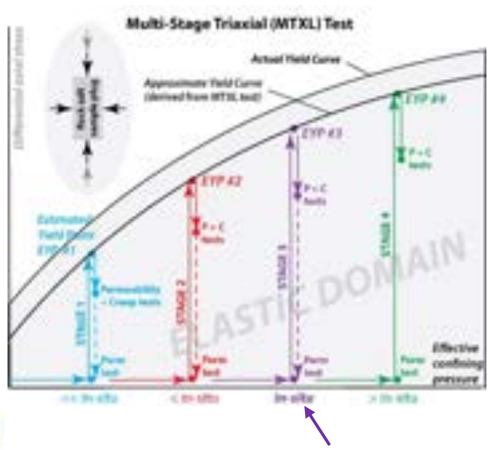
$\phi$ = 0.8 to 1.1%

*k* = 50 to 500 µD



# Geomechanical appraisal

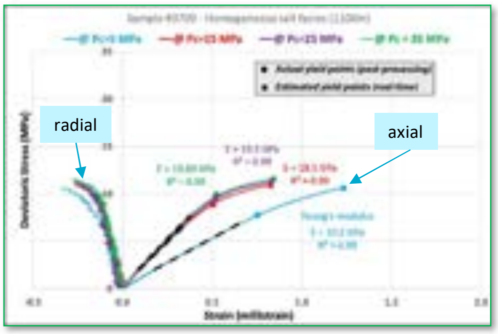
- Four-stage triaxial deformation experiment
- Evaluate mechanical ***yield characteristics*** of rock salt (strength versus stress/depth)
- Evaluate mechanical ***creep*** rates
- Monitor gas ***permeability*** evolution
- Room temperature (27 °C)

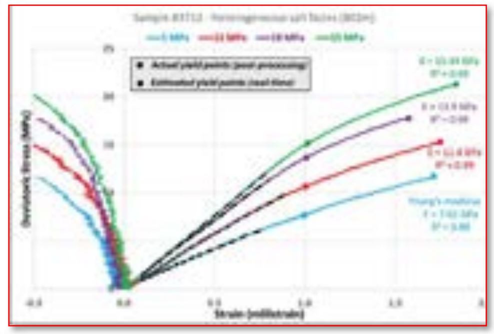



native confining pressure at (depth)

## Stress-strain response of two contrasting facies

To evaluate the strength and the stability of the salt formation



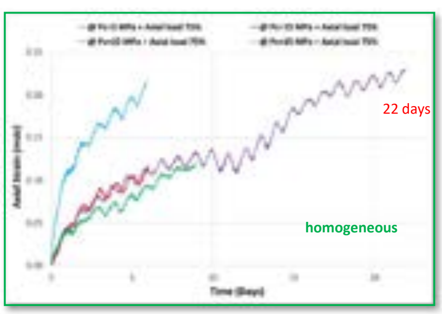



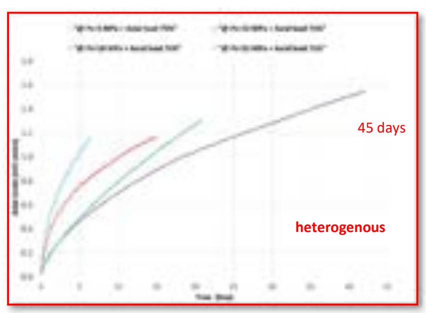
**Clean/homogeneous salt facies:**
- **Stiffer (> Youngs modulus, e.g. 19.3 MPa <>13.9 MPa)**
- **Weaker (shear stress 2 x <) than the dirty/heterogeneous facies**



## Creep response of two contrasting salt facies

To evaluate the long-term stability of the borehole wall




- ***In situ***, the shallower dirty/heterogeneous salt facies creeps **5** times faster than the deeper clean/homogeneous salt facies

- Creep data and the derived creep rates are to be used in numerical simulation with boundary conditions to predict:
  - **Short-term** borehole closure in salt formation
  - **Long-term** salt formation behaviour

## Conclusions

- Homogeneous salt facies (1100 m) has lowest porosity (~0.2% ) and permeability (1-20 micro D), is mechanically stiffer than heterogeneous facies
- Heterogeneous salt facies (802 m) has higher porosity (~0.8% ) and permeability (50-500 micro D), is mechanically stronger and more pressure sensitive
- Heterogeneous salt facies creeps 5 times faster than heterogeneous facies
- Creep rates will be used in numerical simulations to predict:
  - Short-term borehole closure in salt formation
  - Long-term salt formation deformation



# Thank you

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1. Doblin C., Gulizia, S., Mallants, D. (2022). Cold spray technology applied to nuclear waste disposal canisters for deep boreholes. Proceedings Waste Management 2022 Symposium, 6-10 March 2022, Waste Management Symposium, Phoenix, Arizona, USA
2. Doblin, C., Gulizia, S., Mallants, D. (2022). Assessment of technologies to produce corrosion resistant coatings on nuclear waste disposal canisters. MRS Advances 2022, 1-4.
3. Esteban L., Josh, M., Dewhurst, D., Delle Piane, C., Mallants, D. (2022). Combining Petrophysics and Mineralogy to Infer Containment Potential of Granites for Borehole Disposal of ILW in Australia. Proceedings Waste Management 2022 Symposium, 6-10 March 2022, Waste Management Symposium, Phoenix, Arizona, USA.
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10. Shi, J., Shen, B., Khanal, M., Mallants, D. (2022). Analytical and Numerical Estimation of Fracture Initiation and Propagation Regions around Large-Diameter, Deep Boreholes for Disposal of long-lived intermediate-level waste. Energies, 15, 2445.
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# Status of The Netherlands

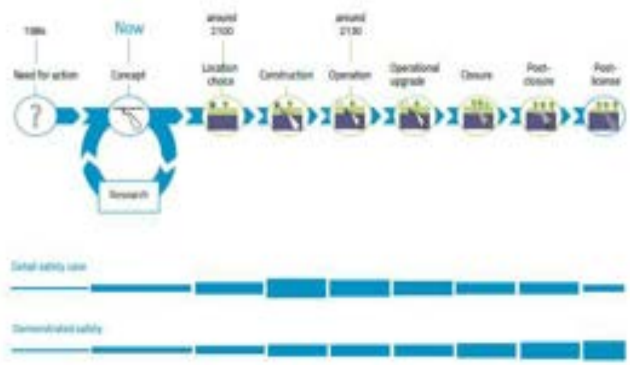
Dr. Jeroen Bartol




# Agenda

- COPERA
- Disposal concept
- Research results

## COPERA




From Verhoef et al., (2017)

3

## COPERA

While we are relative late with an operational repository (2130), there will be repositories operational by the time the Dutch repository opens. Furthermore, the closure of the Dutch repository will be around the same time as some other repositories. In addition:

Need to collect enough funds for a repository.

Learn and collaborate with other countries as many disposal programs are currently active.

Pursue a dual track policy.

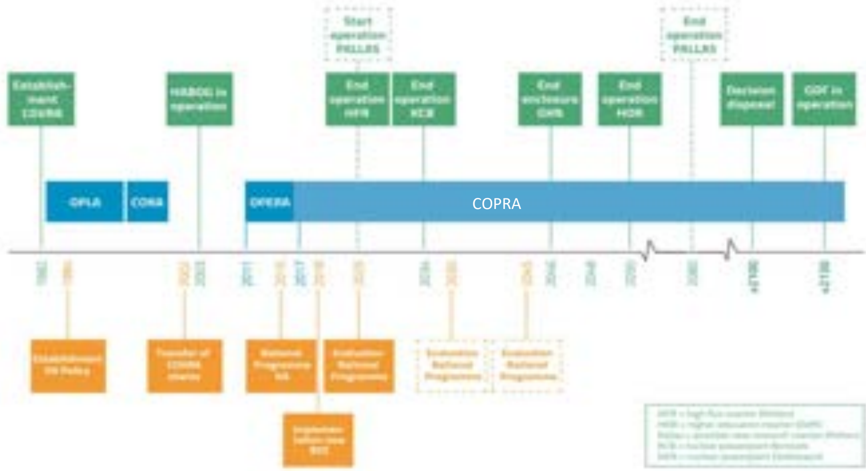

Verhoef et al. (2021)

4

# COPERA

The COPERA research programme is a long term continuous research programme that will last until at least 2130.

Having an continuous research programme will help to avoid periods without any research and possible lost of knowledge. The programme is funded by COVRA.

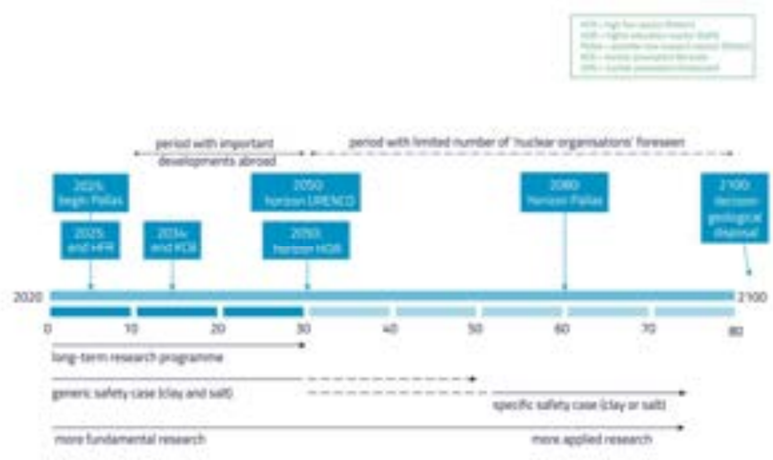



Verhoef et al. (2021)



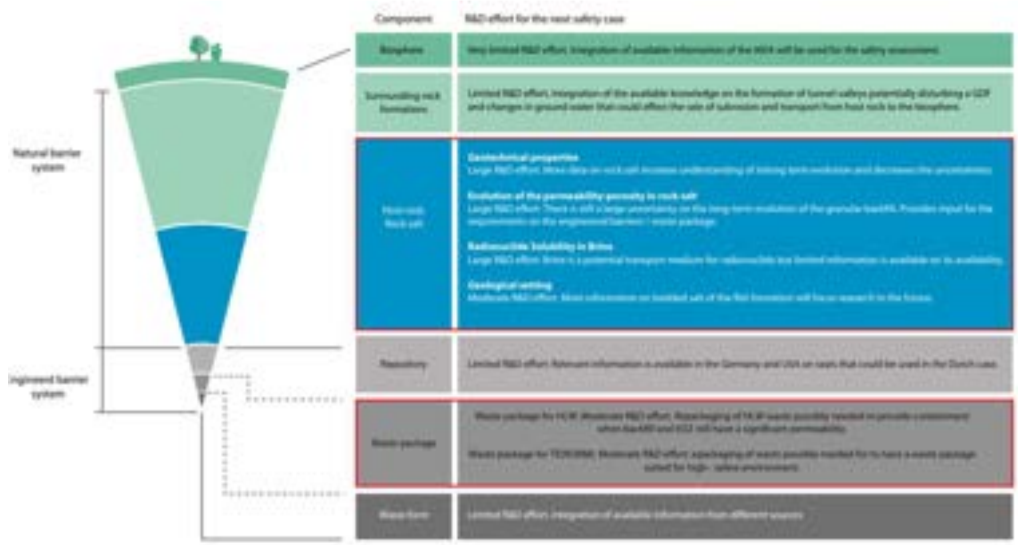
# COPERA

The initial horizon of the research programme is 30 years and is divided in cycles of five years; every 5 years the programme is updated based on the safety cases.




Verhoef et al. (2021)

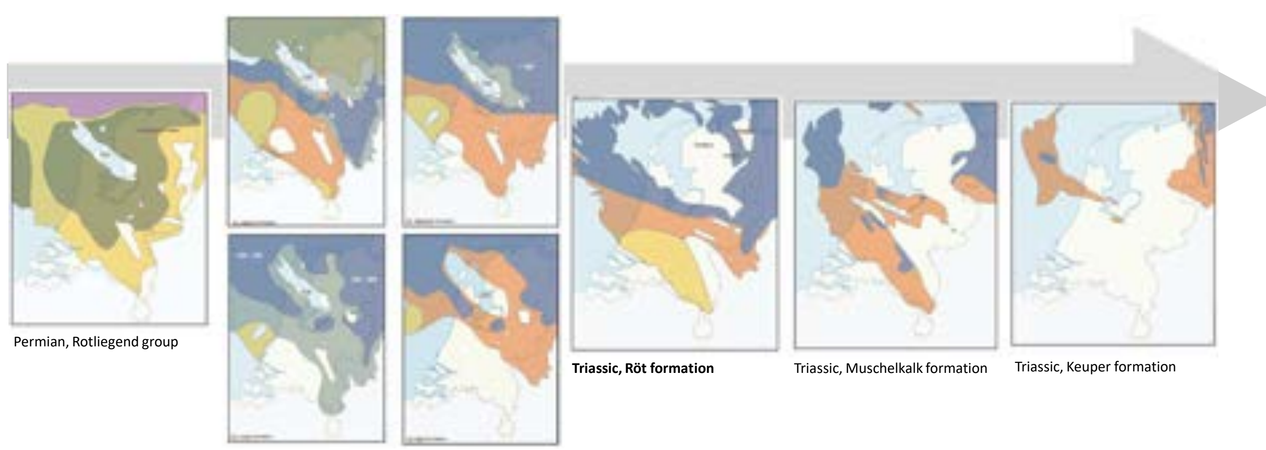
## COPERA




Verhoef et al. (2021)



## Dutch Disposal Concept



Permian, Rotliegend group

**Permian, Zechstein group**

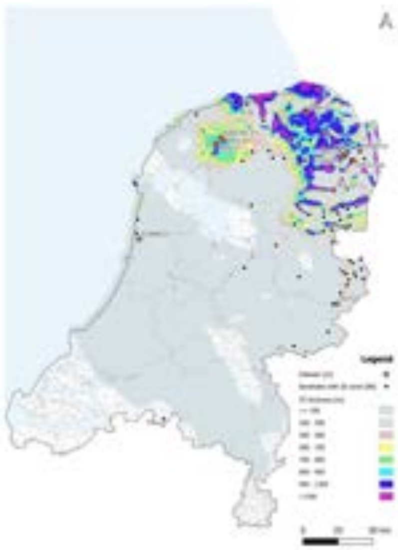
**Triassic, Röt formation**

Triassic, Muschelkalk formation

Triassic, Keuper formation

# Dutch Disposal Concept

Zechstein formation




Röt formation

Hunfeld et al., (2023)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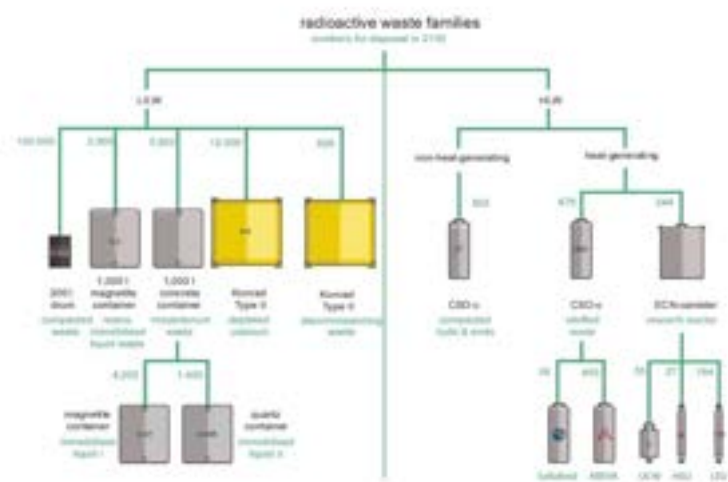
# Dutch Disposal Concept

We have updated the expected waste inventory for disposal. In this base scenario, we assume the current situation and the opening of the Pallas research reactor.

However, things might change as the government is considering the construction of **2 new nuclear power plants** and **extended operation of the current nuclear power plant.**

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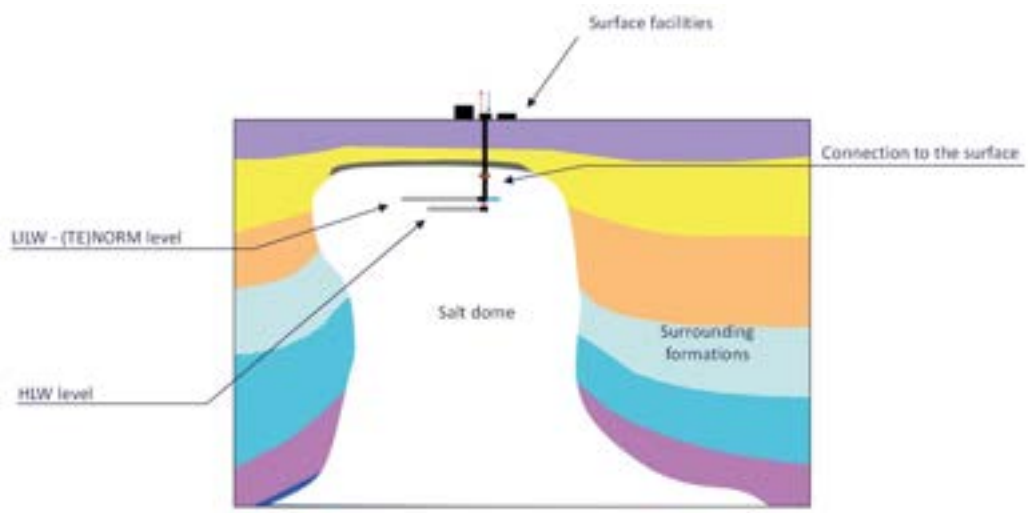
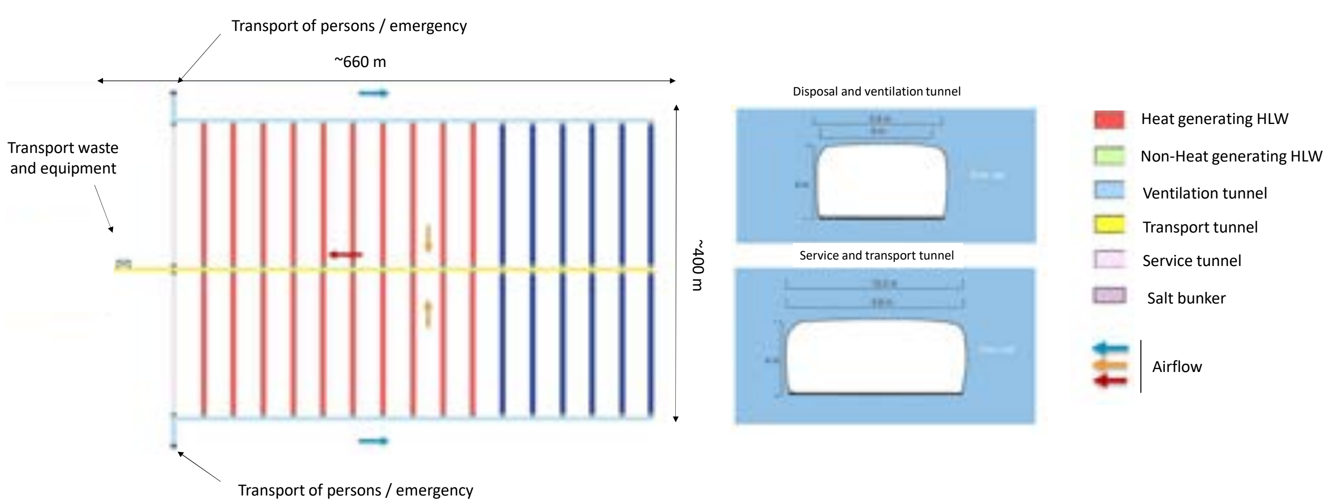
## Dutch Disposal Concept






## Dutch Disposal Concept

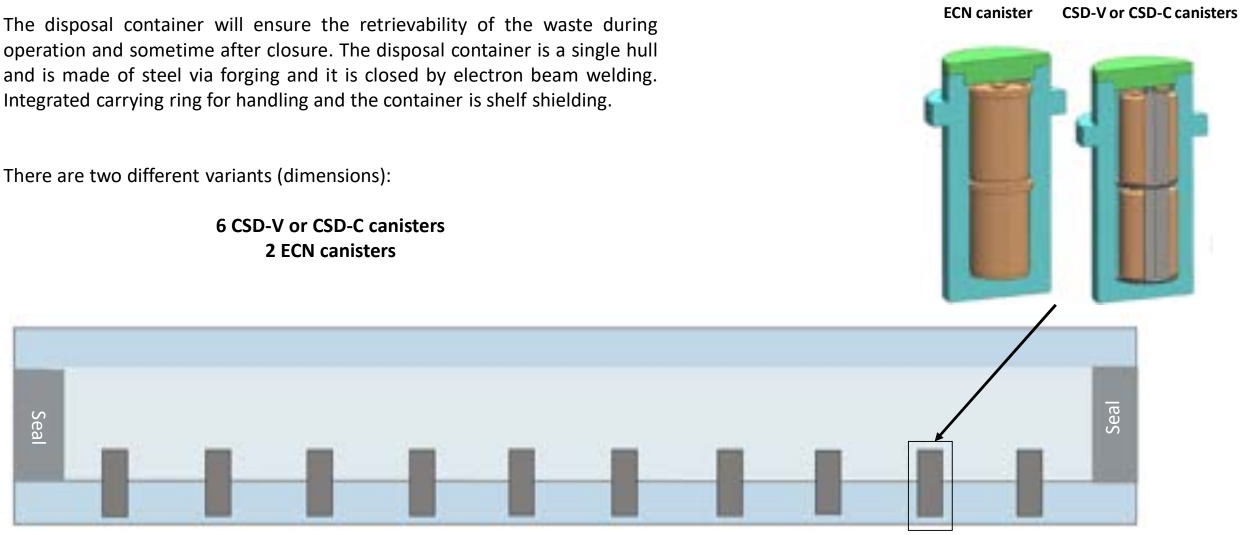


## Dutch Disposal Concept

The disposal container will ensure the retrievability of the waste during operation and sometime after closure. The disposal container is a single hull and is made of steel via forging and it is closed by electron beam welding. Integrated carrying ring for handling and the container is shelf shielding.

There are two different variants (dimensions):

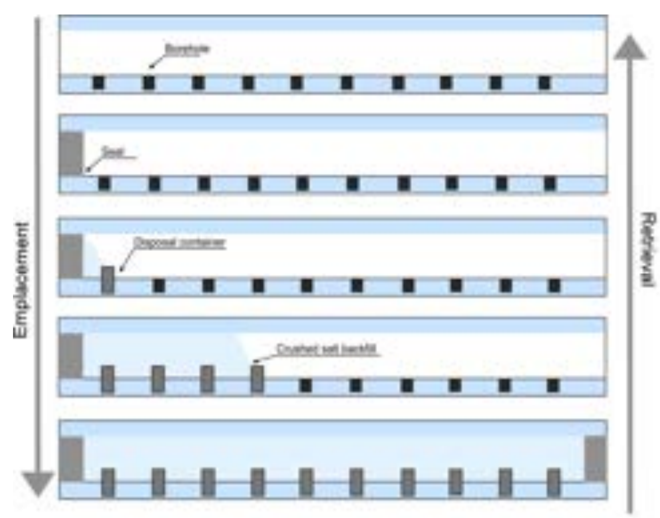
**6 CSD-V or CSD-C canisters**
**2 ECN canisters**



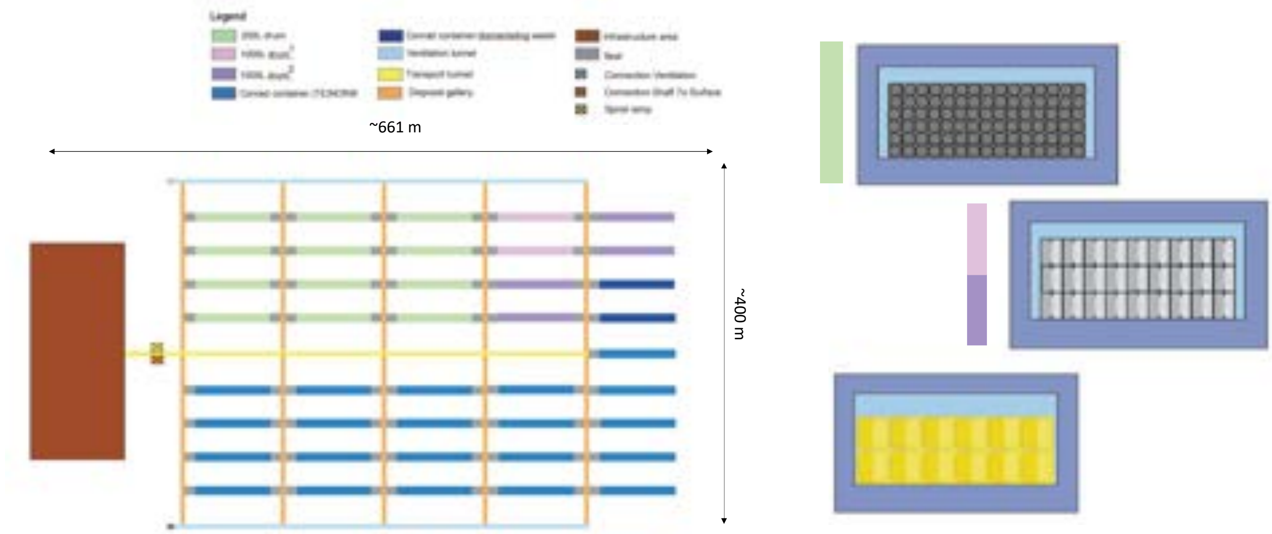



## Dutch disposal concept

Based on the time needed to emplace the waste it was decided to construct the lower level first and then emplace the waste. During the emplacement of the HLW in the lower level, the upper level can be constructed.



# Dutch disposal concept

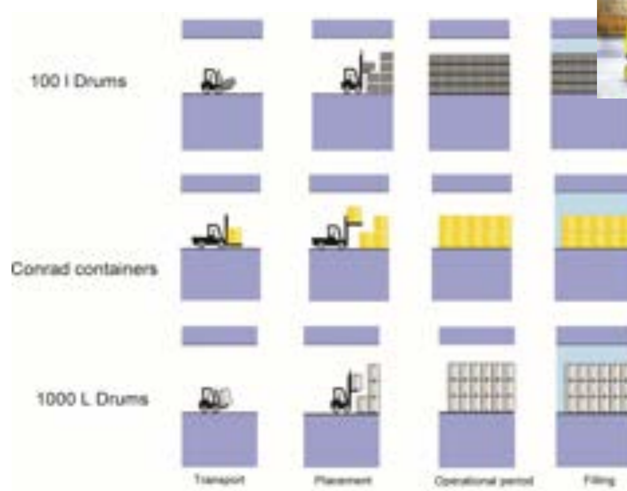





# Dutch Disposal Concept

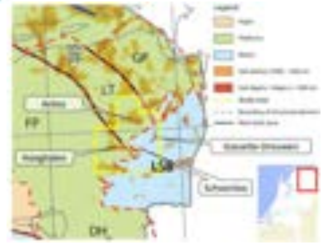
For the emplacement of the low and intermediate level waste, we use techniques that are already used at COVRA.

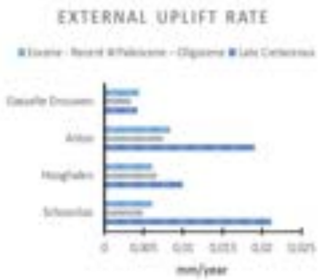
Also, the number of drums stack on top of each other is equal or less of what is currently done at COVRA.

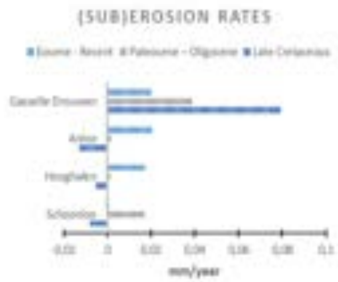


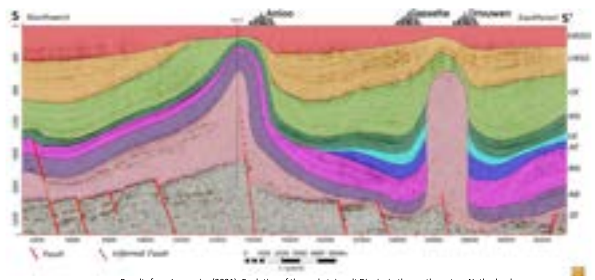

# Research

Of four salt domes in the north of the Netherlands, the external uplift and (sub)erosion rates have been determined. This was done using a salt balance. While the method is not precise, it will give some idea about the subrosion and external uplift rate.





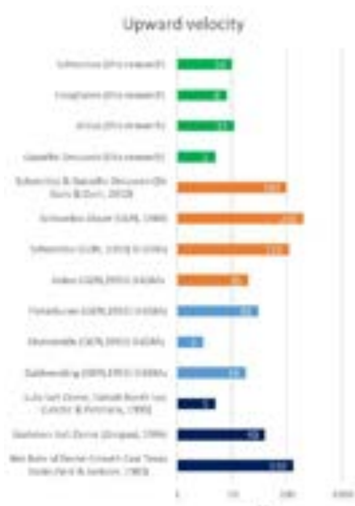



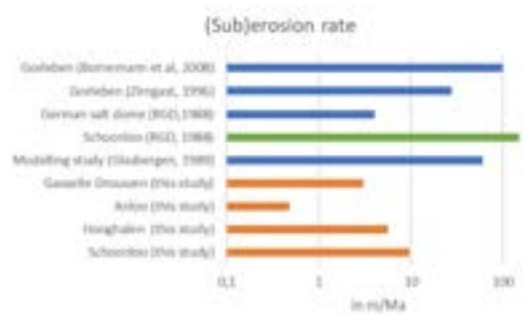



Results from Lauwerier (2021). Evolution of the zechstein salt Diapirs in the north-eastern Netherlands.



# Research



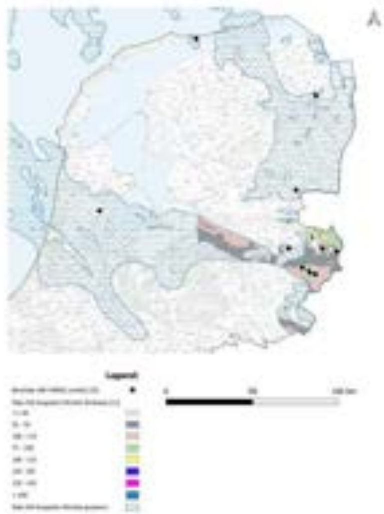



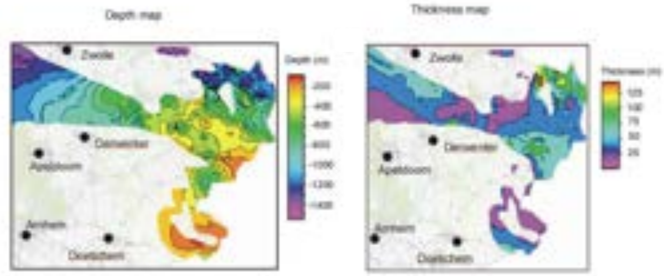

Results from Lauwerier (2021). Evolution of the zechstein salt Diapirs in the north-eastern Netherlands.

# Research

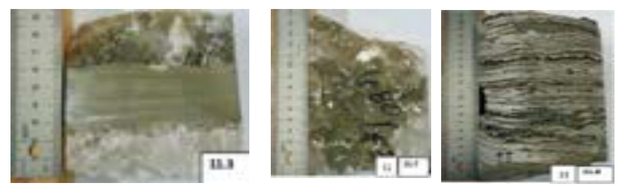
**Röt formation**

Hunfeld et al., (2023)






Altenburg (2022)



Altenburg (2022)



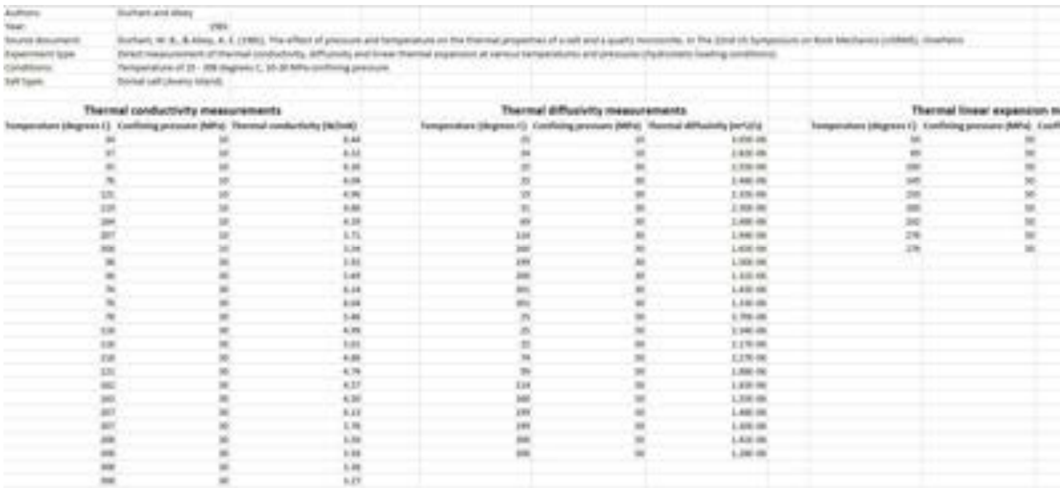
# Research

The Dutch geological survey have collected Thermal, Hydrological, Chemical data. Most of the data is from Dutch Zechstein and Rot formation salt, but it does also include data from

All the data is collected in excel documents and can be freely downloaded from our website (www.covra.nl).

This database is just the beginning and we have plans to expand it.

# Research



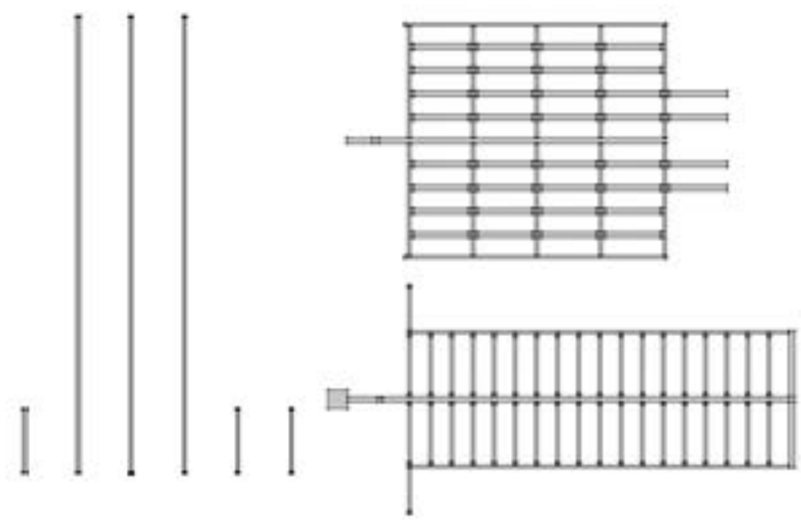



# Research

For the safety assessment, we use our experience from DECOVALEX 2023. In our model, we plan include the following processes:

Convection
Diffusion
Decay
Compaction
Solubility limits

It will be a first approximation and conservative, but it will give a preliminary idea how the repository will preform. In following research cycles, we will improve the model.




Research
Published in 2020
COVRA
LONG-TERM
RESEARCH
PROGRAMME
Now
COVRA
Rock salt
safety case
Will be published in 2024

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Questions?

24

# SESSION 2: Modeling

Chair: Kris Kuhlman (SNL)

# Simulations of Container Compaction to Support Nuclear Criticality Assessments

Benjamin Reedlunn and James Bean
Sandia National Laboratories


Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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 presentation 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. SAND2023-05250C



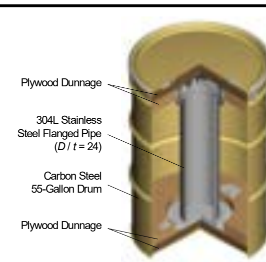
# Agenda

1. Motivation
2. Setup
   1. Geomechanical model
   2. Container model
3. Results
   1. Roof fall
   2. Gradual compaction
4. Summary

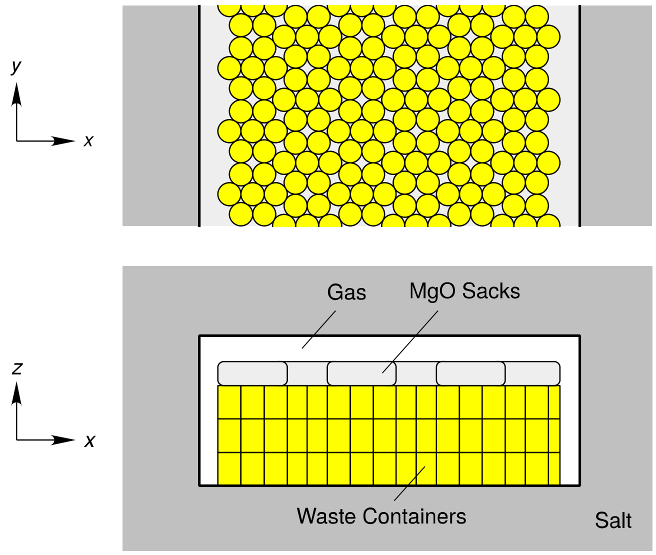
# Motivation



## Standard, POP, and CCO Containers

| Name | Standard<br>(with surrogate waste) | 6" and 12" Pipe Overpack (POP) | Criticality Control Overpack (CCO) |
|---|---|---|---|
| Photo / Schematic | <br>Jensen et al. (2023) | <br>Modified from Porter (2013) | <br>Modified from McGonagill (2015) |
| Max fissile mass equivalent to Pu | 200 g per 7-pack of containers | 200 g per container | 380 g per container |

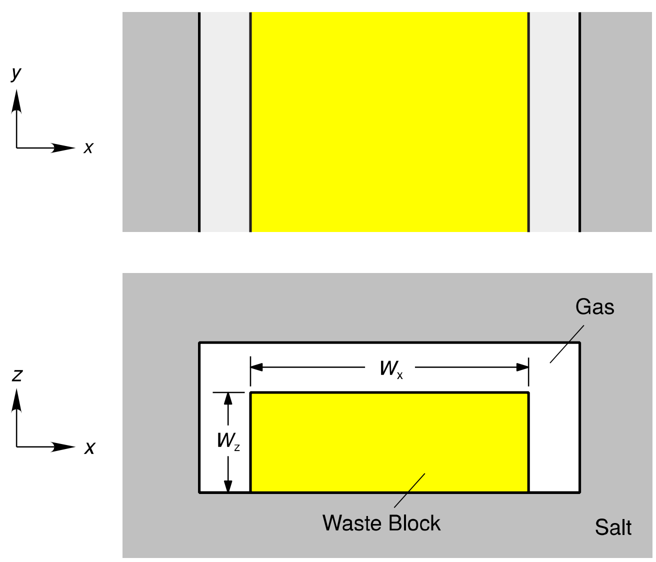
## Initial Container Emplacement





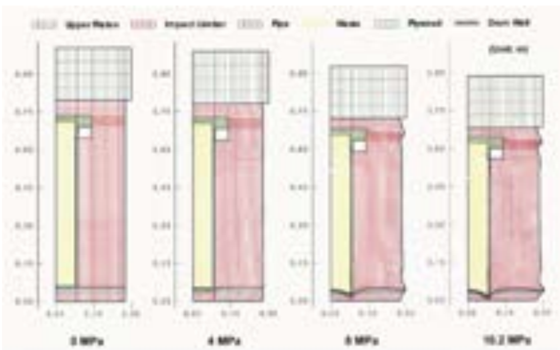



## Park and Hansen (2005) Homogenization



## Park and Hansen (2005) Homogenization

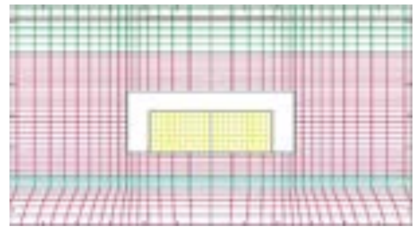
6-inch POP Uniaxial Compression Simulation



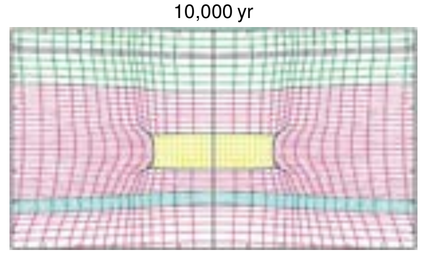
Park, B.Y. and Hansen, F. D., "Simulations of the pipe overpack to compute constitutive model parameters for use in WIPP room closure calculations", 2004, SAND2004-1390

6-inch POP Room Compaction Simulation (zero gas generation)

0 yr



10,000 yr

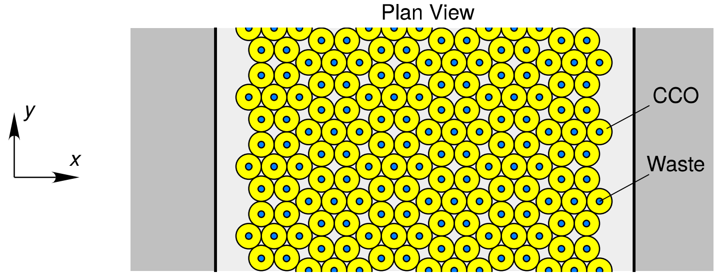


Park, B.Y. and Hansen, F. D., "Determination of the Porosity Surfaces of the Disposal Room Containing Various Waste Inventories for WIPP PA", 2005, SAND2005-4236

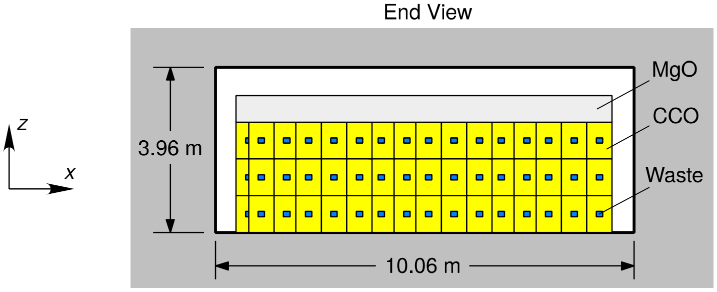


## Saylor & Scaglione (2018) Compaction Assumptions

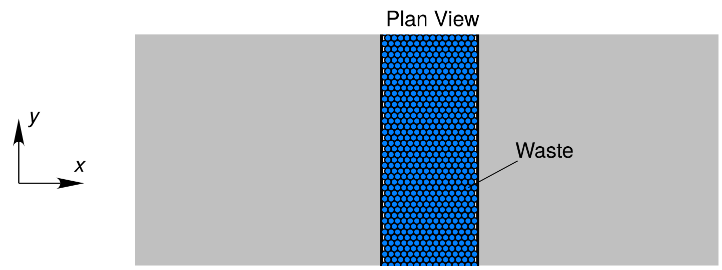
Plan View

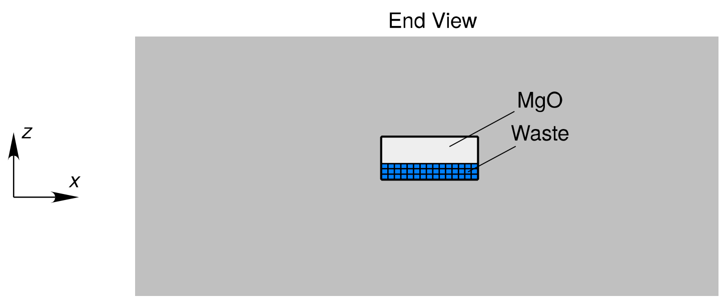



End View



## Saylor & Scaglione (2018) Compaction Assumptions

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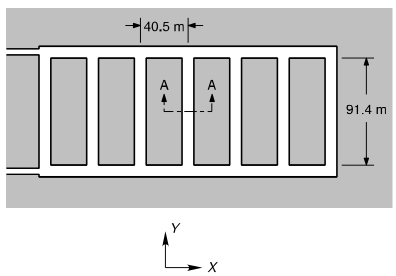
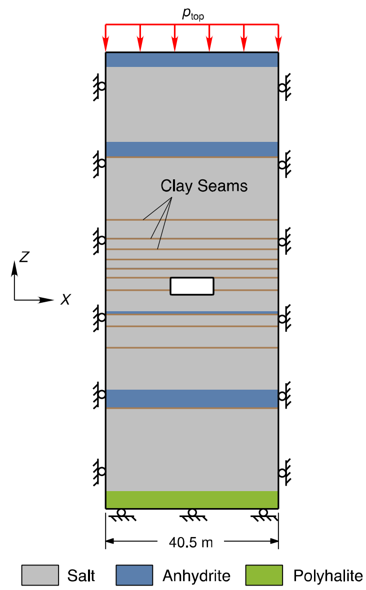
# Setup: Geomechanical Model

# Geomechanical Model

Plan View




Section A-A

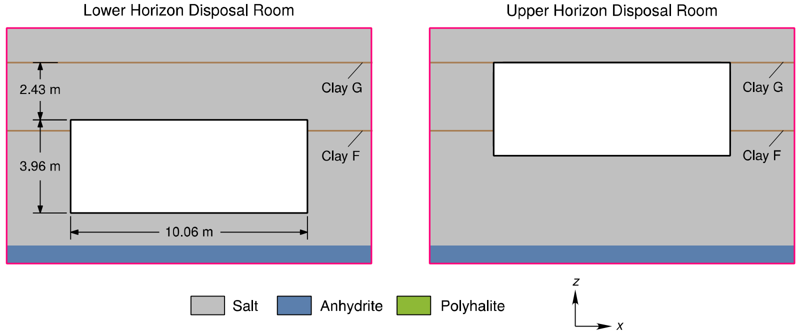


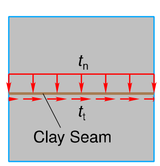



# Gradual Compaction Setups

Lower Horizon Disposal Room

Upper Horizon Disposal Room




Coulomb Friction

$t_t \le \mu_c \, t_n$

$\mu_c = 0.2$

$\mu_c^F = \mu_c^G = 0.2$

$\mu_c^F = \mu_c^G = 0.5$

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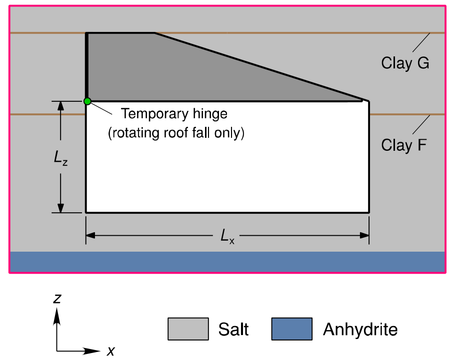
## Roof Fall Setup

Photo of Panel 7, Room 4

Idealization




Carrasco, R. (Sept. 2019b). *Roof Fall Photographs*. Personal Communication.

Carrasco, R. (Mar. 2019). *Panel 7, Room 4, Roof Fall Dimensions.* Personal Communication.



13

## Setup: Container Model

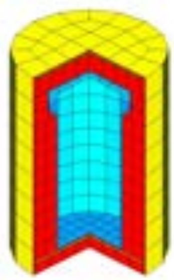
## Container Finite Element Meshes

6-inch POP

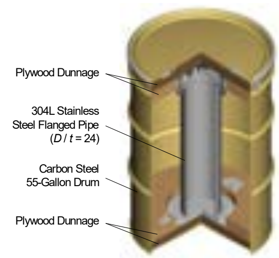
Modified from Porter (2013)

12-inch POP

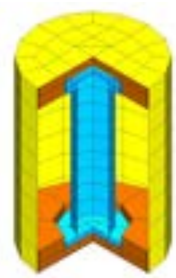
Modified from Porter (2013)



CCO




Modified from McGonagill (2015)



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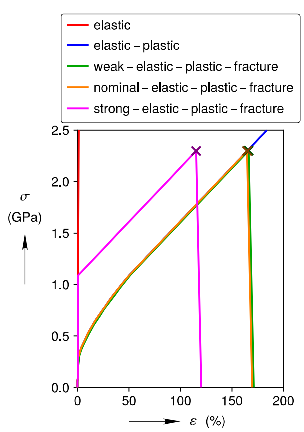
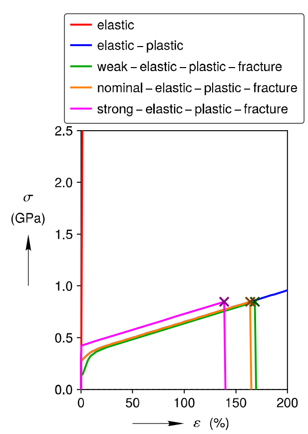
## Container Material Models

1. Elastoplastic models with failure
2. No rate dependence
3. Strength varied

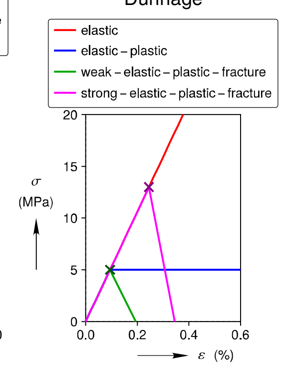
Stainless Steel




Carbon Steel
55-Gallon Drum




Plywood
Dunnage

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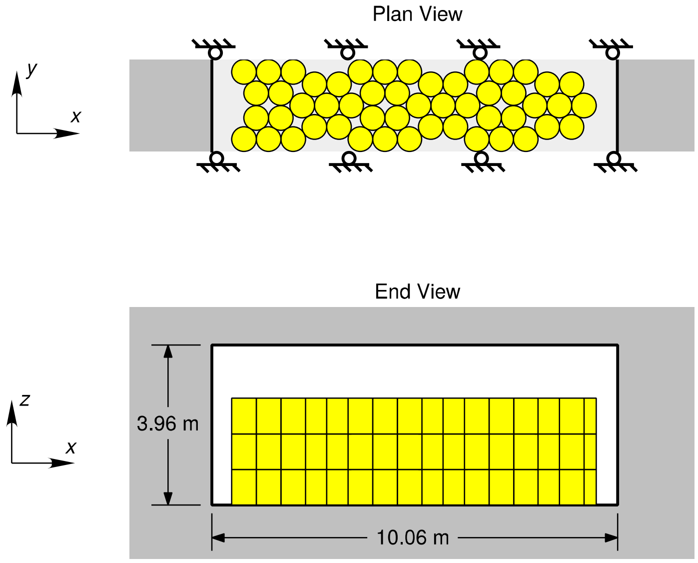
## Hexagonal Array Emplacement

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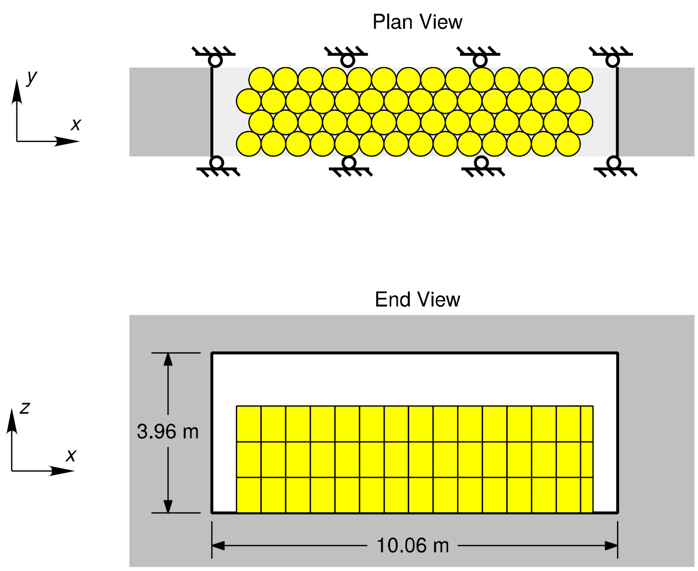
## Triangular Array Emplacement

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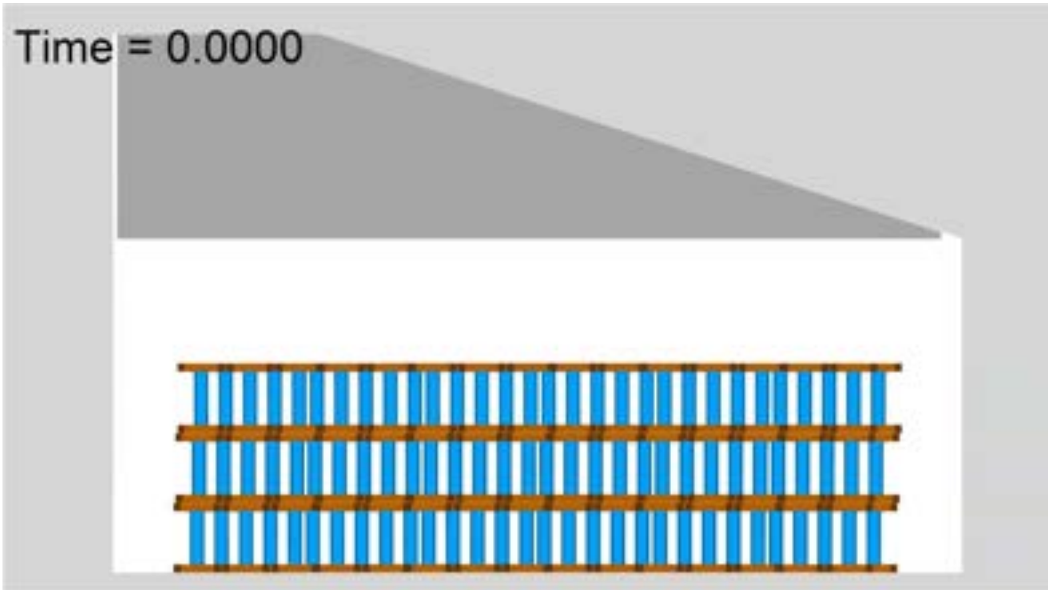
## Results: Roof Fall



## Roof Fall Conservatisms

1. Biggest roof fall known to occur at WIPP
   1. Thin on right side, thick on left side
2. Each container stacked 25 mm to the right of the container beneath
3. Block dropped immediately after room excavation
4. MgO sacks ignored
5. Block not allowed to break into smaller pieces
6. Conservative stainless steel, carbon steel, and plywood behavior
   1. Rate dependence ignored
   2. Weak yield strengths
7. Half containers ignored

## Roof Fall onto CCOs

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## Results: Gradual Compaction

## Gradual Compaction Uncertainties

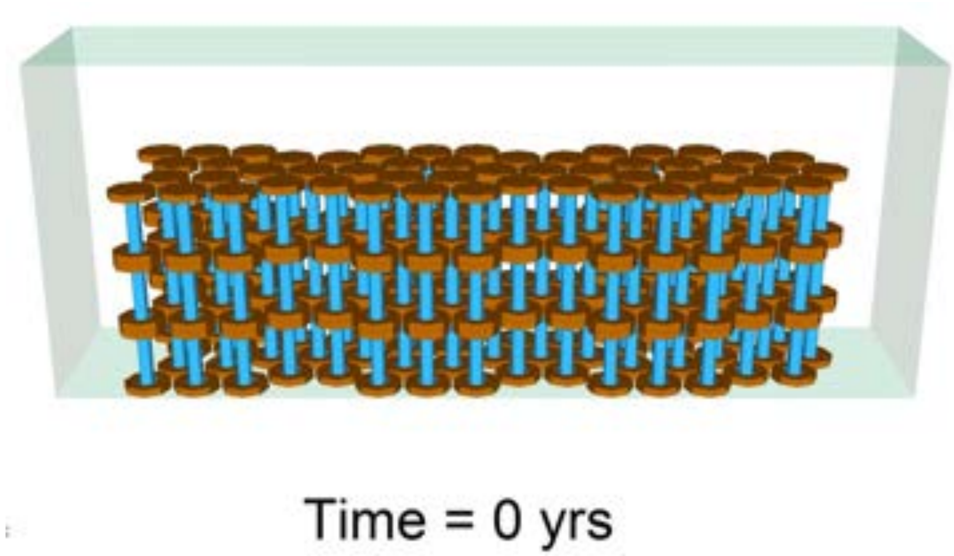
1. Finite element mesh was somewhat coarse
2. Container strength was assumed to be rate independent
3. Containers were compacted in the middle of a room, in the middle of a panel
4. Gradual compaction after a roof fall was not performed
5. Rooms were filled with only one container type



## Gradual Compaction Conservatisms

1. Waste inside the stainless steel pipes omitted
2. MgO sacks ignored
3. Gas pressure due to cellulose degradation, metal corrosion, and radiolysis not included
4. Container materials were relatively weak
5. Container finite elements deleted from the simulation when they became severely distorted

## CCO Gradual Compaction Video, $\mu_c^F = \mu_c^G = 0.5$



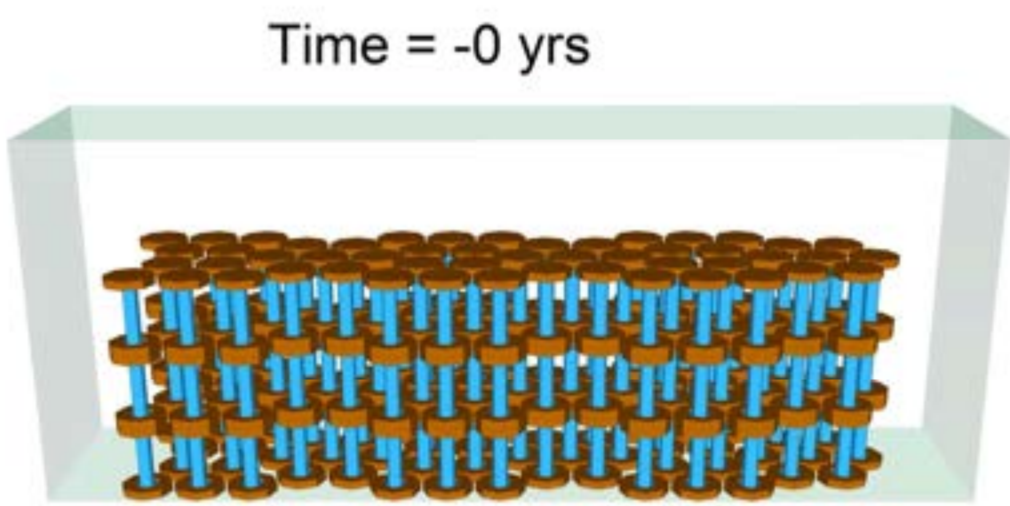

Upper Horizon

$\mu_c^F = \mu_c^G = 0.5$, $\mu_c^{other} = 0.2$





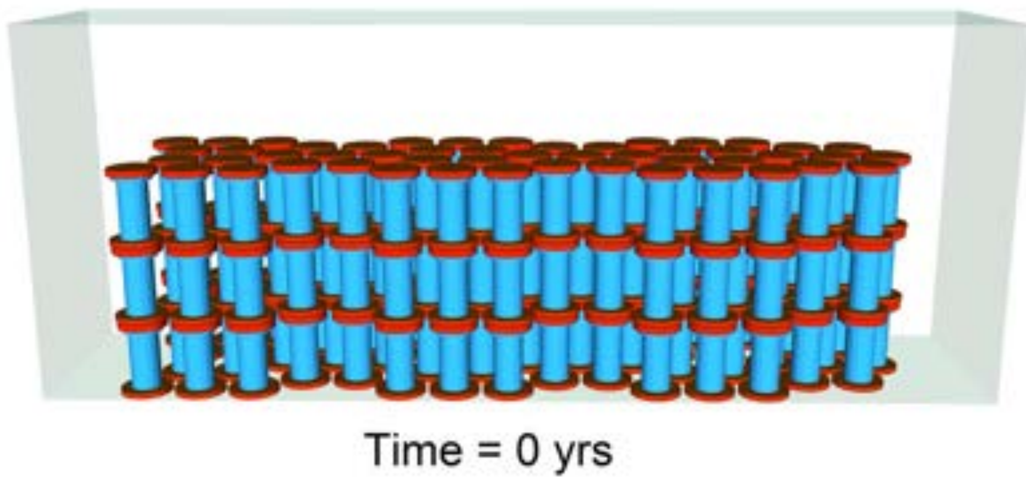
## CCO Gradual Compaction Video, $\mu_c^F = \mu_c^G = 0.2$




Upper Horizon

$\mu_c^{all} = 0.2$

## 12-inch POP Gradual Compaction Video



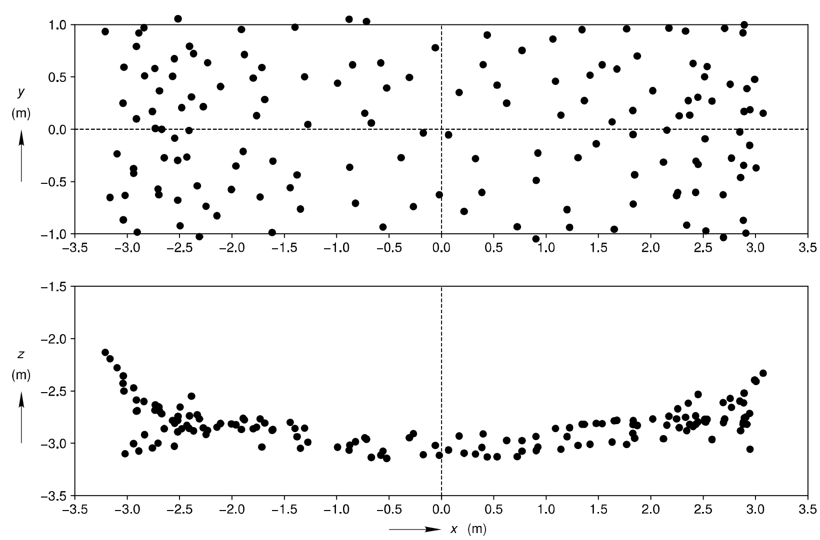

Lower Horizon

$\mu_c^F = \mu_c^G = 0.5$, $\mu_c^{other} = 0.2$





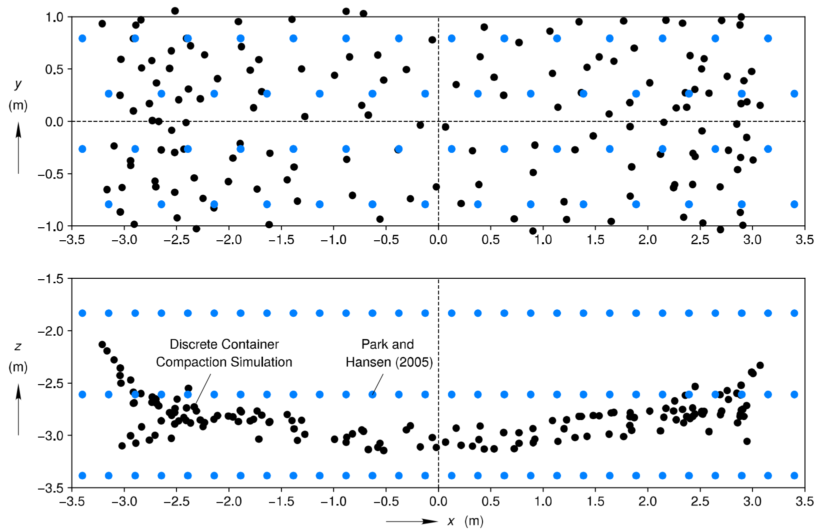
## CCO Pipe Center Locations at 1,000 yr




Upper Horizon

$\mu_c^F = \mu_c^G = 0.5$, $\mu_c^{other} = 0.2$

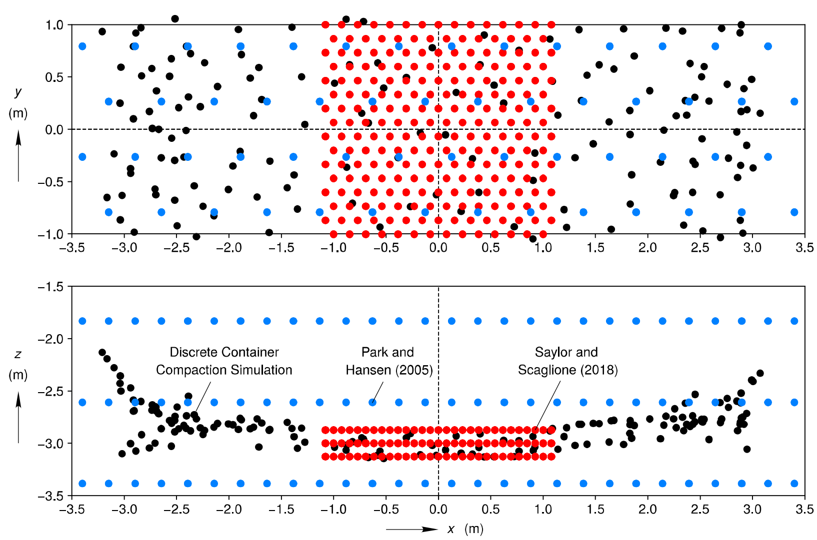
# Pipe Center Locations Compared




29



# Pipe Center Locations Compared

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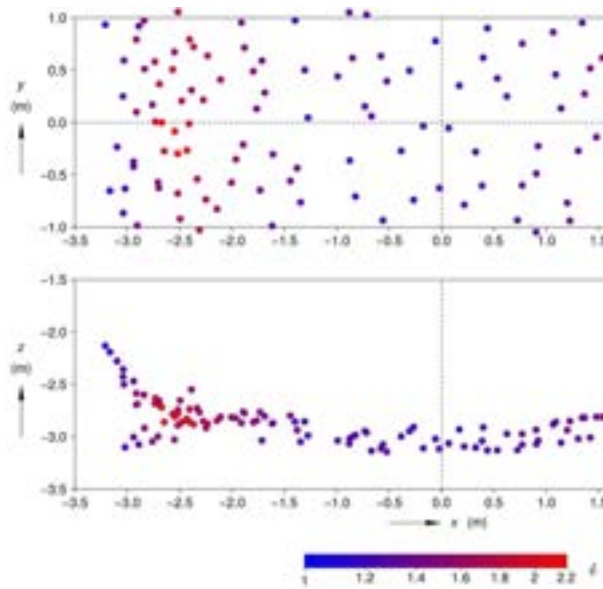
# Pipe Center Concentrations

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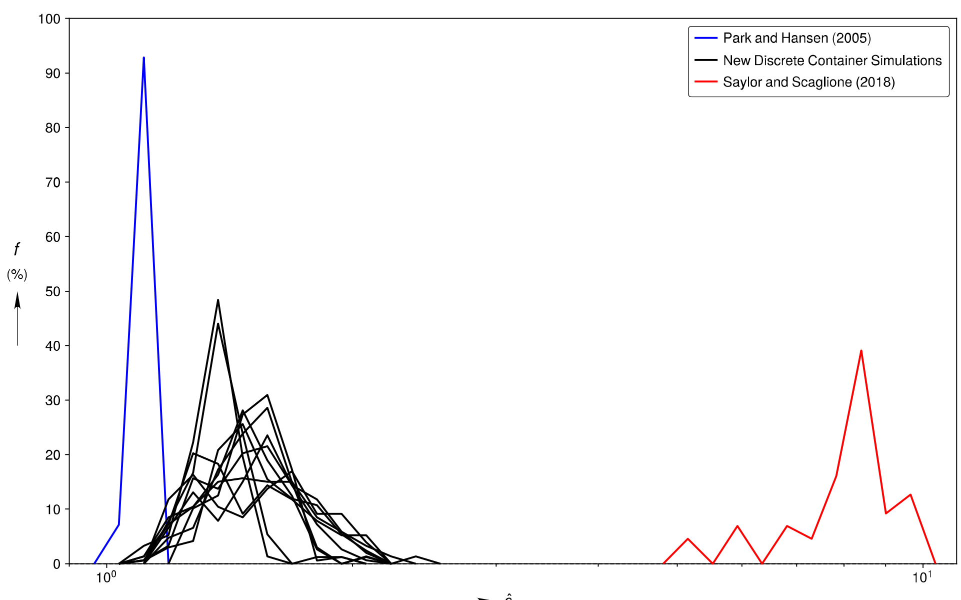
# Pipe Center Concentration Distributions

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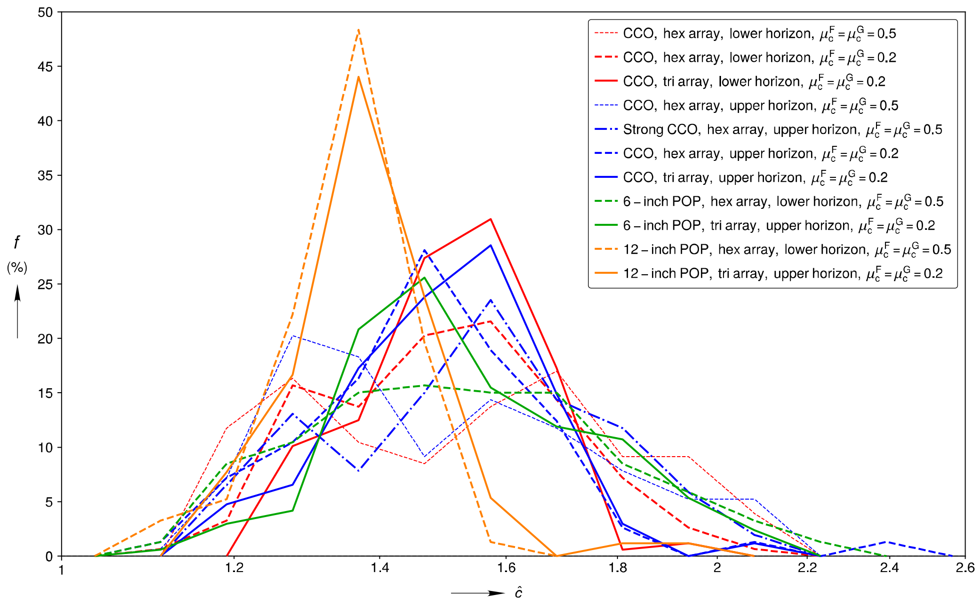
## Pipe Center Concentration Distributions



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# Summary

## Summary

1. Motivation
    1. Park and Hansen (2005) POP compaction model was too stiff.
    2. Saylor and Scaglione (2018) CCO compaction assumptions were too compliant.
2. Simulation Setup
    1. Explicitly simulated each container and its components
3. Simulation Results
    1. Roof Fall Compaction
        1. The block simply settled on top of the containers and caused almost negligible container deformation or clustering.
    2. Gradual Compaction
        1. The ceiling and floor severely compacted the containers at room mid-width, which pinched off the horizontal closure and resulted in a bow tie shaped envelope of containers.
        2. Pipe centers were 1.4X more concentrated than in Park and Hansen (2005) and about 5X less concentrated than in Saylor and Scaglione (2018).
        3. Pipe center concentrations were relatively insensitive to container stiffness, disposal horizon, the clay F and G friction coefficient, and emplacement configuration.





Thank you for your attention!

## References


1. Park, B. Y. and Hansen, F. D. (2004). Simulations of the pipe overpack to compute constitutive model parameters for use in WIPP room closure calculations. Tech. rep. SAND2004-1390. Sandia National Laboratories.
2. Park, B. Y. and Hansen, F. D. (2005). Determination of the Porosity Surfaces of the Disposal Room Containing Various Waste Inventories for WIPP PA. Tech. rep. SAND2005-4236. Sandia National Laboratories (SNL-NM).
3. Saylor, E. M. and Scaglione, J. M. (2018). Nuclear Criticality Safety Assessment of Potential Plutonium Disposition at the Waste Isolation Pilot Plant. Tech. rep. ORNL/TM-2017/751/R1. Oak Ridge National Laboratory (ORNL).
4. Jensen, R., Broome, S., Herrick, C., and Reedlunn, B. (2023). Improved compaction experiments and modeling of Waste Isolation Pilot Plant standard, non-degraded, waste containers. Technical Report SAND2023-04823, Sandia National Laboratories.
5. Porter, S. (2013). Pipe Overpack Type A Evaluation Report. Tech. rep. POC-REP-0001, Rev. 1. Nuclear Waste Partnership LLC.
6. McGonagill, S. (2015). Criticality Control Overpack - Fabrication Drawing. Tech. rep. CCO-DWG-001, Revision 3. Nuclear Waste Partnership LLC, Carlsbad, NM.






# Backup Slides

## Gradual Compaction Potential Numerical Approaches

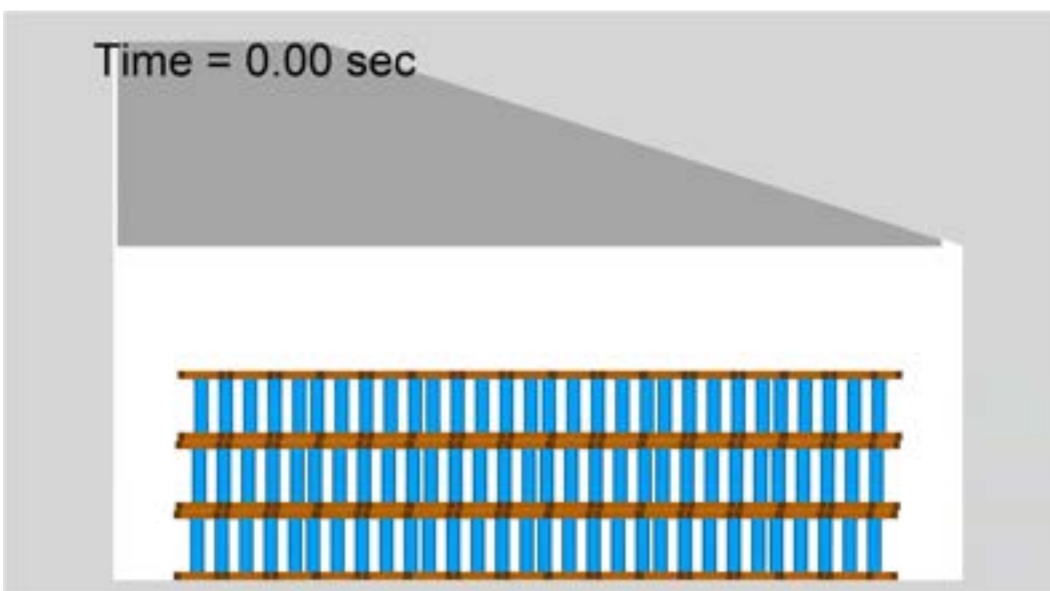
1. Standard approaches:
   1. Explicit Dynamics
      1. Robust
      2. Issue: time step is ~1 μs
   2. Implicit Quasi-statics
      1. Relatively robust, arbitrarily large time steps
      2. Issue: solver cannot converge due to rigid body translations
   3. Implicit Dynamics
      1. Relatively unused,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

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





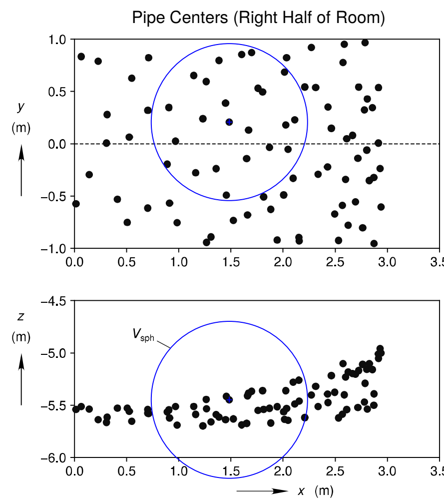
## Flat Roof Fall onto CCOs



# Pipe Center Concentration Calculation

Simple Concentration

$$c = \frac{N}{V_{\mathrm{sph}}}$$

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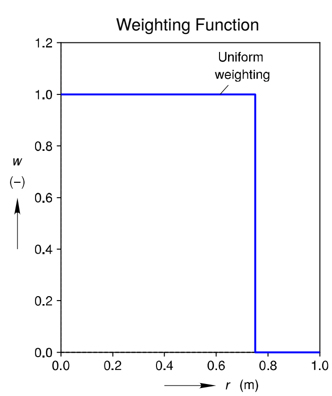
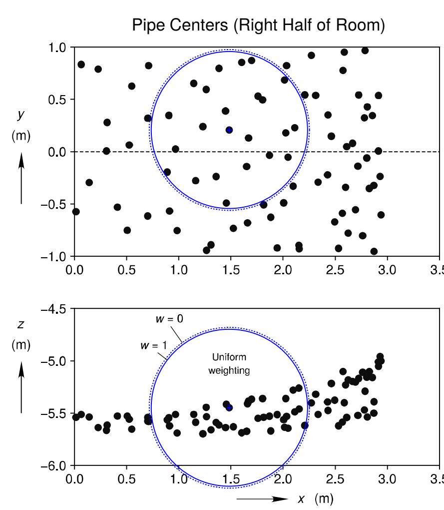
# Pipe Center Concentration Calculation

Weighted Concentration

$$c = \frac{\sum_{n=1}^{N} w(r_n)}{\int_{V_{\mathrm{sph}}} w(r)\,\mathrm{d}V}$$

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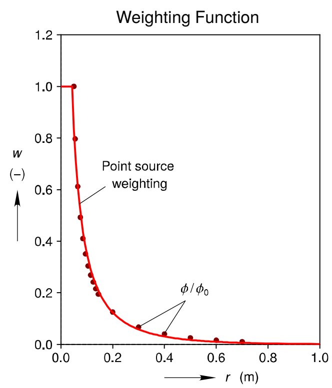
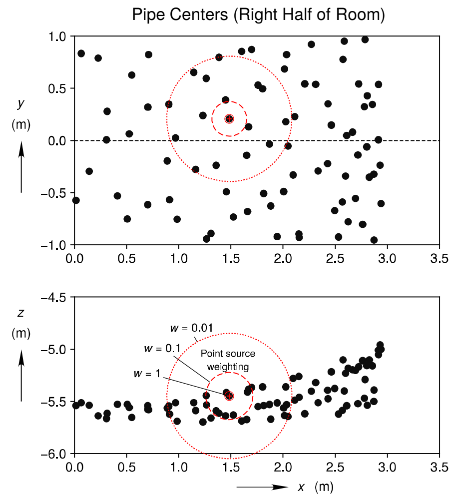
# Pipe Center Concentration Calculation

Weighted Concentration

$$c = \frac{\sum_{n=1}^{N} w(r_n)}{\int_{V_{sph}} w(r)\,dV}$$








# Pipe Center Concentration Calculation

Weighted Concentration

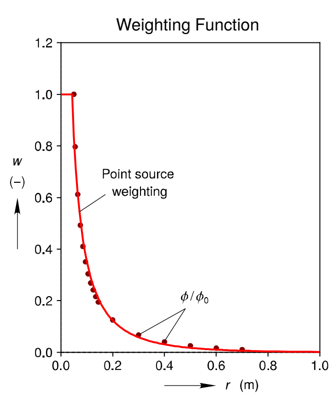
$$c = \frac{\sum_{n=1}^{N} w(r_n)}{\int_{V_{sph}} w(r)\,dV}$$

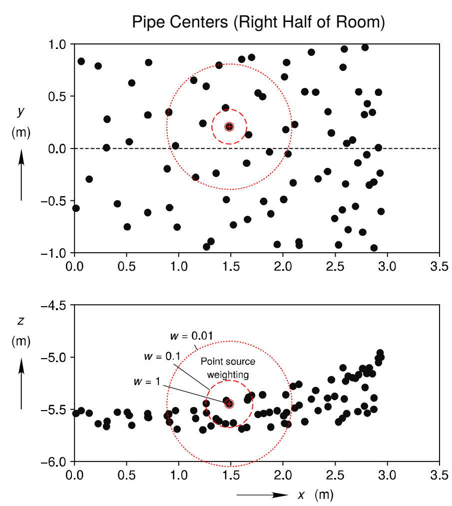
Relative Weighted Concentration

$$\hat{c} = \frac{c}{c_0}$$

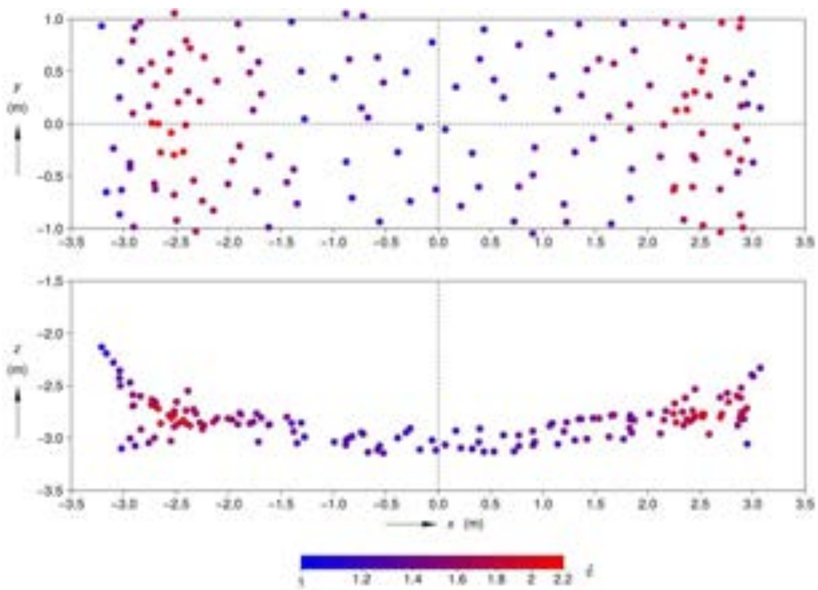
Reference Weighted Concentration

$$c_0 = \frac{w(0)}{\int_{V_{sph}} w(r)\,dV}$$



## CCO Pipe Center Concentrations at 1,000 yr



Upper Horizon
$\mu_c^F = \mu_c^G = 0.5$, $\mu_c^{other} = 0.2$

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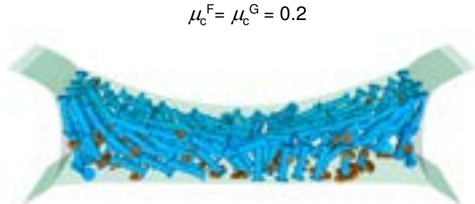
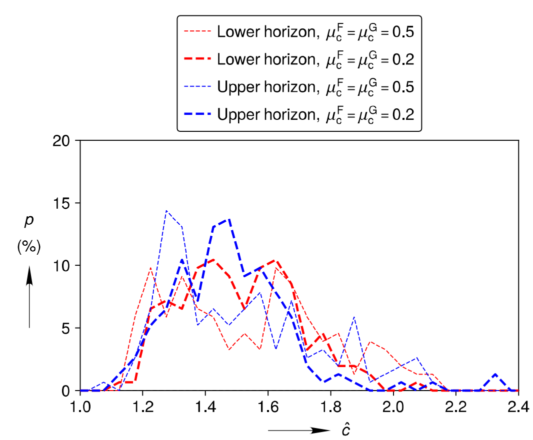
## Clay Seam F & G Friction Coefficient

CCOs, Upper Horizon, *t* = 100 yr

$\mu_c^F = \mu_c^G = 0.5$

$\mu_c^F = \mu_c^G = 0.2$



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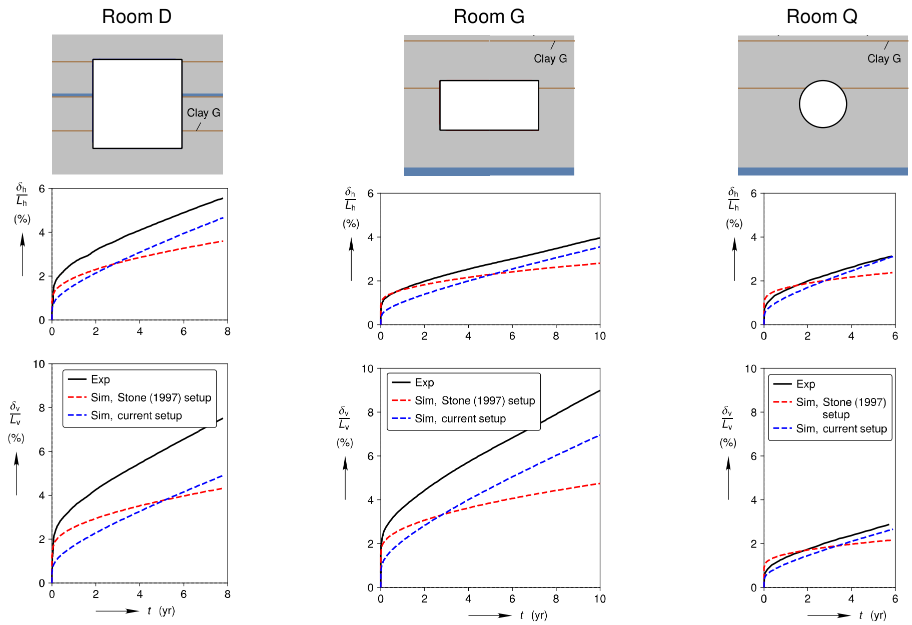
# Gradual Closure Model Validation



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The University of Resources. Since 1765.

# Implementation of salt creep models in OpenGeoSys

T. Nagel[1,2] et al.

▷ [1] Technische Universität Bergakademie Freiberg, Germany
▷ [2] Helmholtz Centre for Environmental Research GmbH – UFZ, Leipzig, Germany

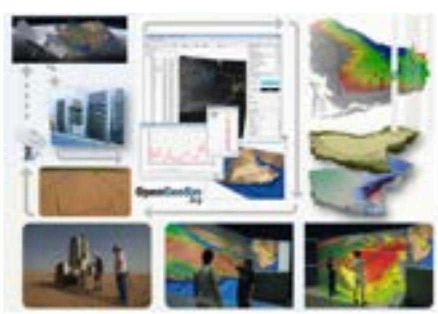
13th US/German Workshop on Salt Repository Research, Design & Operation
Santa Fe, New Mexico, June 20-23, 2023

Visit
https://tu-freiberg.de/en/soilmechanics
https://tu-freiberg.de/zewaf
https://ufz.de/environmental-geotechnics

## The framework

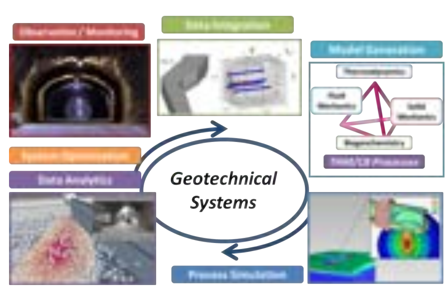
### OPEN-SOURCE SOFTWARE DEVELOPMENT

Workflows Groundwater Flow



OpenGeoSys
OPEN-SOURCE MULTI-PHYSICS

Workflows Geotechnics




## SOME ENTRY POINTS

Use the following links to get to ...

- ▷ OpenGeoSys homepage
- ▷ User guide
- ▷ Python interfaces: ogs6py and VTUio
- ▷ Using OGS with Jupyter notebooks
- ▷ Developer Guide
- ▷ Benchmarks
- ▷ Tools and Workflows
- ▷ Discourse
- ▷ Source code, issues, merge requests ...

**Current primary reference:**

L. Bilke et al. "Development of Open-Source Porous Media Simulators: Principles and Experiences". In: Transport in Porous Media 130.1 (10/2019), pp. 337–361. DOI: 10.1007/s11242-019-01310-1

ogs6py and VTUinterface: streamlining OpenGeoSys workflows in Python

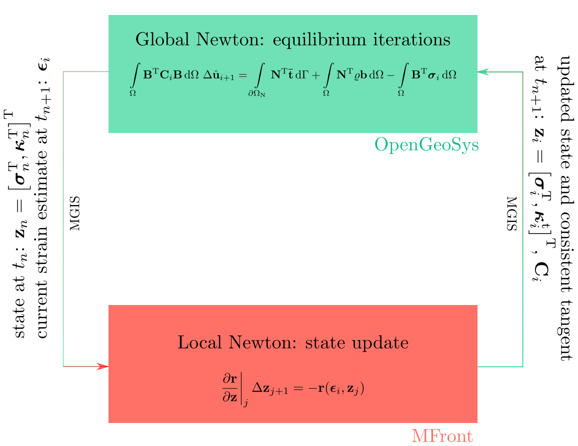
Jörg Buchwald[1, 2], Olaf Kolditz[1, 3, 4], and Thomas Nagel[2, 4]

[BKN21]



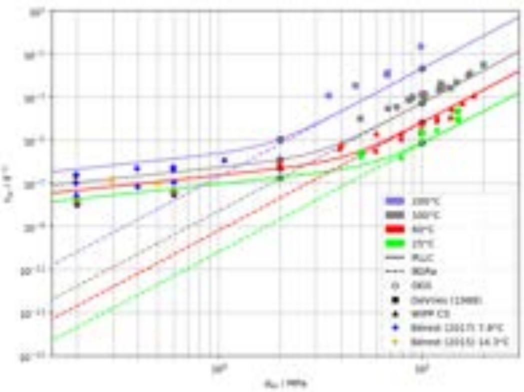


## IMPLICIT ALGORITHM




[Hel+20]

## STATIONARY CREEP MODELS



$$\dot{\boldsymbol{\sigma}} = \boldsymbol{\mathcal{C}} : (\dot{\boldsymbol{\epsilon}} - \dot{\boldsymbol{\epsilon}}^{\mathrm{cr}})$$

$$\dot{\boldsymbol{\epsilon}}^{\mathrm{cr}} = \sqrt{\frac{3}{2}} A_1 e^{-Q_1/(RT)} \left(\frac{\bar{\sigma}}{\sigma_{\mathrm{ref}}}\right)^m \frac{\boldsymbol{s}}{\|\boldsymbol{s}\|} + \sqrt{\frac{3}{2}} \frac{A_2}{D^3} e^{-Q_2/(RT)} \left(\frac{\bar{\sigma}}{\sigma_{\mathrm{ref}}}\right) \frac{\boldsymbol{s}}{\|\boldsymbol{s}\|}$$

- Power-law (dislocation) creep with linear (pressure-solution) creep (contains BGRa as special case)
- temperature dependence, (parametric) grain size dependence

[Bér+19; MSG16; ZWN22]





## IMPLEMENTATION SNAPSHOT

```
@Integrator {
    const auto s = deviator(sig);
    const auto norm_s = sigmaeq(sig) / std::sqrt(3. / 2.);
    constexpr auto Pdev = Stensor4::K();

    bPL = std::pow(3. / 2., (m + 1) / 2) * A1 * exp(-Q1 / (Ru * T_)) /
          std::pow(sig0, m);
    bL = 3. / 2. * A2 / (power<3>(Dgrain) * T_) * exp(-Q2 / (Ru * T_)) / sig0;

    const auto norm_s_pow = std::pow(norm_s, m - 1);
    const auto norm_s_pow2 = std::pow(norm_s, m - 3);

    depsPL = dt * bPL * norm_s_pow * s;
    depsL = dt * bL * s;
    feel += depsPL + depsL;
    dfeel_ddeel +=
        2. * mu * dt *
        (bPL * (norm_s_pow * Pdev + norm_s_pow2 * ((m - 1) * s ^ s)) +
         bL * Pdev);
}
```

## LUBBY2 & CODE OPTIMIZATION

Basic equations

$$\boldsymbol{\sigma} = K_{\mathsf{M}} e \boldsymbol{I} + 2G_{\mathsf{M}} \left[\boldsymbol{\epsilon}^{\mathsf{D}} - \boldsymbol{\epsilon}^{\mathsf{D}}_{\mathsf{M}} - \boldsymbol{\epsilon}^{\mathsf{D}}_{\mathsf{K}}\right]$$
$$\dot{\boldsymbol{\epsilon}}^{\mathsf{D}}_{\mathsf{K}} = \frac{1}{2\eta_{\mathsf{K}}}\left(\boldsymbol{\sigma}^{\mathsf{D}} - 2G_{\mathsf{K}}\boldsymbol{\epsilon}^{\mathsf{D}}_{\mathsf{K}}\right)$$
$$\dot{\boldsymbol{\epsilon}}^{\mathsf{D}}_{\mathsf{M}} = \frac{1}{2\eta_{\mathsf{M}}}\boldsymbol{\sigma}^{\mathsf{D}}$$

$$\eta_{\mathsf{M}} = \eta_{\mathsf{M}0} e^{m_1 \sigma_{\mathsf{eq}}}$$
$$\eta_{\mathsf{K}} = \eta_{\mathsf{K}0} e^{m_2 \sigma_{\mathsf{eq}}}$$
$$G_{\mathsf{K}} = G_{\mathsf{K}0} e^{m_{\mathsf{G}} \sigma_{\mathsf{eq}}}$$
$$\sigma_{\mathsf{eq}} = \sqrt{\frac{3}{2}\boldsymbol{\sigma}^{\mathsf{D}} : \boldsymbol{\sigma}^{\mathsf{D}}}$$

[HLR83; Nag+17; ZN20]

Implementation 1:

$$\boldsymbol{r}^j_1 = \Delta\boldsymbol{\epsilon}^j_{\mathsf{el}} + \Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{K}} + \Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{M}} - \Delta\boldsymbol{\epsilon}$$
$$\boldsymbol{r}^j_2 = \Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{K}} - \frac{\Delta t}{2\eta_{\mathsf{K}}}\left(\boldsymbol{\sigma}^{\mathsf{D},j} - 2G_{\mathsf{K}}\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{K}}\right)$$
$$\boldsymbol{r}^j_3 = \Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{M}} - \frac{\Delta t}{2\eta_{\mathsf{M}}}\boldsymbol{\sigma}^{\mathsf{D},j}$$

Implementation 2:

$$\boldsymbol{r}^j_1 = \Delta\boldsymbol{\epsilon}_{\mathsf{el}} + \Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{K}} + \Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{M}} - \Delta\boldsymbol{\epsilon}$$

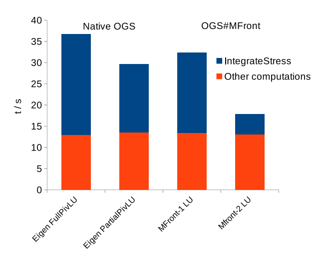
with $\Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{K}} = \frac{\Delta t}{2\left(\eta_{\mathsf{K}} + \Delta t G_{\mathsf{K}}\right)}\left(\boldsymbol{\sigma}^{\mathsf{D},j} - 2G_{\mathsf{K}}\boldsymbol{\epsilon}^{\mathsf{D},t}_{\mathsf{K}}\right)$

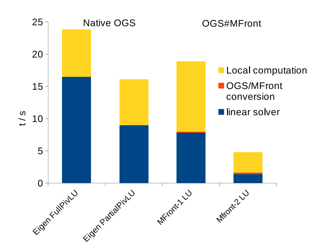
and $\Delta\boldsymbol{\epsilon}^{\mathsf{D},j}_{\mathsf{M}} = \frac{\Delta t}{2\eta_{\mathsf{M}}}\boldsymbol{\sigma}^{\mathsf{D},j}$



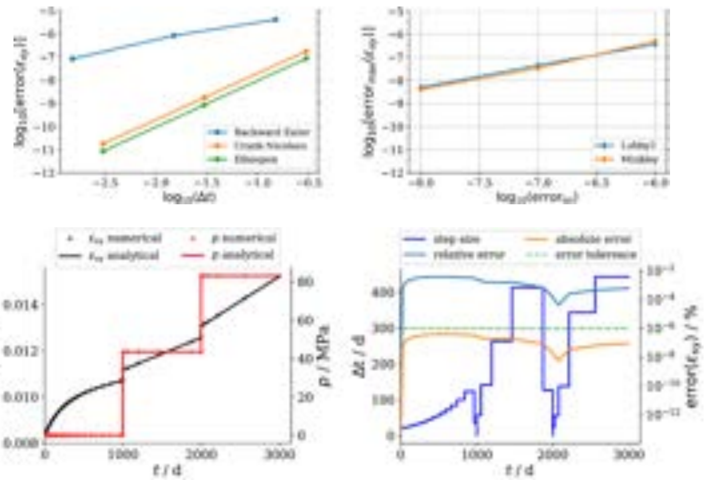


## LUBBY2 & CODE OPTIMIZATION



## LUBBY2 / MINKLEY – TIME STEPPING




[ZN20]





## NON-LINEAR SOLID RHEOLOGY: ROCK SALT

(A few) equations of the Günther-Salzer model (with ca. 27 parameters):

$$\dot{\boldsymbol{\epsilon}}_{\mathsf{cr}} = \sqrt{\frac{3}{2}}\dot{\epsilon}_{\mathsf{cr}}\frac{\boldsymbol{s}}{\|\boldsymbol{s}\|}$$

$$\dot{\epsilon}_{\mathsf{cr}} = \dot{\epsilon}_{\mathsf{cr}}^{\mathsf{V}} + \dot{\epsilon}_{\mathsf{cr}}^{\mathsf{E}} + \dot{\epsilon}_{\mathsf{cr}}^{\mathsf{dam}}$$

$$\dot{\epsilon}_{\mathsf{cr}} = A_{\mathsf{p}}\frac{(\bar{\sigma}/\sigma_{\mathsf{ref}})^{n_{\mathsf{p}}}}{(\epsilon_0^{\mathsf{V}} + \epsilon_{\mathsf{cr}}^{\mathsf{V}})^{\mu_{\mathsf{p}}}} \quad \text{with} \quad \bar{\sigma} = \sqrt{\frac{3}{2}}\|\boldsymbol{s}\|$$

$$\dot{\epsilon}_{\mathsf{cr}}^{\mathsf{E}} = \sum_{i=1}^{2} A_{\mathsf{s},i}\exp\left(-\frac{Q_i}{RT}\right)\left(\frac{\bar{\sigma}}{\sigma_{\mathsf{ref}}}\right)^{n_i}$$

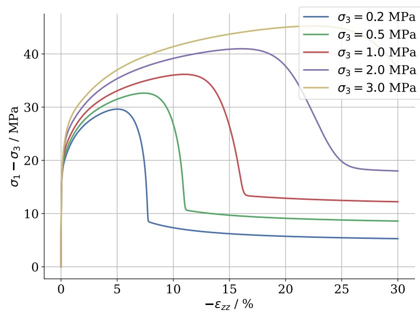
$$\dot{\epsilon}_{\mathsf{cr}}^{\mathsf{dam}} = \dot{\epsilon}_{\mathsf{dil}} = A_1(\sigma_3) + A_2(\sigma_3)\mathsf{exp}\left[A_3(\sigma_3)U_{\mathsf{dil}}\right]\dot{U}_{\mathsf{Dil}}$$

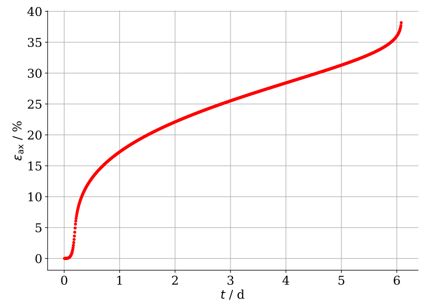
$$\text{with} \quad U_{\mathsf{dil}} = \int \langle\bar{\sigma} - \bar{\sigma}_{\mathsf{dil}}(\sigma_3)\rangle \mathsf{d}\epsilon_{\mathsf{cr}}$$

R.-M. Günther, K. Salzer, and T. Popp. "Advanced Strain – Hardening Approach Constitutive model for rock salt describing transient , stationary , and accelerated creep and dilatancy". In: 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium. Salt Lake City: ARMA, American Rock Mechanics Association, 2010
R.-M. Günther, K. Salzer, T. Popp, and C. Lüdeling. "Steady-State Creep of Rock Salt: Improved Approaches for Lab Determination and Modelling". In: Rock Mechanics and Rock Engineering 48.6 (11/2015), pp. 2603–2613. DOI: 10.1007/s00603-015-0839-2

## Implemented constitutive models for salt

### ROCK SALT



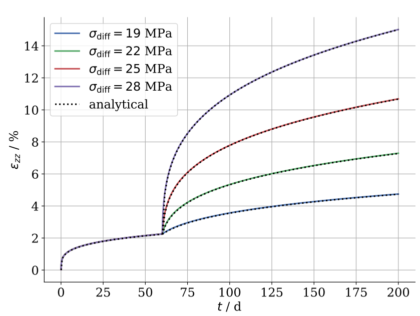



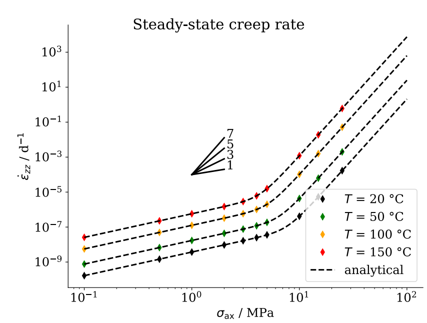

- from quasi-brittle to ductile
- stress-dependent dilatancy, hardening and softening
- primary, secondary, tertiary creep



## Implemented constitutive models for salt

### ROCK SALT




- stress- and temperature-dependent creep
- different steady-state creep mechanisms (dislocation, pressure-solution)
- rates span orders of magnitude

## CRUSHED SALT

We start from the non-linear elastic law

$$\underline{\sigma} = K^{\star}\,\mathrm{tr}\left(\underline{\varepsilon}^{\mathrm{el}}\right)\,\underline{I} + 2\,\mu\,\underline{s}^{\mathrm{el}} \quad \text{with} \quad K^{\star} = K \cdot e^{-c_k\cdot\eta\cdot\left(\dfrac{1-\eta_0}{1-\eta}\right)}$$

The inelastic strain $\underline{\varepsilon}^{\mathrm{in}}$ is split as the sum of two contributions $\underline{\varepsilon}^{\mathrm{vp}}$ and $\underline{\varepsilon}^{\mathrm{g}}$ which respectively describe the viscoplastic deformation of single salt grains and the relative displacement between grains, as follows:

$$\underline{\dot{\varepsilon}}^{\mathrm{in}} = \underline{\dot{\varepsilon}}^{\mathrm{vp}} + \underline{\dot{\varepsilon}}^{\mathrm{g}}$$

The grain deformation strain rate tensor $\underline{\dot{\varepsilon}}^{\mathrm{vp}}$ follows an associated Norton-Hoff behaviour based on a Green stress criterion. This criterion is expressed as:

$$\sigma_{\mathrm{eq}} = \sqrt{h_1(\eta)\,p^2 + h_2(\eta)\,q^2}$$

$$h_1(\eta) = \frac{a}{\left(\eta^{-c} - \eta_0^{-c}\right)^m} \quad \text{and} \quad h_2(\eta) = b_1 + b_2\,h_1$$



Implemented constitutive models for salt

## CRUSHED SALT II

The normal $\underline{n}$ to the Green criterion is given by:

$$\underline{n} = \frac{1}{\sigma_{\mathrm{eq}}}\left(\frac{1}{3}\,h_1(\eta)\,p\,\underline{I} + h_2(\eta)\,\underline{s}\right)$$

Finally, the viscoplastic strain rate can be expressed as follows:

$$\underline{\dot{\varepsilon}}^{\mathrm{vp}} = A_{\mathrm{vp}}\,\exp\left(-\frac{Q_c}{R_m\,T}\right)\sigma_{\mathrm{eq}}^{n_{\mathrm{vp}}}\,\underline{n}$$

The porosity evolution is given by:

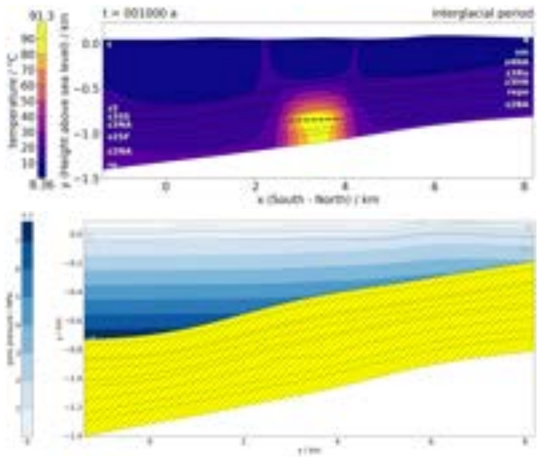
$$\dot{\eta} = (1-\eta)\,\mathrm{tr}\left(\underline{\dot{\varepsilon}}^{\mathrm{to}}\right)$$

This ordinary differential equation can be integrated exactly between $t$ and $t+\theta\,\Delta\,t$ by separation of variables and the porosity at the end of time step is then given by:

$$\eta|_{t+\Delta\,t} = 1 - \left(1 - \eta|_t\right)\,\exp\left(-\mathrm{tr}\left(\Delta\,\underline{\varepsilon}^{\mathrm{to}}\right)\right)$$

More details:
`https://thelfer.github.io/MFrontGallery/web/CrushedSaltKorthausBehaviour.html`

## LARGE-SCALE SIMULATIONS – TM (SALT) + THM (ELSEWHERE)



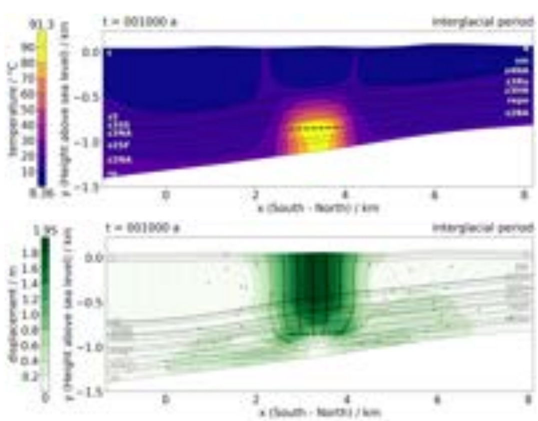

- Partial / domain-specific assembly
- No artificial parameterization
- Improvements in stability and post-processing

[Car+23]





## LARGE-SCALE SIMULATIONS – TM (SALT) + THM (ELSEWHERE)




- Partial / domain-specific assembly
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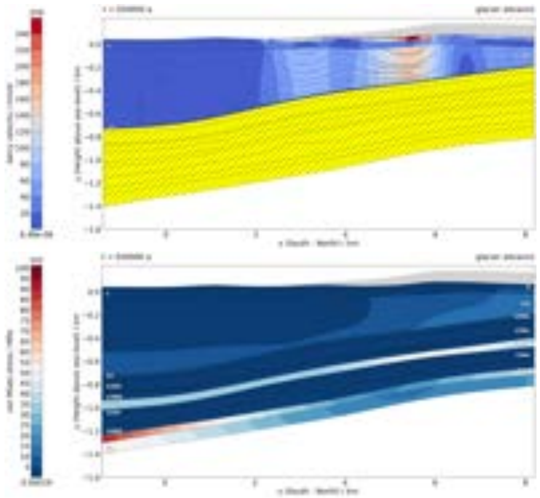
[Car+23]

## LARGE-SCALE SIMULATIONS – TM (SALT) + THM (ELSEWHERE)



- Partial / domain-specific assembly
- No artificial parameterization
- Improvements in stability and post-processing

[Car+23]





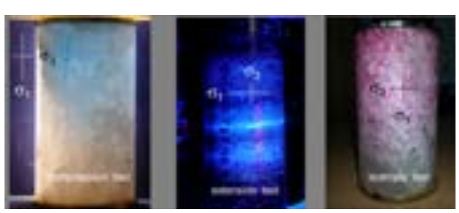
## DILATANCY-DRIVEN GAS TRANSPORT: SECONDARY HM COUPLING

**Orthotropic permeability model:**

$$\boldsymbol{k} = k_\mathrm{m}\boldsymbol{I} + \sum_{i=1}^{3} \frac{b_i}{a_i}\left(\frac{b_i^2}{12} - k_\mathrm{m}\right)(\boldsymbol{I} - \boldsymbol{M}_i)$$

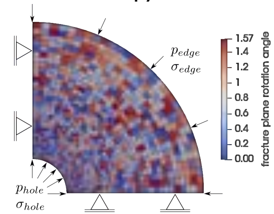
$$b_i = b_{i0} + a_i\langle \boldsymbol{\varepsilon} : \boldsymbol{M}_i - \varepsilon_{0i}\rangle$$

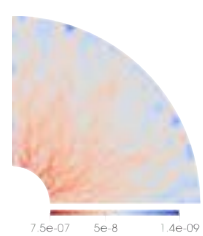
$$\frac{\partial \boldsymbol{k}}{\partial \boldsymbol{\varepsilon}} = \sum_{i=1}^{3}\left(\frac{b_i^2}{4} - k_\mathrm{m}\right)(\boldsymbol{\varepsilon} : \boldsymbol{M}_i - \varepsilon_{0i})(\boldsymbol{I} - \boldsymbol{M}_i) \otimes \boldsymbol{M}_i$$



From: W. Minkley. Integrität von Salzgesteinen und praktische Relevanz für die Verwahrung von Salzkavernen. Twente University, Enschede, 27, 2015.

**Quasi-isotropy:**

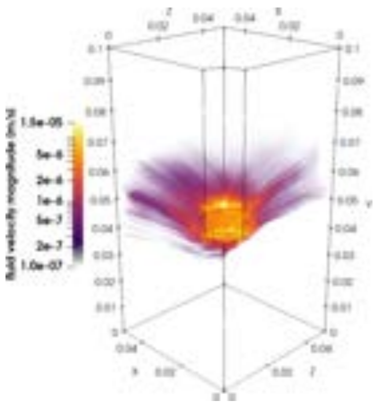


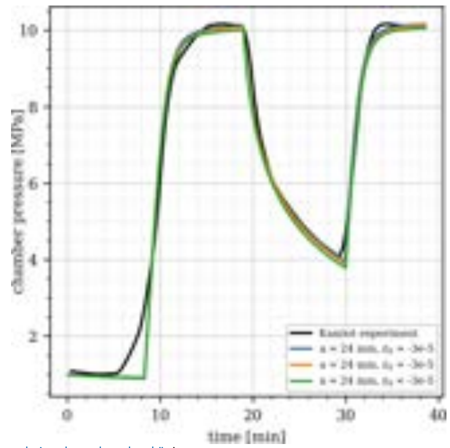
## STRESS FIELD-DEPENDENT FLUID PERCOLATION

Setup:

Flow plane




Model vs. experiment




F. Zill, C. Lüdeling, O. Kolditz, and T. Nagel. "Hydro-mechanical continuum modelling of fluid percolation through rock salt". In: International Journal of Rock Mechanics and Mining Sciences 147.August (11/2021), p. 104879. DOI: 10.1016/j.ijrmms.2021.104879

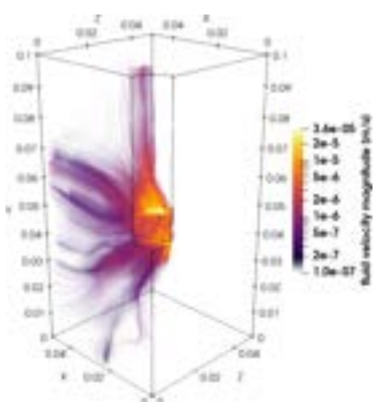




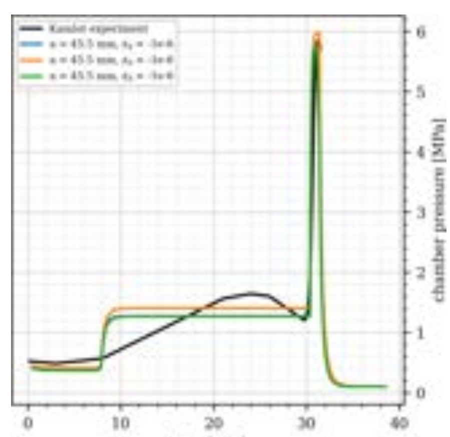
## STRESS FIELD-DEPENDENT FLUID PERCOLATION

Setup:

Flow plane




Model vs. experiment




F. Zill, C. Lüdeling, O. Kolditz, and T. Nagel. "Hydro-mechanical continuum modelling of fluid percolation through rock salt". In: International Journal of Rock Mechanics and Mining Sciences 147.August (11/2021), p. 104879. DOI: 10.1016/j.ijrmms.2021.104879

## ITERATIVE SCHEME

Linearized weak form in Total Lagrangian description:

$$
\begin{aligned}
{}^{i-1}\boldsymbol{\Psi} &= \int\limits_{\Omega^0} \left[ {}^{i-1}\boldsymbol{S}^{t+\Delta t} : {}^{i}\Delta\delta\boldsymbol{E} + {}^{i-1}\delta\boldsymbol{E}^{t+\Delta t} : {}^{i-1}\boldsymbol{\mathcal{C}}_{\mathrm{m}}{}^{t+\Delta t} : {}^{i}\Delta\boldsymbol{E} \right] \mathrm{d}\Omega^0 \\
&= f^{t+\Delta t} - \int\limits_{\Omega^0} {}^{i-1}\boldsymbol{S}^{t+\Delta t} : {}^{i-1}\delta\boldsymbol{E}^{t+\Delta t}\, \mathrm{d}\Omega^0
\end{aligned}
$$

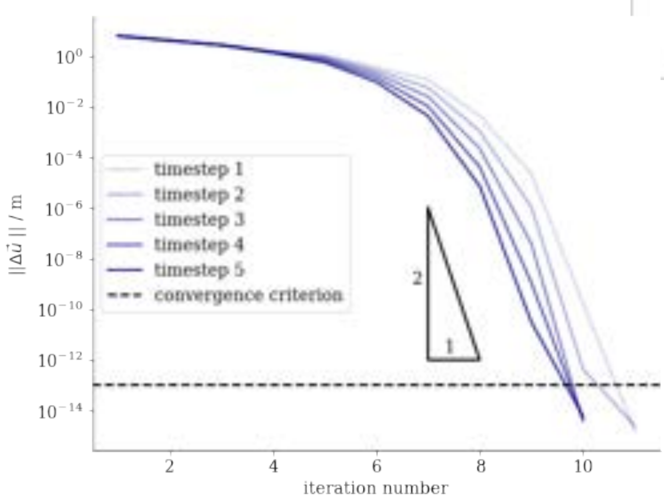
Discretization yields:

$$
\begin{aligned}
{}^{i-1}\underline{\Psi} &= \left[ \int\limits_{\Omega^0} {}^{i-1}\underline{\underline{B}}^{\mathsf{T}\,t+\Delta t}\; {}^{i-1}\underline{\underline{C}}_{\mathrm{m}}{}^{t+\Delta t}\; {}^{i-1}\underline{\underline{B}}^{t+\Delta t}\, \mathrm{d}\Omega^0 + \int\limits_{\Omega^0} \underline{\underline{G}}^{\mathsf{T}}\; {}^{i-1}\underline{\underline{S}}^{t+\Delta t}\underline{\underline{G}}\, \mathrm{d}\Omega^0 \right] {}^{i}\Delta\underline{u} \\
&= \underline{F}^{t+\Delta t} - \int\limits_{\Omega^0} {}^{i-1}\underline{\underline{B}}^{\mathsf{T}\,t+\Delta t}\; {}^{i-1}\underline{S}^{t+\Delta t}\, \mathrm{d}\Omega^0
\end{aligned}
$$





## CONVERGENCE CHECK




$\lambda_{\mathrm{ax}} = 1.5$, $\vartheta_{\mathrm{ax}} = \pi$ in 5 inc.

## Nonlinear kinematics

### (SOME) KINEMATICAL OPTIONS

**Small strain formalism:**

$$\boldsymbol{\epsilon} = \boldsymbol{\epsilon}_\mathrm{e} + \boldsymbol{\epsilon}_\mathrm{i}$$
$$\boldsymbol{\sigma} = K(\mathrm{tr}\,\boldsymbol{\epsilon}_\mathrm{e})\boldsymbol{I} + 2G\boldsymbol{\epsilon}_\mathrm{e}^\mathrm{D}$$
$$\dot{\boldsymbol{\epsilon}}_\mathrm{i} = \frac{1}{2\eta}\boldsymbol{\sigma}^\mathrm{D}$$

**Multiplicative decomposition:**

$$\boldsymbol{F} = \boldsymbol{F}_\mathrm{e}\boldsymbol{F}_\mathrm{i}$$
$$\boldsymbol{S} = 2\varrho_0\frac{\partial\psi(\boldsymbol{C}\boldsymbol{C}_\mathrm{i}^{-1})}{\partial\boldsymbol{C}}$$
$$\dot{\boldsymbol{C}}_\mathrm{i} = \frac{1}{2\eta}(\boldsymbol{C}\boldsymbol{S})^\mathrm{D}\boldsymbol{C}_\mathrm{i}$$

**Hencky strains:**

$$\boldsymbol{E}_\mathrm{H} = \boldsymbol{E}_\mathrm{H,e} + \boldsymbol{E}_\mathrm{H,i}$$
$$\boldsymbol{\sigma}_\mathrm{H} = K(\mathrm{tr}\,\boldsymbol{E}_\mathrm{H,e})\boldsymbol{I} + 2G\boldsymbol{E}_\mathrm{H,e}^\mathrm{D}$$
$$\dot{\boldsymbol{E}}_\mathrm{H,i} = \frac{1}{2\eta}\boldsymbol{\sigma}_\mathrm{H}^\mathrm{D}$$

with the geometric pre- and postprocessors

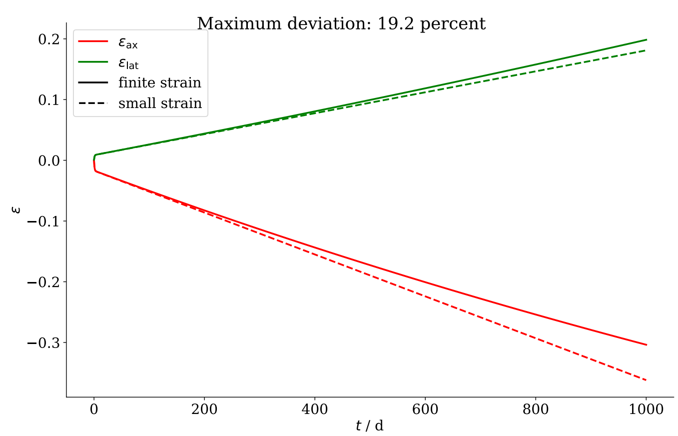
$$\boldsymbol{E}_\mathrm{H} = \ln\boldsymbol{U} = \frac{1}{2}\ln\boldsymbol{C}$$
$$\boldsymbol{S} = \frac{\partial\ln\boldsymbol{C}}{\partial\boldsymbol{C}} : \boldsymbol{\sigma}_\mathrm{H}$$



## Nonlinear kinematics

### LUBBY2 WITH HENCKY STRAINS: TRIAXIAL CREEP

Triaxial creep under constant Cauchy stress deviators:



## LUBBY2 WITH HENCKY STRAINS: SIMPLE & PURE SHEAR

**Simple shear:**

$$\boldsymbol{F} = \begin{bmatrix} 1 & \gamma \\ 0 & 1 \end{bmatrix}, \quad \vartheta_R \approx \frac{\gamma}{2}, \quad \det \boldsymbol{F} = 1$$

$$\boldsymbol{E} = \begin{bmatrix} 0 & \frac{\gamma}{2} \\ \frac{\gamma}{2} & \frac{\gamma^2}{2} \end{bmatrix}$$

$$\boldsymbol{\epsilon} = \begin{bmatrix} 0 & \frac{\gamma}{2} \\ \frac{\gamma}{2} & 0 \end{bmatrix}$$

$$\lambda_1 = \frac{\sqrt{2\gamma^2 + 2\gamma\sqrt{\gamma^2+4} + 4}}{2}$$

$$\lambda_2 = \frac{\sqrt{2\gamma^2 - 2\gamma\sqrt{\gamma^2+4} + 4}}{2}$$

$$\text{tr}\, \boldsymbol{E}_\text{H} = 0$$

**Pure shear:**

$$\boldsymbol{F} = \begin{bmatrix} 1 & \frac{\gamma}{2} \\ \frac{\gamma}{2} & 1 \end{bmatrix} = \boldsymbol{U}, \quad \boldsymbol{R} = \mathbf{o}, \quad \det \boldsymbol{F} = 1 - \frac{\gamma^2}{4}$$

$$\boldsymbol{E} = \begin{bmatrix} \frac{\gamma^2}{8} & \frac{\gamma}{2} \\ \frac{\gamma}{2} & \frac{\gamma^2}{8} \end{bmatrix}$$

$$\boldsymbol{\epsilon} = \begin{bmatrix} 0 & \frac{\gamma}{2} \\ \frac{\gamma}{2} & 0 \end{bmatrix}$$

$$\lambda_1 = \frac{2+\gamma}{2}$$

$$\lambda_2 = \frac{2-\gamma}{2}$$

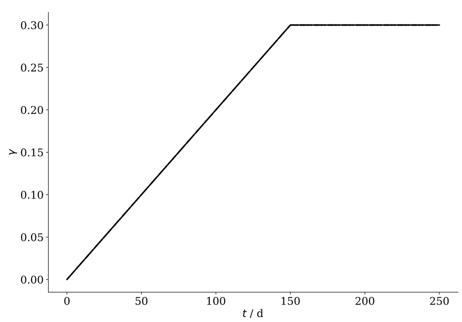
$$\text{tr}\, \boldsymbol{E}_\text{H} = \ln\left(1 - \frac{\gamma^2}{4}\right)$$

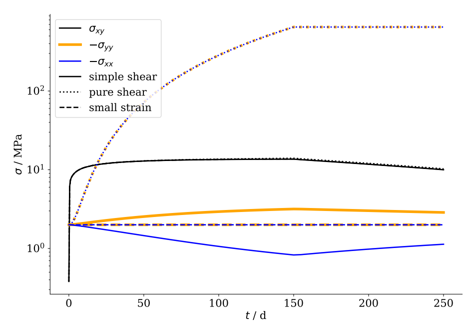
$$0 \le \gamma < 2$$





## LUBBY2 WITH HENCKY STRAINS: SIMPLE & PURE SHEAR




- shear response consistent
- strong differences in normal stress development (volumetric response!)
- rotation of principal axes

## Outlook

### CONCLUSIONS

- Extension of material models
- Extension to finite strains
- THM coupling
- Contributions are welcome!



## Outlook

### ACKNOWLEDGEMENTS

Contributors:

- Lars Bilke
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- Hua Shao
- Christian Silbermann
- Wenqing Wang
- Keita Yoshioka
- . . .

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BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Bundesamt für die Sicherheit der nuklearen Entsorgung

DFG Deutsche Forschungsgemeinschaft

PTKA Projektträger Karlsruhe

PtJ

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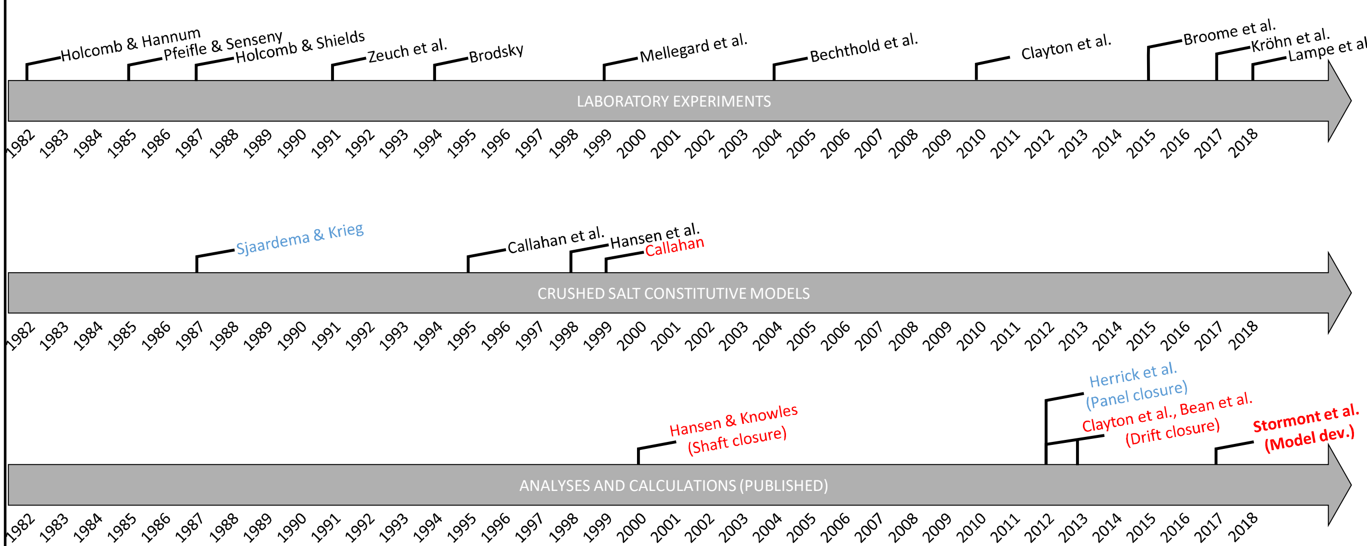
# Crushed salt modeling at Sandia National Labs.

## Assessment of capabilities and future developments

Jibril B. Coulibaly, Benjamin Reedlunn, James E. Bean
Sandia National Laboratories




## Motivations – Timeline of (Sandia) research



## Motivations – Assessment of the model

"We found that the Callahan model was extremely difficult to work with because of the large number of parameters associated with it.

Parameter fitting of consolidation data to the Callahan model suggested that equivalent model responses could be obtained with different sets of parameters.

Further, the Callahan model was originally developed to be consistent with and represent consolidation mechanisms. However, it was not possible to associate parameter values with actual mechanisms.

Finally, because of the extremely complicated and involved nature of the model, it was not possible to include pore pressure in a straightforward manner."

(Stormont et al., 2017)





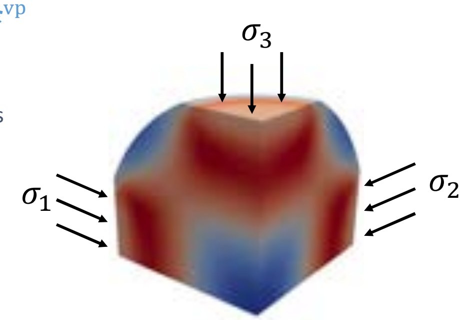
## Outline

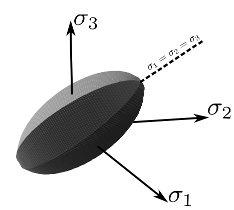
- Formulation of the Callahan model
- Review of model concepts and structure
- Calibration
- Verification attempts
- Conclusions and Perspectives

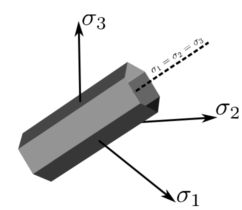
# Formulation

Elastic – Viscoplastic model: $\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}^{\mathrm{vp}}$

- Elasticity: $\dot{\boldsymbol{\varepsilon}}^{\mathrm{e}}$
  - Porosity-dependent model (Sjaardema & Krieg, 1987) → 4 material parameters
- Multi-mechanism viscoplasticity: $\dot{\boldsymbol{\varepsilon}}^{\mathrm{vp}} = \left[\dot{\varepsilon}^{\mathrm{dc}}\left(\sigma_{\mathrm{eq}}^{\mathrm{f}}\right) + \dot{\varepsilon}^{\mathrm{ps}}\left(\sigma_{\mathrm{eq}}^{\mathrm{f}}\right)\right]\frac{\partial \sigma_{\mathrm{eq}}}{\partial \boldsymbol{\sigma}}$
  1. Dislocation creep: $\dot{\varepsilon}^{\mathrm{dc}}$
     - Intact salt model (Munson & Dawson, 1982) → 24 material parameters
  1. Pressure solution: $\dot{\varepsilon}^{\mathrm{ps}}$
     - Micromechanical model (Spiers & Brzesowsky, 1993) → 7 material parameters
- Equivalent stress measure: $\sigma_{\mathrm{eq}}^{\mathrm{f}}$
  - Local stress in porous material (Sofronis & McMeeking, 1992) → 3 parameters
- Flow potential: $\sigma_{\mathrm{eq}}$
  - Compressible to incompressible flow transition → 4 material parameters



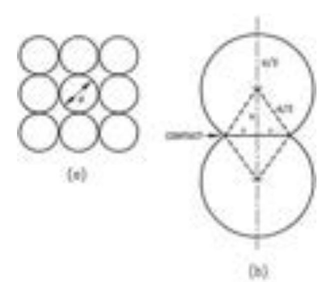






# Review

- Equivalent stress measure $\sigma_{\mathrm{eq}}^{\mathrm{f}}$: spherical void in power-law creep material
  - Low and disconnected porosity
    - Invalid for most laboratory experiments with $\phi > 5\%$
  - Dislocation creep mechanism
    - Shear-driven bulk deformation
- Pressure solution $\dot{\varepsilon}^{\mathrm{ps}}\left(\sigma_{\mathrm{eq}}^{\mathrm{f}}\right)$: locally normal contact stress
  - Equivalent stress measure $\sigma_{\mathrm{eq}}^{\mathrm{f}}$ not valid for pressure solution
    - Unrelated physical mechanisms
    - Irrelevant / inconsistent geometry information
  - Strain rate $\dot{\varepsilon}^{\mathrm{ps}}$ turns off when fully reconsolidated
    - Valid for hydrostatic stress, not for equivalent stress measure $\sigma_{\mathrm{eq}}^{\mathrm{f}}$
- Multi-mechanism formalism: $\left[\dot{\varepsilon}^{\mathrm{dc}}\left(\sigma_{\mathrm{eq}}^{\mathrm{f}}\right) + \dot{\varepsilon}^{\mathrm{ps}}\left(\sigma_{\mathrm{eq}}^{\mathrm{f}}\right)\right]\frac{\partial \sigma_{\mathrm{eq}}}{\partial \boldsymbol{\sigma}}$
  - Same flow potential for pressure solution and dislocation creep
    - Mechanisms inter-connection
  - Direction – magnitude interplay: $\frac{\partial \sigma_{\mathrm{eq}}}{\partial \sigma_{\mathrm{eq}}^{\mathrm{f}}} \neq 0$

Sofronis & McMeeking, 1992



Spiers & Brzesowsky, 1993

## Calibration – Preliminary

Two sets of parameters from different studies

1. 24 intact salt material parameters
   - Munson-Dawson model parameters → not directly related to crushed salt
   - Calibrated against intact salt experimental data (DeVries, 2011 for Sondershausen and Asse salt)

2. 18 crushed salt material parameters
   - Callahan, 1999 legacy Calibration against WIPP salt
     - 40 hydrostatic creep tests: Brodsky, 1994; Holcomb & Hannum, 1982; Holcomb & Shields, 1987; Pfeifle & Senseny, 1985
     - 18 triaxial compression creep tests: Brodsky, 1994; Zeuch et al., 1991; Mellegard et al., 1999

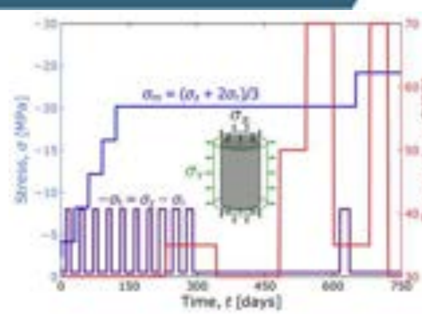
     - Not designed and performed for model calibration
     - Short duration (4 to 110 days)



## Calibration – KOMPASS test TUC-V2

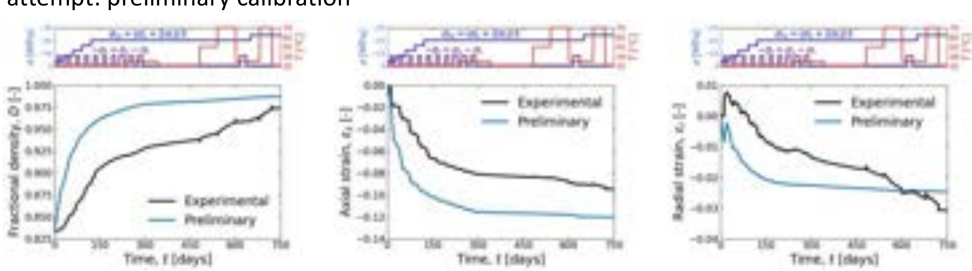
- KOMPASS test TUC-V2
  - KOMPASS reference material
    - Sondershausen salt
    - D < 8 mm
  - Initial porosity: $\phi_0 = 16.7\%$
  - Initial water content: $w = 0.5\%$

  - Session 4: Uwe Düsterloh (TUC)
  - Session 5: Larissa Friedenberg (GRS)




Engineering Mechanics sign convention:
Tensile stress positive
Extensive strain positive

- First attempt: preliminary calibration

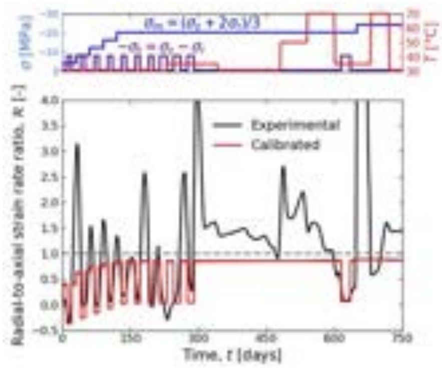


**Slide 7**

1 this slide is kinda ugly, figure out a way to make it make sense
Coulibaly, Jibril Birante, 5/29/2023

# Calibration – KOMPASS test TUC-V2

1. Calibration of flow potential
   - Radial-to-axial strain rate ratio: $\mathcal{R} = \dot{\varepsilon}_r / \dot{\varepsilon}_z$
     - Model cannot capture $\mathcal{R} > 1$
     - Calibrated against $\mathcal{R} < 1$ (4 parameters)

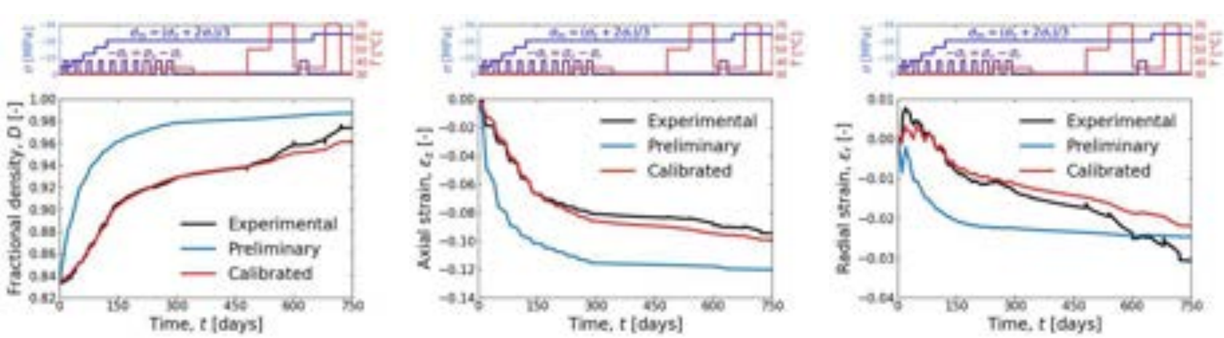



2. Reduction of parameters space: insufficient information
   - Elasticity → Sjaardema & Krieg, 1987 (4 parameters)
   - Grain size and water content → not varied (2 parameters)
   - Pressure solution geometry and activation energy → Spiers & Brzesowsky, 1993 (4 parameters)



# Calibration – KOMPASS test TUC-V2

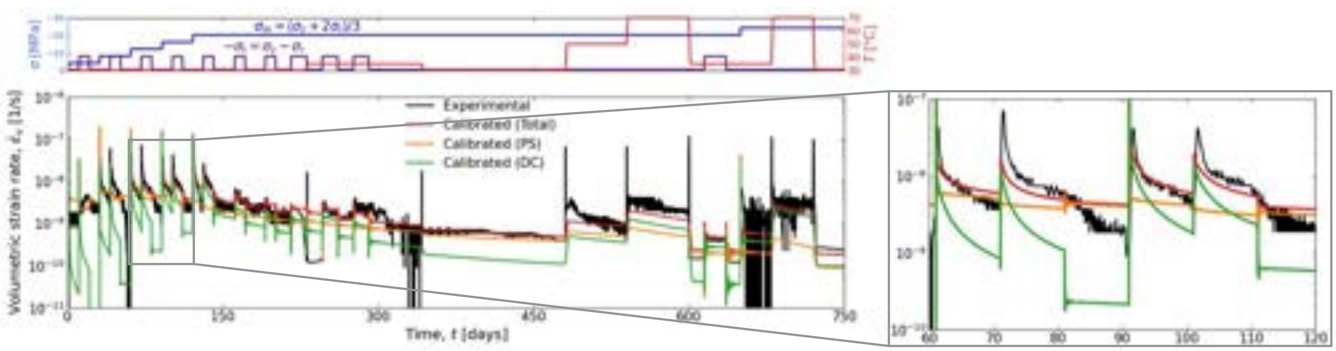
3. Calibration of deformation magnitude (4 parameters left)
   - Major improvement over preliminary parameter set
   - Deviation in high-temperature response
   - Deviation in directional response (phases with strain rate ratio $\mathcal{R} > 1$)



# Calibration – KOMPASS test TUC-V2

3. Calibration of deformation magnitude (4 parameters left)

   - Dislocation creep characterizes transient phases (slow hardening)
   - Pressure solution dominates rate, even at high stress (numerical prediction, not physical breakdown)





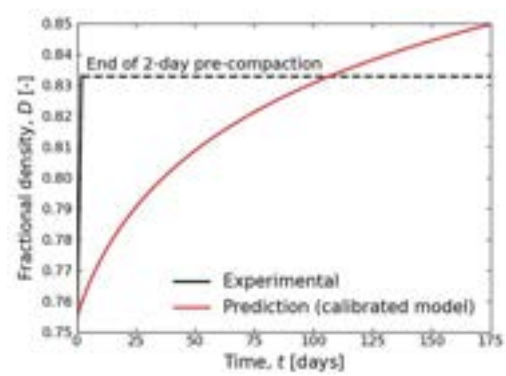



# Verification attempts – TUC-V2 pre-compaction

- Plane strain pre-compaction before KOMPASS test TUC-V2
  - Fixed vertical displacement
  - Radial pressure $\sigma_{\mathrm{r}} = -5$ Mpa
  - Preparation porosity: $\phi_0 = 25\%$
  - Initial water content: $w = 0.5\%$

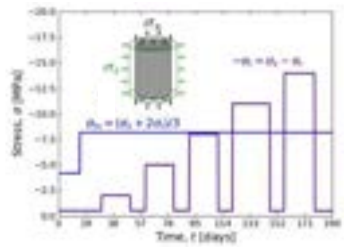
- Severe underestimation of deformation
  - Grain rearrangement and cataclasis not modeled

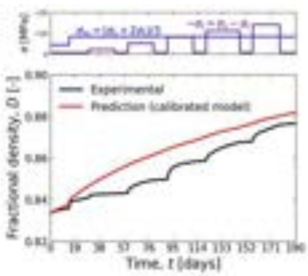
Source: TU Clausthal

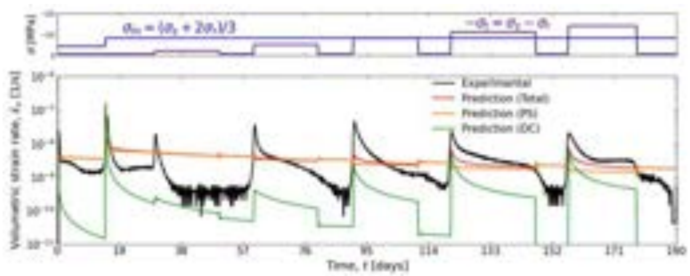


# Verification attempts – KOMPASS test TUC-V4

- Same material / initial conditions as KOMPASS test TUC-V2
  - Overestimated compaction
  - Qualitatively acceptable directional response
  - Insufficient transient response to deviatoric phases
    - Model dominated by pressure solution






# Conclusions

1. Strengths of the Callahan model
   - 3D tensor form with pressure solution and dislocation creep mechanisms
   - Transition from porous to intact salt behavior
   - Satisfactory calibration against complex experimental test (TUC-V2)

2. Known limitations
   - Interconnection of deformation mechanisms (equivalent stress measure)
   - Direction – magnitude interplay (multi-mechanism formalism)
   - Difficult / inadequate identification and separation of mechanisms contributions
   - Difficult / fragile calibration of the model

3. Potential issues
   - Absence of rate-independent mechanisms
   - Overestimation of compaction resistance at high porosity (drifts)

## Perspectives

1. Correct the identified limitations
   - Existing constitutive models (e.g., Olivella and Gens, 2002 ; Kröhn, 2017)
   - New constitutive model (new physics: anisotropy, cohesion-density separation)

2. Quantify the potential issues
   - Reference laboratory tests and case studies
   - Model comparison, validation and blind prediction

3. Address the open questions
   - Models can do well in spite of limitations
   - Realistic expectations and goals for improvements





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## Thank you

## Danke

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## Extra slides

Extra slides

18

## Extra slides – detailed Callahan formulation

Elasticity

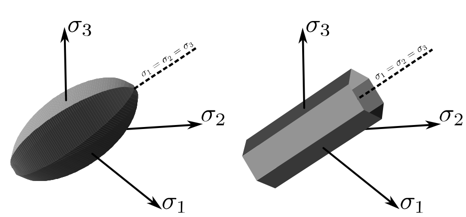
- Isotropic elasticity: $\dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} = \frac{\sigma_{\mathrm{m}}}{3K}\boldsymbol{I} + \frac{\boldsymbol{\sigma}^{\mathrm{dev}}}{2G}$
  - Mean stress: $\sigma_{\mathrm{m}} = \mathrm{tr}(\boldsymbol{\sigma})/3$
  - Deviatoric stress: $\boldsymbol{\sigma}^{\mathrm{dev}} = \boldsymbol{\sigma} - \sigma_{\mathrm{m}}\,\boldsymbol{I}$
- Porosity-dependent elastic moduli: $G = G_0\exp(G_1\rho)$ and $K = K_0\exp(K_1\rho)$
  - Crushed salt density: $\rho$
  - Material parameters: $G_0$, $G_1$, $K_0$, $K_1$



## Extra slides – detailed Callahan formulation

Equivalent stress and flow potential

- Equivalent stress: $\sigma_{\mathrm{eq}}^{\mathrm{f}} = \left[\eta_0\Omega_{\mathrm{f}}^{\eta_1}\sigma_{\mathrm{m}}^2 + \left(\frac{2-D}{D}\right)^{\frac{2n_{\mathrm{f}}}{n_{\mathrm{f}}+1}}\sigma_{\mathrm{t}}^2\right]^{\frac{1}{2}}$ with, $\Omega_{\mathrm{f}} = \left[\frac{(1-D)n_{\mathrm{f}}}{\left[1-(1-D)^{1/n_{\mathrm{f}}}\right]^{n_{\mathrm{f}}}}\right]^{\frac{2}{n_{\mathrm{f}}+1}}$
- Flow potential: $\sigma_{\mathrm{eq}} = \left[\kappa_0\Omega^{\kappa_1}\sigma_{\mathrm{m}}^2 + \left(\frac{2-D}{D}\right)^{\frac{2n}{n+1}}\sigma_{\mathrm{t}}^2\right]^{\frac{1}{2}}$ with, $\Omega = \left[\frac{(1-D_{\mathrm{v}})n}{\left[1-(1-D_{\mathrm{v}})^{1/n}\right]^{n}}\right]^{\frac{2}{n+1}}$ and $D_{\mathrm{v}} = \max(D, D_{\mathrm{t}})$
  - Current fractional density: $D = \rho/\rho_{\mathrm{int}}$
  - Intact salt density: $\rho_{\mathrm{int}}$
  - Tresca equivalent stress: $\sigma_{\mathrm{t}} = \sigma_{\max} - \sigma_{\min}$
  - Maximum/minimum principal stress $\sigma_{\max}$, $\sigma_{\min}$
  - Material parameters: $\eta_0, \eta_1, \kappa_0, \kappa_1, n_{\mathrm{f}}, n, D_{\mathrm{t}}$



## Extra slides – detailed Callahan formulation

Dislocation creep

- Steady-state + transient creep strain rate: $\dot{\varepsilon}^{\mathrm{dc}} = \dot{\varepsilon}^{\mathrm{ss}} + \dot{\varepsilon}^{\mathrm{ts}}$
- Steady-state: $\dot{\varepsilon}^{\mathrm{ss}} = \sum_{i=0}^{3} \dot{\varepsilon}_i^{\mathrm{ss}}$
  - Low-stress ($i = 0$), climb ($i = 1$), cross-slip ($i = 2$) mechanisms: $\dot{\varepsilon}_i^{\mathrm{ss}} = A_i \left(\frac{\sigma_{\mathrm{eq}}^{\mathrm{f}}}{\mu}\right)^{n_i} \exp\left(-\frac{Q_i}{RT}\right)$ for $i < 3$
  - Dislocation slip ($i = 3$): $\dot{\varepsilon}_3^{\mathrm{ss}} = H(\sigma_{\mathrm{eq}}^{\mathrm{f}} - \sigma_0) \sum_{i=0}^{2} B_i \exp\left(-\frac{Q_i}{RT}\right) \sinh\left[q\left(\frac{\sigma_{\mathrm{eq}}^{\mathrm{f}} - \sigma_0}{\mu}\right)\right]$
- Transient: $\dot{\varepsilon}^{\mathrm{ts}} = (F-1)\dot{\varepsilon}^{\mathrm{ss}}$
  - Branches: $F = \begin{cases} \exp\left[\Delta\left(1-\frac{\varepsilon^{\mathrm{ts}}}{\varepsilon^{\mathrm{tl}}}\right)^2\right] & \varepsilon^{\mathrm{ts}} < \varepsilon^{\mathrm{tl}} \\ 1 & \varepsilon^{\mathrm{ts}} = \varepsilon^{\mathrm{tl}} \\ \exp\left[-\delta\left(1-\frac{\varepsilon^{\mathrm{ts}}}{\varepsilon^{\mathrm{tl}}}\right)^2\right] & \varepsilon^{\mathrm{ts}} > \varepsilon^{\mathrm{tl}} \end{cases}$, with $\begin{cases} \Delta = \alpha_{\mathrm{h}} + \beta_{\mathrm{h}} \log_{10}\left(\frac{\sigma_{\mathrm{eq}}^{\mathrm{f}}}{\mu}\right) \\ \delta = \alpha_{\mathrm{r}} + \beta_{\mathrm{r}} \log_{10}\left(\frac{\sigma_{\mathrm{eq}}^{\mathrm{f}}}{\mu}\right) \end{cases}$, and $\varepsilon^{\mathrm{tl}} = \sum_{i=0}^{1} k_i \exp(c_i T)\left(\frac{\sigma_{\mathrm{eq}}^{\mathrm{f}}}{\mu}\right)^{m_i}$
    - Universal gas constant: $R$
    - Absolute temperature: $T$
    - Heaviside function: $H(\cdot)$
    - Intact salt shear modulus: $\mu$
    - Material parameters: $A_0, A_1, A_2, B_0, B_1, B_2, Q_0, Q_1, Q_2, n_0, n_1, n_2, q, \sigma_0, k_0, k_1, c_0, c_1, m_0, m_1, \alpha_{\mathrm{h}}, \beta_{\mathrm{h}}, \alpha_{\mathrm{r}}, \beta_{\mathrm{r}}$



## Extra slides – detailed Callahan formulation

Pressure solution

- Equivalent stress: $\dot{\varepsilon}^{\mathrm{dc}} = \frac{r_1 w^a}{d^p} \exp(-\bar{\varepsilon}_{\mathrm{v}}) \left(\frac{\exp(r_3 \bar{\varepsilon}_{\mathrm{v}})}{|\exp(\bar{\varepsilon}_{\mathrm{v}})-1|^{r_4}}\right) \frac{\exp\left(-\frac{Q_s}{RT}\right)}{T} \Gamma \sigma_{\mathrm{eq}}^{\mathrm{f}}$
  - Shifted volumetric strain: $\bar{\varepsilon}_{\mathrm{v}} = \varepsilon_{\mathrm{v}} + \varepsilon_{\mathrm{v}}^*$
  - Fictitious initial strain: $\varepsilon_{\mathrm{v}}^* = \ln\left(\frac{\rho^*}{\rho_0}\right) = \ln\left(\frac{D^*}{D_0}\right)$, with $D^* = 1 - \phi^* = 0.64$ (random close packing of spheres)
- Large consolidation function: $\Gamma = \begin{cases} 1 & \text{small consolidation } (\exp(\bar{\varepsilon}_{\mathrm{v}}) > 0.85) \\ \left[\frac{\exp(\bar{\varepsilon}_{\mathrm{v}}) + \phi^* - 1}{\phi^* \exp(\bar{\varepsilon}_{\mathrm{v}})}\right]^{n_{\mathrm{s}}} & \text{large consolidation } (\exp(\bar{\varepsilon}_{\mathrm{v}}) < 0.85) \end{cases}$
  - Water content: $w$
  - Grain size: $d$
  - Material parameters: $r_1, r_3, r_4, a, p, Q_{\mathrm{s}}, n_{\mathrm{s}}$

# RANGERS: Integrity of shaft seals

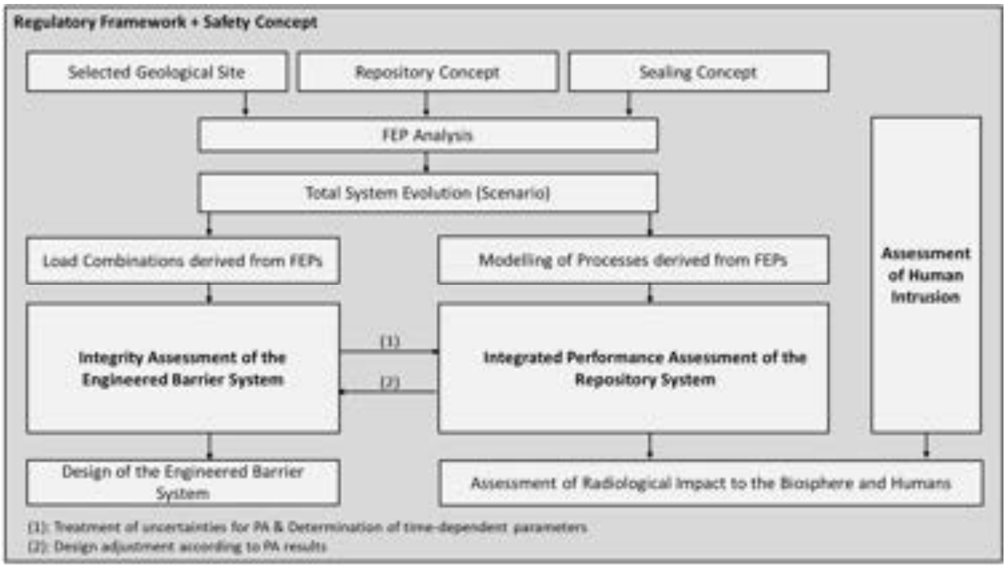
Eric Simo, R. Paola Leon Vargas, Ajmal Gafoor, Philipp Herold
BGE TECHNOLOGY GmbH




## About RANGERS

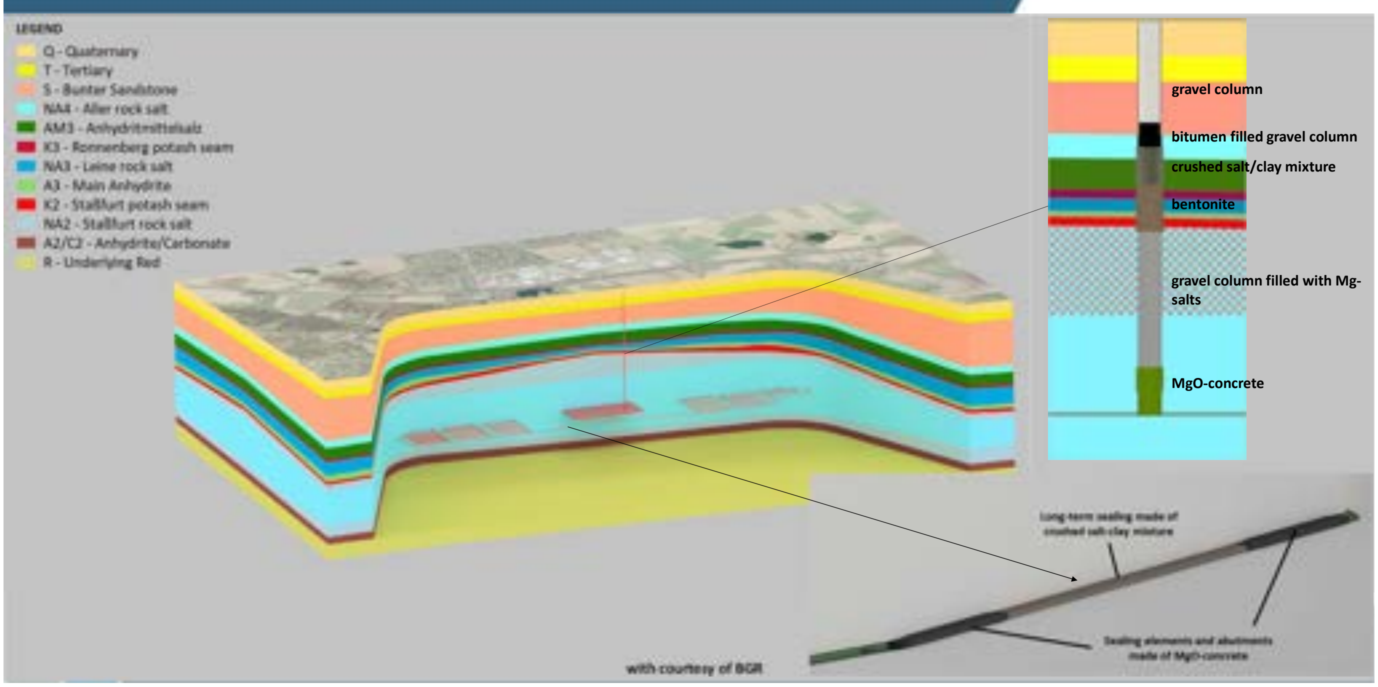
- Methodology for design and performance assessment of geotechnical barriers in a HLW repository in salt formations
- Joint project of Sandia National Laboratories and BGE TECHNOLOGY GmbH
- Main goals:
  - Compilation of existing knowledge and experience to design salt-relevant:
    - Geotechnical Barriers
    - Engineered Barrier System (EBS)
  - Including their preliminary design and verification
- Secondary goals:
  - Optimization of EBS in salt repositories
  - Analysis of the safety assessment impact of gases on EBS
  - Coupling safety assessment simulations by SANDIA and BGE TEC

# RANGERS Methodology






# Repository Geology for Hypothetical Site



## FEPs for EBS in Salt Formations

FEP = Features, Events & Processes

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



## Relevant Scenarios for EBS in Salt

- Reference Scenario: The EBS retains its function over 50,000 years
  - Case 1: Water from overburden into shaft and disposal zones
  - Case 2: Repository gas production from container corrosion
  - Case 3: Water sourced from from inter- / intra-granular brine in salt
- Alternative Scenario 1:
  - Shaft seal loses its function
  - Drift seals retain their function
  - Same cases as reference scenario
- Alternative Scenario 2:
  - Shaft seal retains its function
  - Drift seals lose their function
  - Same cases as reference scenario

# FEP Analysis and System Evolution

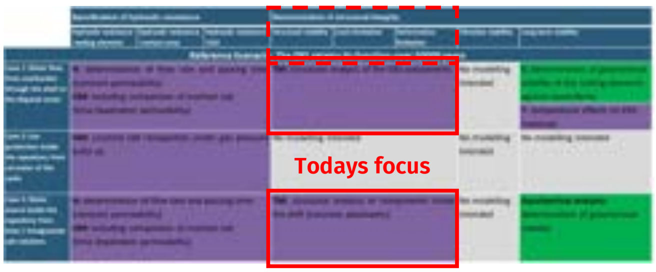
- Modeling approach derived from FEP / scenario analysis

FEP Analysis

Total System Evolution (Scenario)

Load Combinations derived from FEPs

Modeling of Processes derived from FEPs

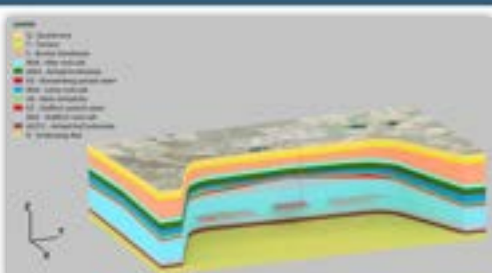



**by Sandia**

**by BGE TEC**

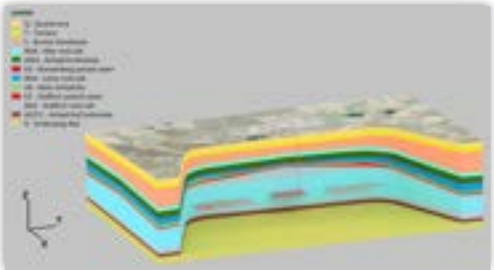


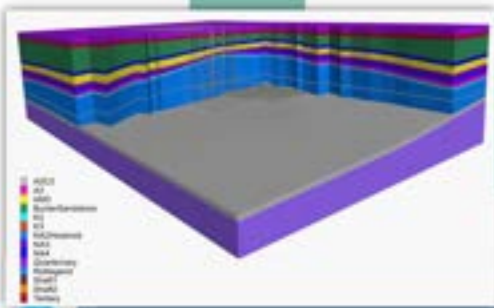
# Model Set-up



- The code used for numerical simulations was FLAC3D v7 and v9
- Model Geometrie:
  - Lenght, X = 3917 m
  - Lenght, Y = 5922 m
  - Depth, Z = -3090 m
- Shaft configuration based on ELSA-II, TH-Coupled Simulation

# Model Set-up





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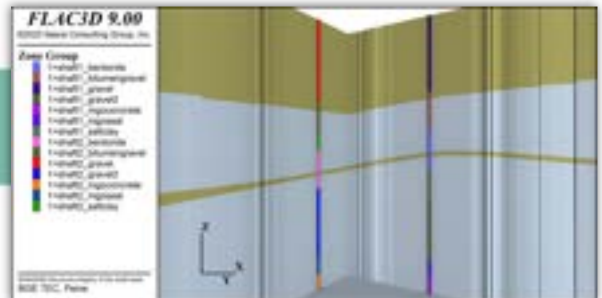
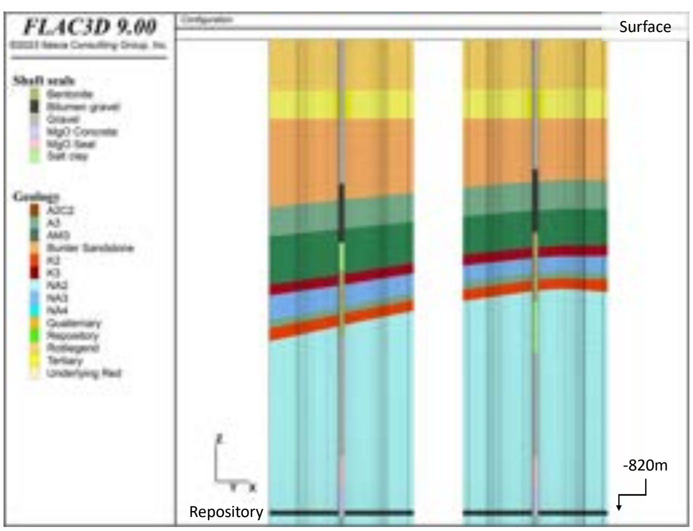





# Configuration




- Shaft 1 and Shaft 2 have the same geometry and backfilling materials, but different geometrical setting
- During ***excavation,*** Shell elements representing shaft lining (d=0.30m) are going to be installed in each shaft
- During ***closure,*** *32a after emplacement*, the shell elements are going to be dismantled
- Three Models are going to be tested:
  - Up to 3Mio Zones
  - Up to 7Mio Zones
  - Up to 10Mio Zones
- Due to the number of time zones, calculation time is lengthy, but:
  - FLAC3D v5: 5 years in 1 day
  - FLAC3D v7: 7 years in 1 day
  - FLAC3D v9: 50 years in 2 days

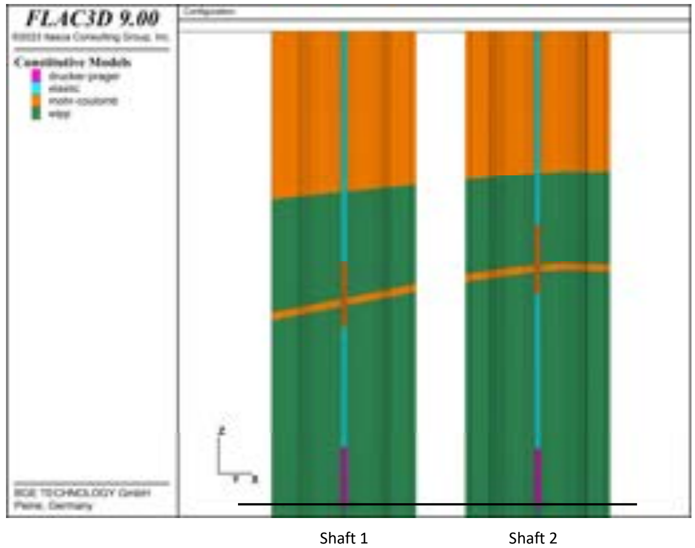
# Configuration

Material Parameters

| Homogeneous zones | Symbol | Constitutive Modell | Density<br>ρ in [kg/m³] | Thermal conductivity<br>λ in [W/(m·K)] | Specific heat capacity<br>$c_p$ in [J/(kg·K)] | Thermal expansion coefficient<br>α in [1/K] | Young's modulus<br>E in GPa | Poisson ratio<br>ν in [-] |
|---|---|---|---|---|---|---|---|---|
| Quaternary | Q | MC | 2000 | 2.3 | 950 | 1.0E-05 | 0.1 | 0.33 |
| Tertiary | T | MC | 2100 | 2.1 | 905 | 1.0E-05 | 0.5 | 0.33 |
| Bunter | S | MC | 2500 | 2.6 | 760 | 1.0E-05 | 15 | 0.27 |
| Aller rock salt | NA4 | wipp, BGRa | 2235 | 5.2 | 860 | 4.0E-05 | 25 | 0.27 |
| Anhydritmittelsalz | AM3 | wipp, BGRa | 2275 | 5 | 860 | 3.5E-05 | 30 | 0.27 |
| Potash seam Ronnenberg | K3 | wipp, BGRa | 1850 | 1.5 | 903 | 2.5E-05 | 16 | 0.26 |
| Leine rock salt | NA3 | wipp, BGRa | 2160 | 5.2 | 860 | 4.0E-05 | 25 | 0.25 |
| Main anhydrite | A3 | MC | 2700 | 4.2 | 860 | 1.6E-05 | 60 | 0.25 |
| Potash seam Staßfurt | K2 | wipp, BGRa | 1850 | 1.5 | 903 | 2.5E-05 | 17 | 0.28 |
| Stassfurt rock salt | NA2 | wipp, BGRb | 2160 | 5.2 | 860 | 4.0E-05 | 33 | 0.25 |
| Anhydrite/carbonate | A2/C2 | elastic | 2700 | 4.2 | 860 | 1.6E-05 | 30 | 0.27 |
| Underlying red | R | elastic | 2500 | 2.7 | 760 | 1.0E-05 | 17 | 0.27 |

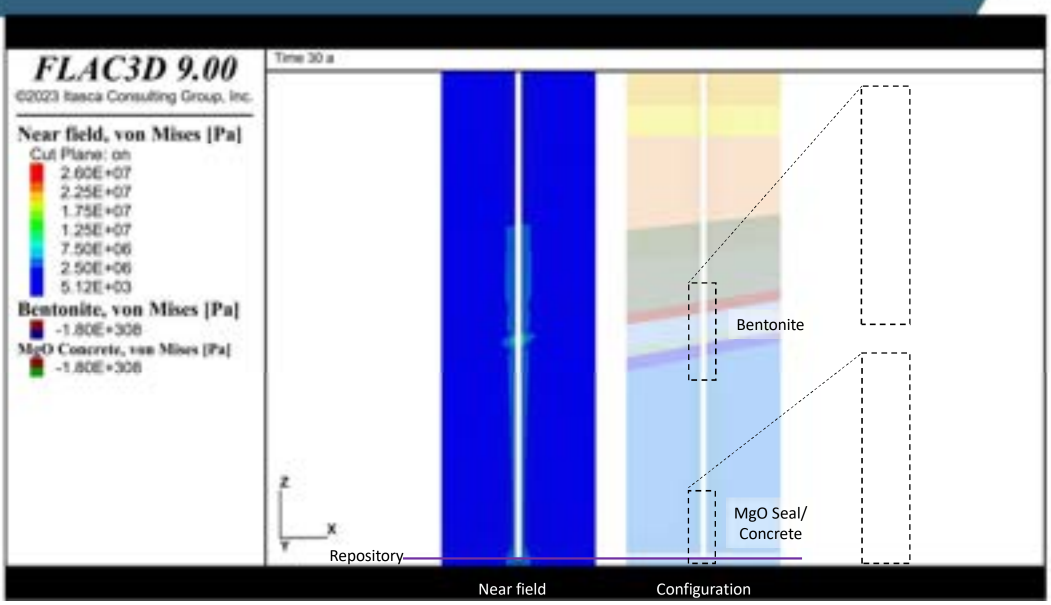
Creep Prefix Factors

| Homogeneous zones | Symbol | recommended formula (with Prefix Factor) |
|---|---|---|
| Aller rock salt | NA4 | 1/8·$BGR_a$ |
| Anhydritmittelsalz | AM3 | 1/16·$BGR_a$ |
| Potash seam Ronnenberg | K3 | $BGR_a$ |
| Leine rock salt | NA3 | 1/4·$BGR_a$ |
| Potash seam Staßfurt | K2 | $BGR_a$ |
| Stassfurt rock salt | NA2 | 2·$BGR_b$ |



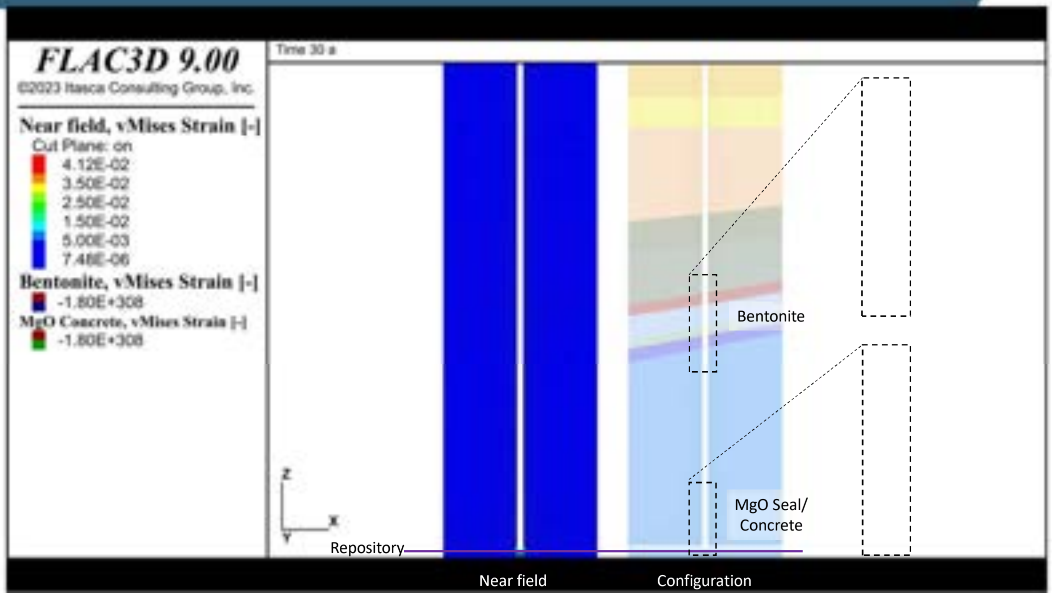



# Preliminary Results: Shaft 2




Von Mises Stress

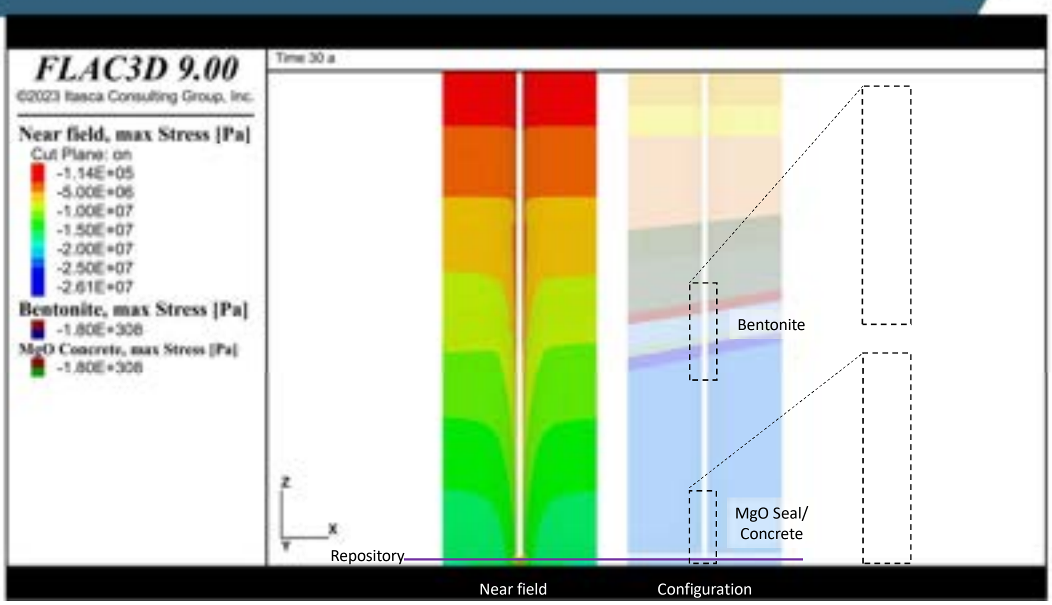
# Preliminary Results: Shaft 2




Von Mises Strain

13

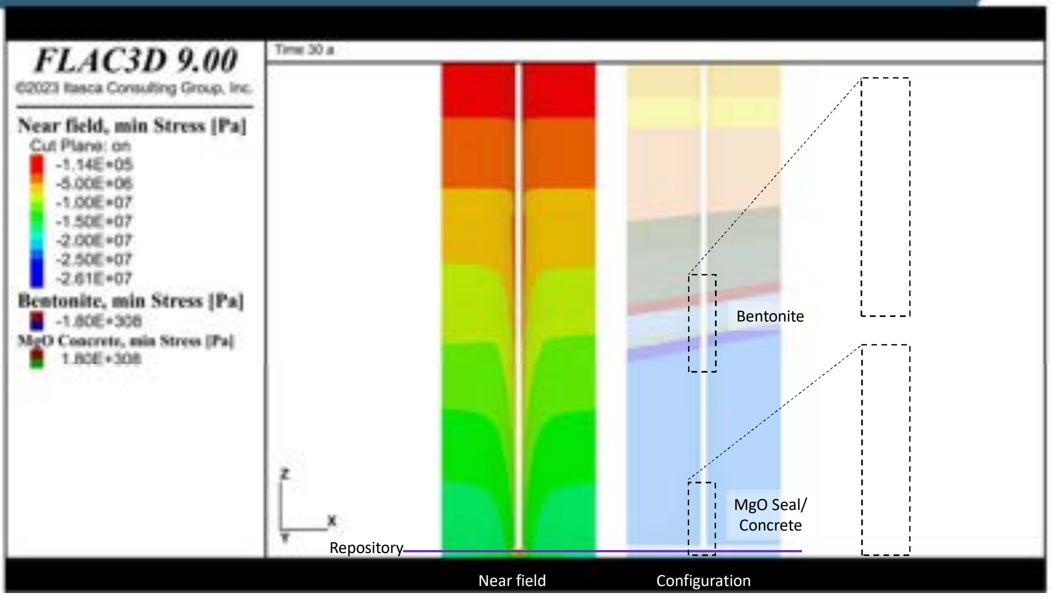
# Preliminary Results: Shaft 2




max. Stress (σ1)

14

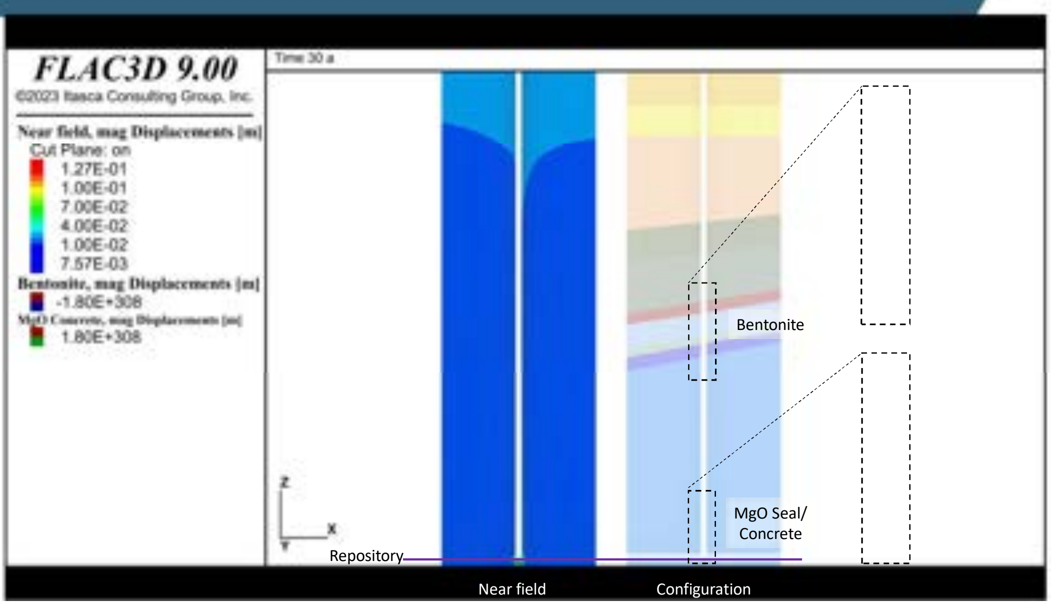
# Preliminary Results: Shaft 2




min. Stress (σ3)

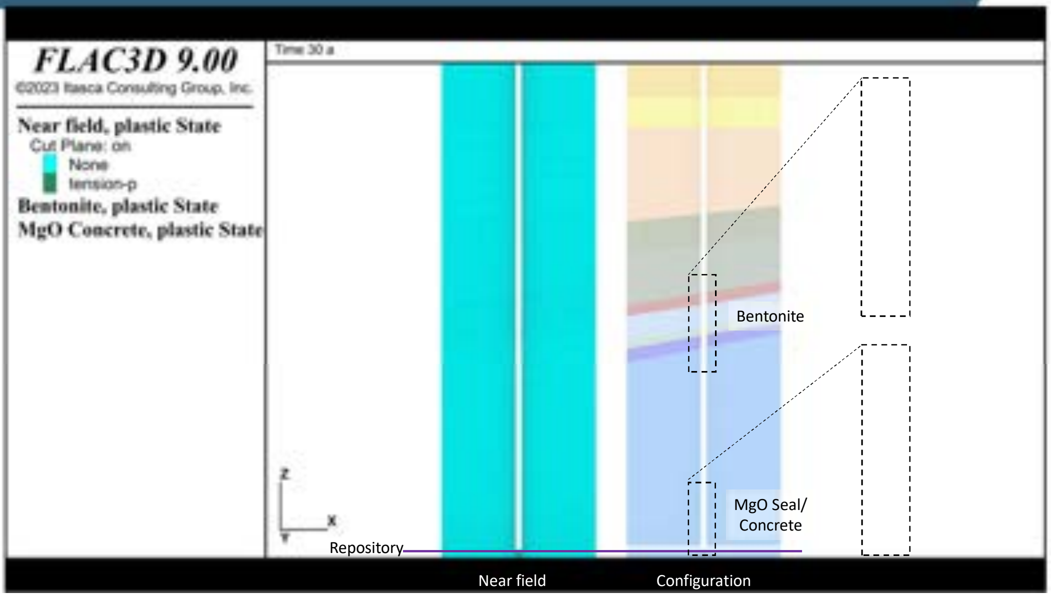


# Preliminary Results: Shaft 2




Displacements, magnitude

## Preliminary Results: Shaft 2

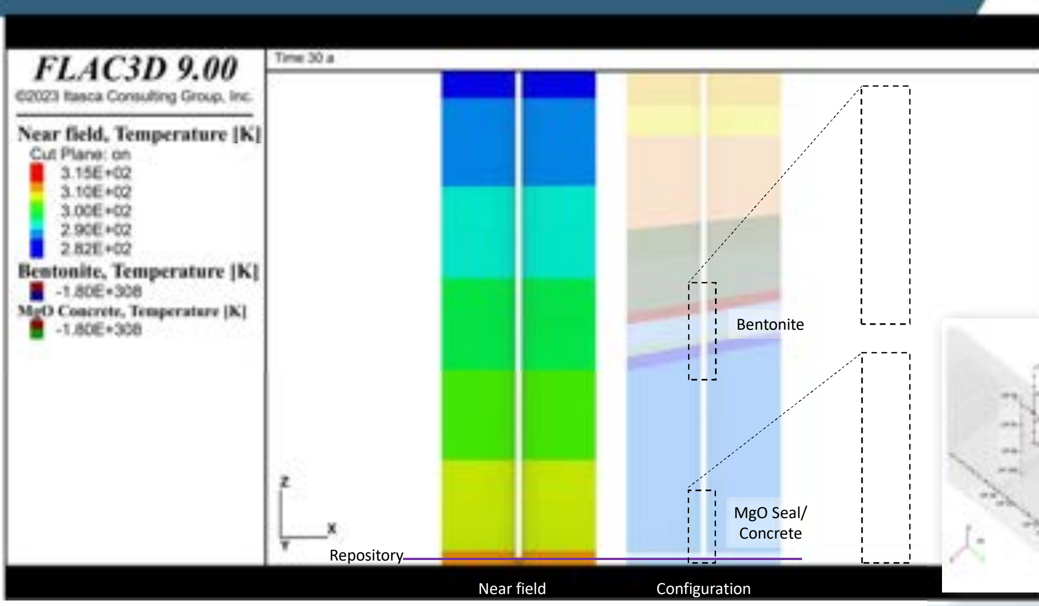



Plastic State

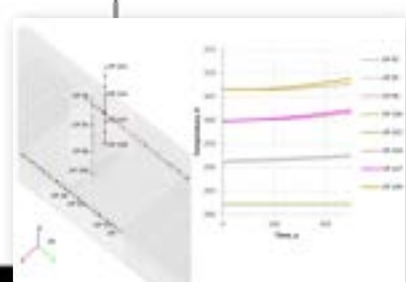
- On seals components only at the onset of the closure phase.

17

## Preliminary Results: Shaft 2




Temperature [K]



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## Summary of the preliminary results

- It is possible to simulate complex in big global models and also by using many constitutive models together
  - It is possible to evaluate shaft (and drift seal) integrity issues due to HLW emplacement within ONE big global model (T-M-coupled analysis)
- Temperature differences don't show a significant impact in the shaft's near field
  - HLW emplacement and induced temperature increase shows a neglicable p until 300a (=actual state of calculation)
- The influence of competent layers has a substantial effect on the system's tension environment
- New features in FLAC3D v9 allow faster calculations



## Outlook

- Interfaces elements to simulate a more realistic behavior in the contact zone of the seal materials and the shaft is going to be implemented
- Evaluation of safety/integrity criteria (sealing body / contact zone / surrounding host rock)


BGE TEC
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
Thank you for your attention!
"Coming together is a beginning.
Keeping together is progress.
Working together is success."
- Henry Ford
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation

# THM Modeling of the Salt Block Heating Experiment

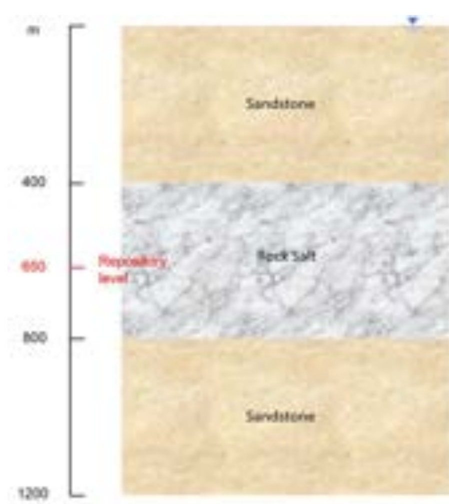
Hafssa Tounsi, Jonny Rutqvist, Mengsu Hu
*Energy Geosciences Division*
*Lawrence Berkeley National Lab, Berkeley, CA, USA*




## Motivation

**Undisturbed rock salt :**

- low porosity ∼ 0.001 ;
- low permeability ≤ $10^{-22}$ m$^2$ ;
- not completely dry : connected porosity + fluid inclusions + non-salt grains (clay) ;
- no groundwater flow.



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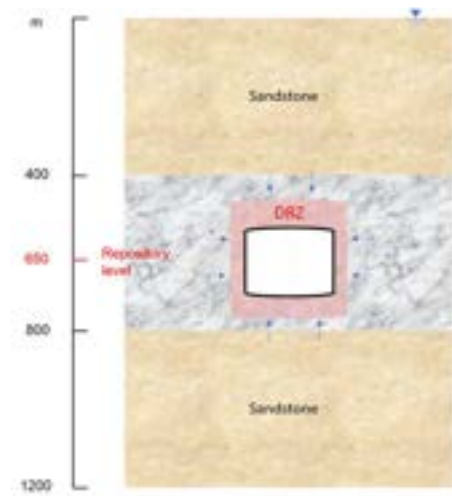




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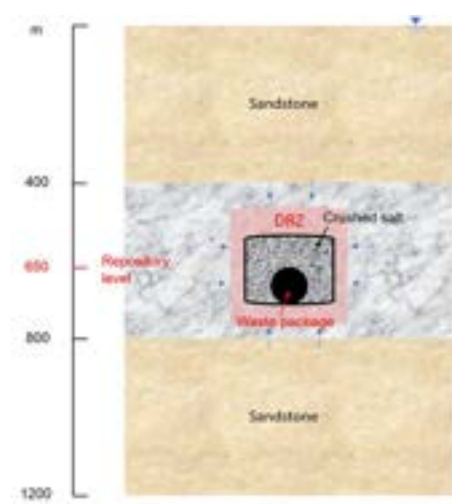

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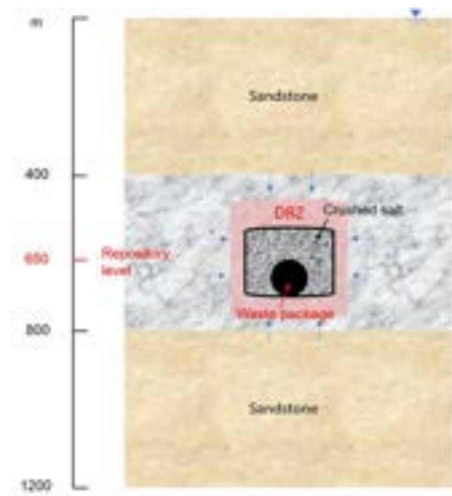
⇒ corrosion of steel waste packages ;

⇒ transport of radionuclides, if released.




5

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**How long ?**
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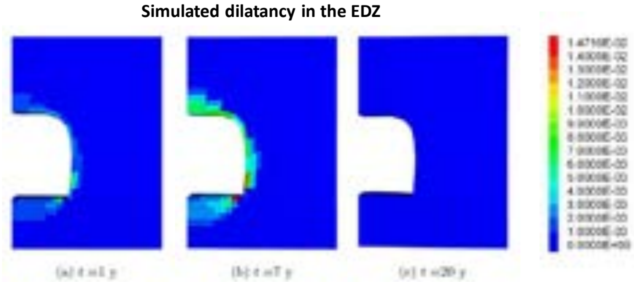
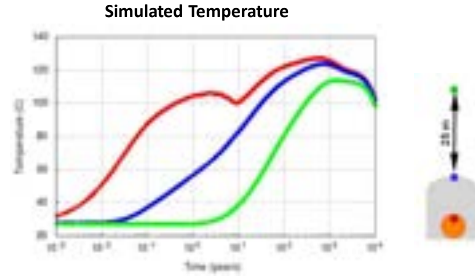
- heating/cooling lasts much longer!

**Simulated dilatancy in the EDZ**



**Simulated Temperature**



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# Motivation

**We need to quantitatively predict the brine flow in a nuclear waste repository in salt rock as a result of excavation, heating/cooling and damage.**

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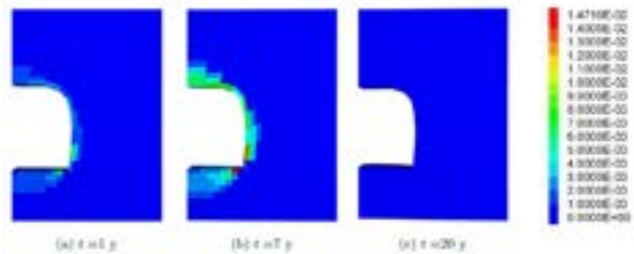

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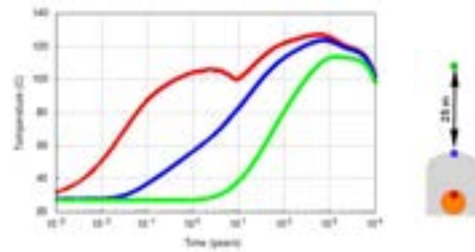


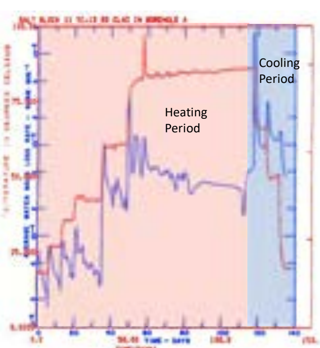


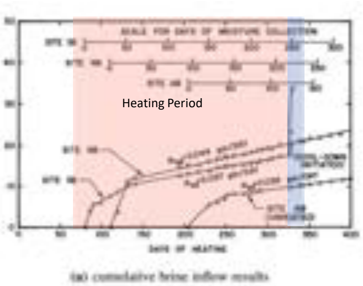
# Motivation

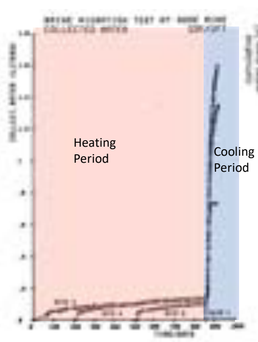
**We need to quantitatively predict the brine flow in a nuclear waste repository in salt rock as a result of excavation, heating/cooling and damage.**

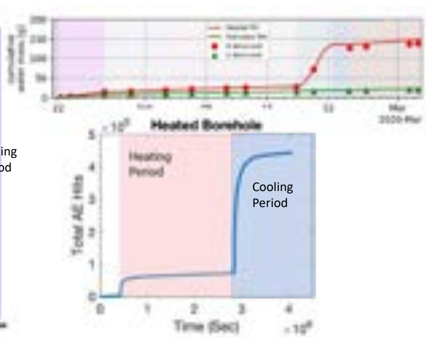
**We need:**

1- to understand THMC processes impacting brine availability;
2- coupled THMC numerical models supplemented with constitutive models of rock salt;
3- experimental data to verify, validate and build confidence in the THM coupled simulations




Salt Block II (lab) (Hohlfelder, 1979) › Avery island (Krause, 1983) › Asse mine ( Rothfuchs, 1999) › WIPP (Kuhlman, 2020)

**Examples of Heated Borehole experiments**

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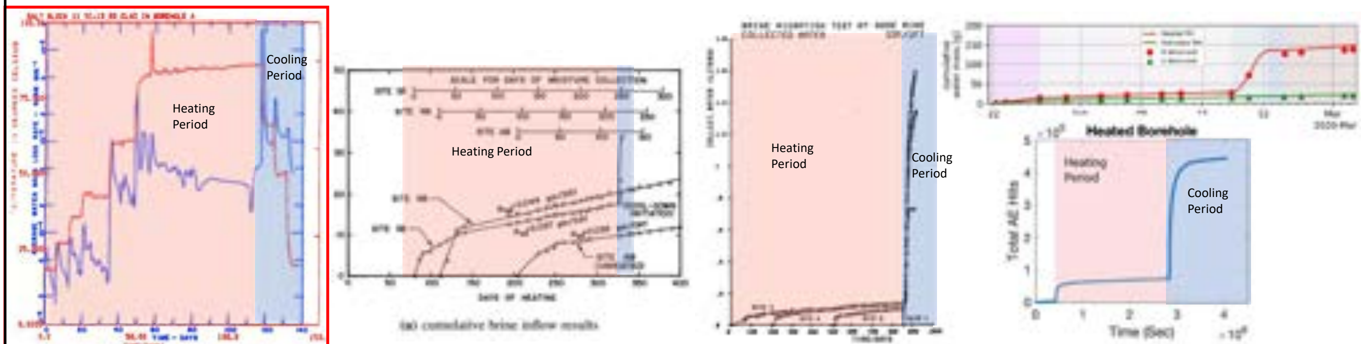



Salt Block II (lab) (Hohlfelder, 1979) → Avery island (Krause, 1983) → Asse mine ( Rothfuchs, 1999) → WIPP (Kuhlman, 2020)

**Examples of Heated Borehole experiments**

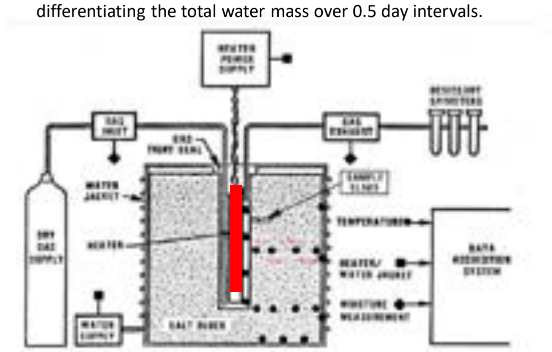


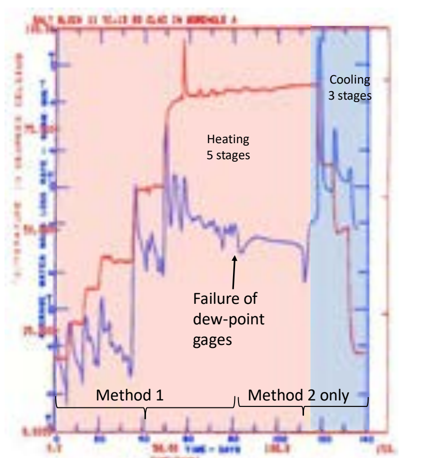
# The SB II experiment

- 1-m cylindrical salt block from a potash mine in New Mexico, USA.
- Axial Borehole of 0.13 m diameter and 0.8 m length.
- Mineralogy ∼ halite (88%), polyhalite (8%), and sylvite (4%) but variability exists.
- Temperature : thermocouples and heat flux gauges
- Brine inflow rate:

  Method 1: measurement, at the inlet & outlet, of temperature, pressure, dew point, and flow rate of nitrogen gas.

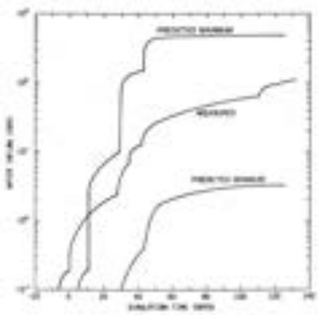
  Method 2: weighing of downstream desiccant canisters and differentiating the total water mass over 0.5 day intervals.



# Why the SB II experiment ?

1. Stepped heating and cooling with a maximum temperature of 200°C near the heater.
2. The good quality of the collected temperature and brine inflow data during heating and cooling.
3. A controlled laboratory setting that is good for model's verification and benchmarking.
4. Previous attempts to model the experiment were not successful and cooling phase was disregarded:
   - Model combining brine inclusions movement and liquid flow through connected porosity without thermal expansion effects *(Ratigan, 1984b)*



N.B. : **Post-Mineralogical Analysis of** the SB:

- No agreement on how far brine inclusions have moved in the SB.

BUT

- Their contribution to the collected amount of water is deemed negligible except within 2 cm of the heater.

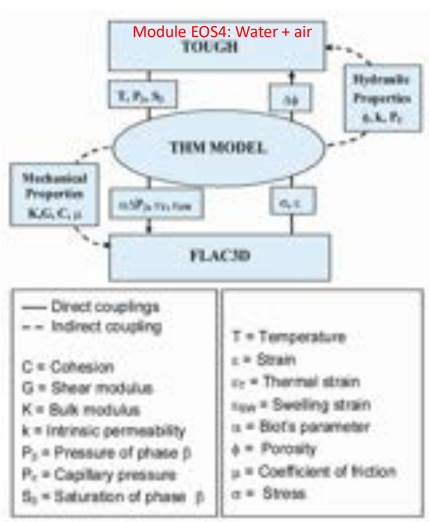
↓

**We only consider brine flow through connected intergranular porosity**

- Thermoporoelastic model using *McTigue (1986)* solution only allowed to reproduce the early brine inflow stages..



# TOUGH-FLAC simulator




## Rock salt constitutive models

- *Lux/Wolters* model (Clausthal University of Technology)

$$\dot{\varepsilon_{ij}} = \dot{\varepsilon_{ij}}^{e} + \dot{\varepsilon_{ij}}^{v} + \dot{\varepsilon_{ij}}^{s} + \dot{\varepsilon_{ij}}^{t} + \dot{\varepsilon_{ij}}^{h}$$

Elastic

Viscous:
-Transient creep
-Stationary creep

Damage due to high shear stresses

Damage due to tensile stresses

Healing due to:
-increase of confining pressure
-closure of micro-fissures

- Evolution of flow properties with damage

➢ Evolution of intrinsic permeability with TM damage

$$\varepsilon_v^{ne} > \varepsilon_{v,0}^{ne} \ : \ k = f\left(k_0, \varepsilon_v^{ne}, \varepsilon_{v,0}^{ne}, \sigma'_{\perp 2}\right)$$

➢ Evolution of intrinsic permeability with H-induced damage

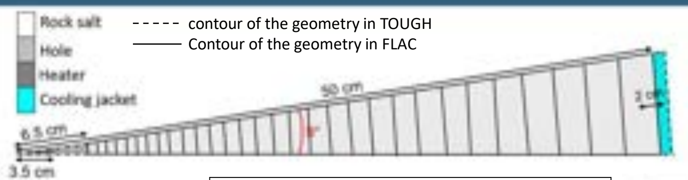
$$k = g(P + \sigma_3 > 0)$$

➢ Evolution of the Biot coefficient with TM damage

➢ Porosity is temperature-, pressure- and strain- dependent.

➢ Leverett scaling of the capillary pressure

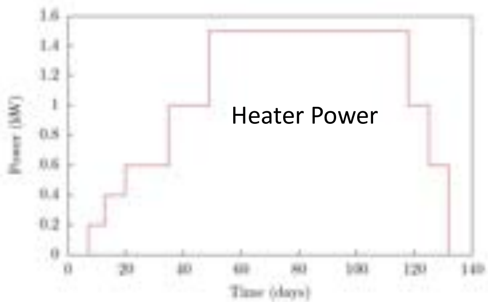
# Geometry and boundary conditions




$\vec{\psi}.\vec{n}$ = h*(T-20) W m$^{-2}$
h=5 W m$^{-2}$ K$^{-1}$ calibrated such that Tmax at heater = 200 °C

P=0.1 MPa
RH=99%

- Initially : P=0.1 MPa, T=20 °C, Sl=99% , σ=-0.15 MPa
- Plane strain assumption
- TH flow in other boundaries is zero

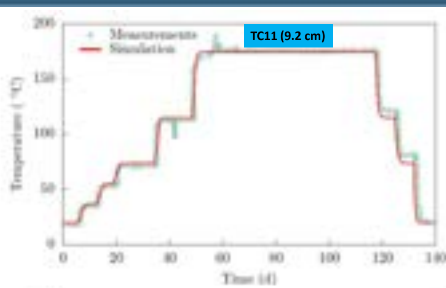


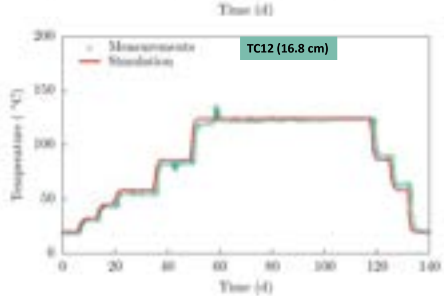

Calibrated against brine inflow rate before heater is turned on.

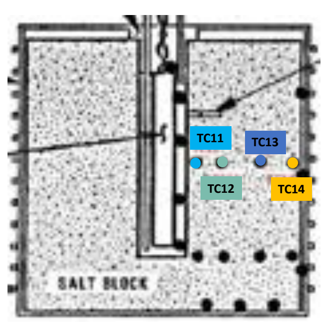
| Property (unit) | Value |
|---|---|
| Solid density $\rho_s$ (kg/m$^3$) | 2154 |
| Initial porosity $\phi_0$ | 0.001 |
| Initial permeability $k_0$ (m$^2$) | $1 \times 10^{-21}$ |
| Dilatancy limit $\varepsilon_{v,D}$ | $9 \times 10^{-4}$ |
| Initial Biot's coefficient | 0.0014 |
| Initial drained bulk modulus $K_{d0}$ (GPa) | 20 |
| Linear thermal expansion coefficient $A_T$ (K$^{-1}$) | $40 \times 10^{-6}$ |
| Corey's residual liquid saturation $S_{lr}$ | 0.05 |
| Corey's residual gas saturation $S_{gr}$ | 0 |
| Van Genuchten's $\mu$ | 0.6 |
| Van Genuchten's $P_0$ (MPa) | 5.7 |
| Van Genuchten's $S_{ls}$ | 0.01 |
| Parameter $l$ of Eq. 19 | 0.4 |

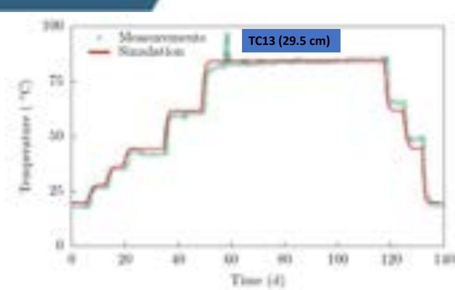


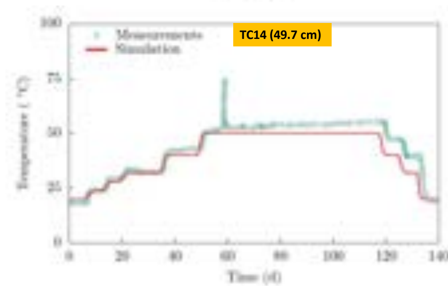
# Temperature evolution




N.B. power outage events during the 4th and 5th heating plateaus were not simulated

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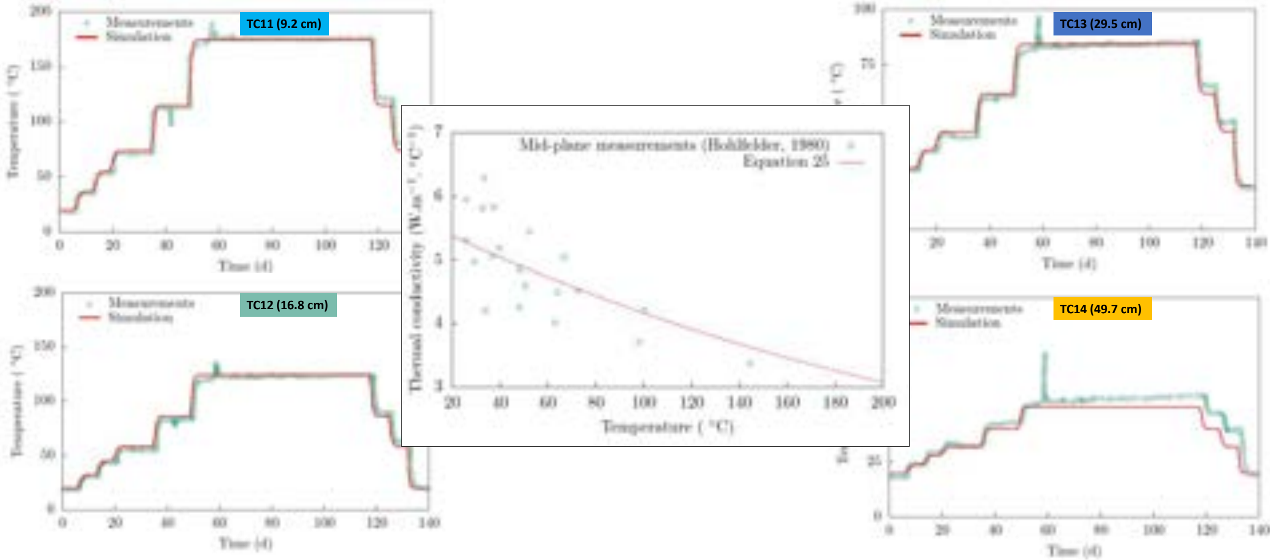


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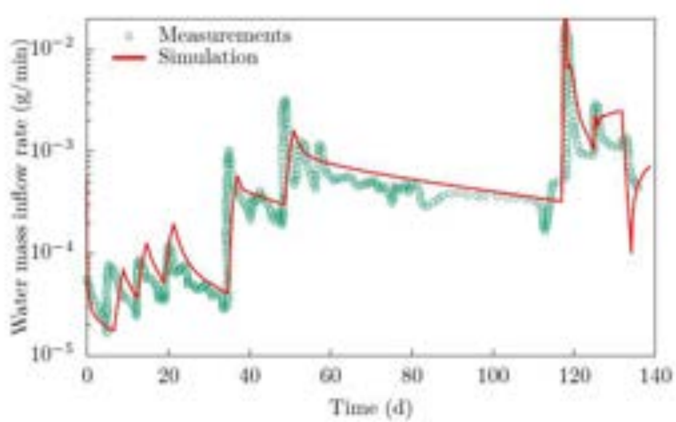
# Brine inflow rate

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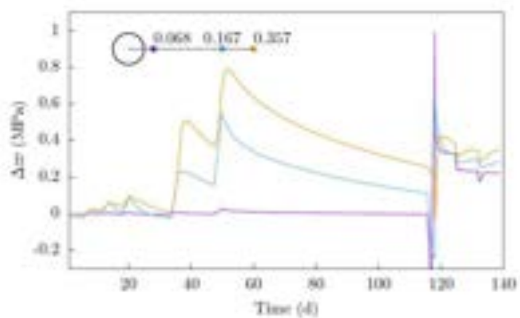
# Pressure changes

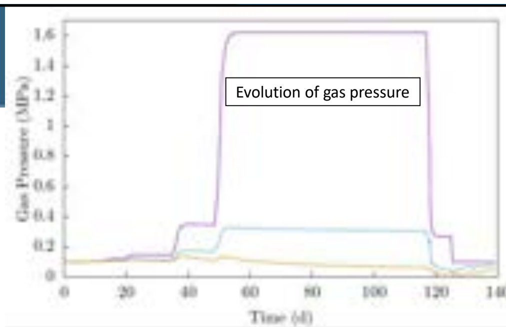
Equivalent pore pressure changes

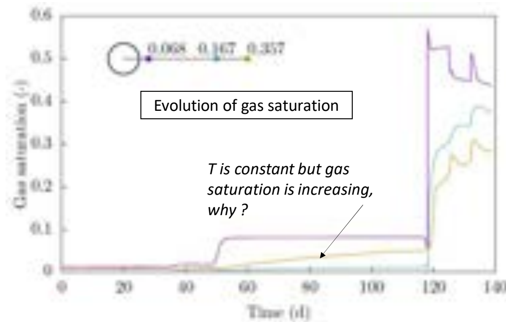



$$\varpi = (1 - S_\Lambda)p_g + S_\Lambda p_\Lambda + \int_{S_\Lambda}^{1} p_c(S)dS$$

Heating
- Thermal expansion of water
- Moderate desaturation near the borehole wall and thermal expansion of air

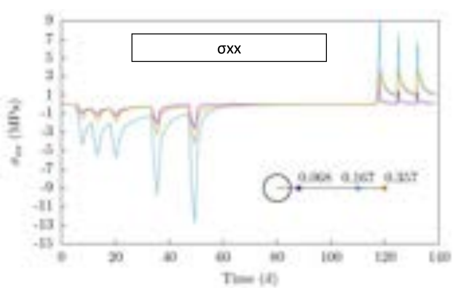
Cooling
- High desaturation, irreversible damage ?

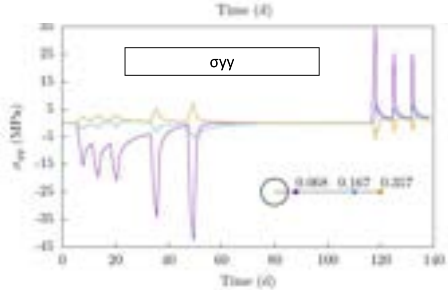





# Stress and damage evolution




Heating

0.068 0.167 0.357

Compressive → Shear dilatancy (starting from the 2nd peak); Healing in the last heating stage after stress drop

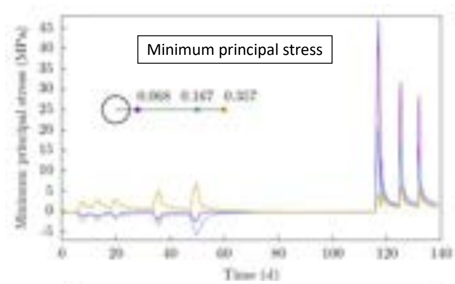
Tensile → Tensile dilatancy

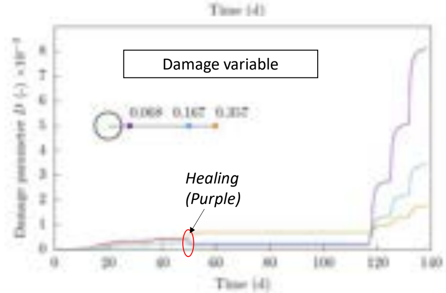
- Shear dilatancy (starting from the 2nd peak)
- Healing in the last heating stage after stress drop

Cooling

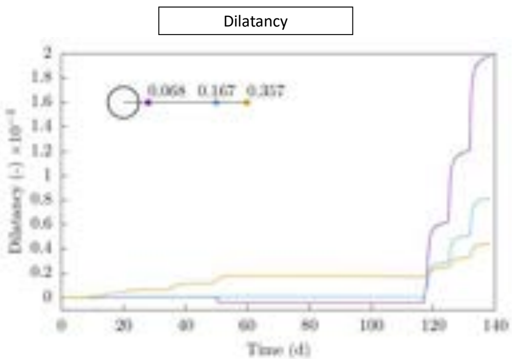
0.068 0.167 0.357

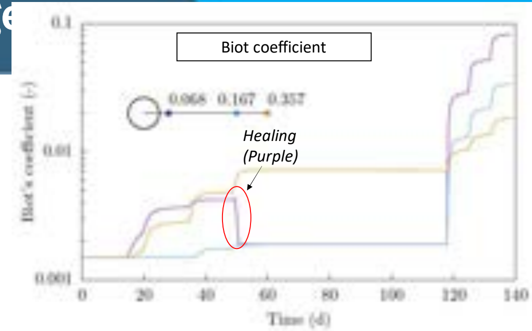
Tensile → Significant tensile dilatancy

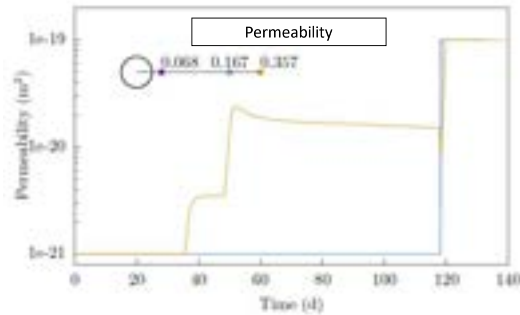


# Evolution of HM properties with damage




Cooling

- increase of the Biot coefficient by a factor of 60 near the borehole wall
- An increase of permeability by a factor of 100 allowed to match the inflow rate data

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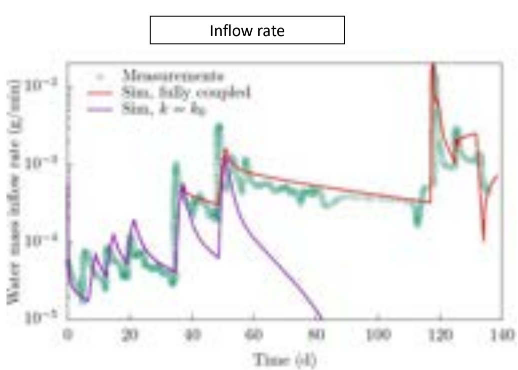
# Conclusions & Perspectives

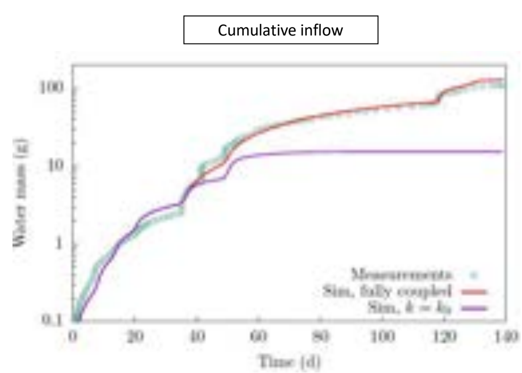
- Thermo-Hydro-Mechanical Simulations:

  We conducted simulations of a salt block multistage heating and cooling laboratory test to evaluate the predictive capabilities of the TOUGH-FLAC simulator.

- Importance of Salt Damage and Permeability Alteration:

  Our simulations highlighted the significance of accounting for thermally-activated salt damage and permeability alteration during dilation, both in compression and tension, to interpret brine inflow observations, particularly during cooling.

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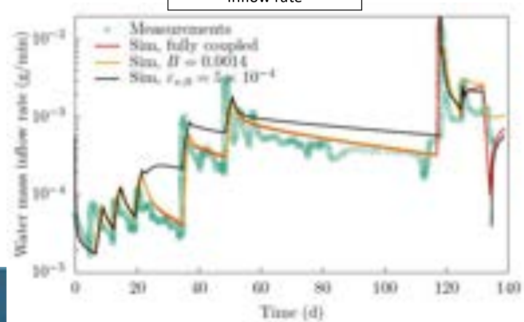
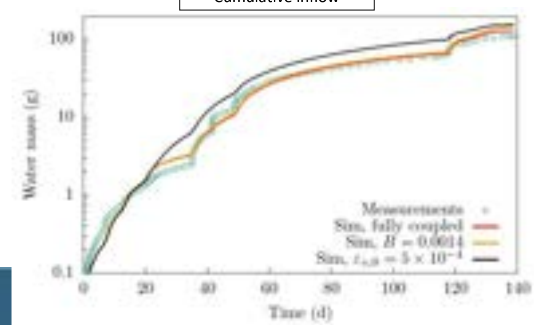
  Further laboratory tests are needed to determine the Biot coefficient and other parameters accurately.

Inflow rate




Cumulative inflow



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- Gradual Cooling Phase:
  Planning and designing a gradual cooling phase instead of a sudden heater turn-off is important, as it better represents in situ conditions in nuclear waste salt repositories.

  A cooling spike is unlikely to happen in a repository given the gentle decay of heat **BUT** the cooling phase allows to validate our models under conditions of significant damage and build confidence in their applicability.

# Thank you!

➢***Content of this presentation and more in our recently published paper:***

Tounsi, H., Rutqvist, J., Hu, M. and Wolters, R., 2023. Numerical investigation of heating and cooling-induced damage and brine migration in geologic rock salt: Insights from coupled THM modeling of a controlled block scale experiment. *Computers and Geotechnics*, *154*.

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# Use of CCO Compaction Simulations in Post-Closure Criticality Screening

Rob Rechard
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Brad Day
Salado Isolation Mining Contractors (SIMCO)

Bret Brickner
Oak Ridge National Laboratory (ORNL)

21 June 2023
13th US/German Workshop on Salt Repository Research
SAND2023-05222O

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## Use of CCO Compaction Simulations to Screening Post-Closure Criticality

- Analysis purpose is to renew evaluation of likelihood of criticality from changes in WIPP inventory
- Analysis directly supports
  - Disposal criteria for CCOs in the WIPP Waste Acceptance Criteria (WAC) (November 2022 revision)
  - Screening of criticality from assessments of WIPP required by US Environmental Protection Agency (EPA)

## Outline

- → Approach and Background: Method for screening out criticality from WIPP performance assessment
- Criticality Study: Modeling neutron transport in compacted CCO array with SCALE and influence of parameters such as hydrogenous material on multiplication factor ($k_{eff}$—index of criticality)
- WIPP WAC: Derivation of waste acceptance criteria for CCOs disposing of contact-handled TRU waste with increased fissile content
- Screening Rationale: Key factors for screening out criticality in CCOs



## Background on WIPP Post-Closure Criticality Screening

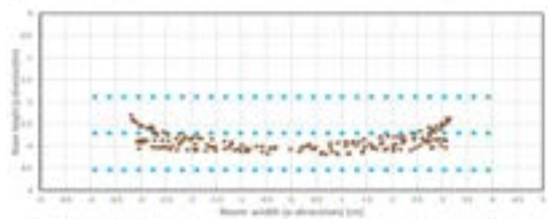
- As room closure from salt creep beneficially encapsulates and isolates TRU waste, the change in waste configuration influences potential for criticality
  - Spacing between containers is not maintained
  - Containers lose structural integrity
- WIPP disposal containers now include criticality control overpacks (CCOs)
  - CCOs can dispose 380 g $^{239}Pu$ (expressed as fissile gram equivalents*)
  - CCOs used to dispose of surplus plutonium material processed to meet WIPP WAC for contact-handled TRU waste
- Assessment of Features, Events and Processes (FEP)—required for Environmental Protection Agency (EPA) WIPP certification—must evaluate evolution of underground and possibility of critical events
  - Most recent in 2019
  - Next in 2024

**Salt Creep Closure of WIPP**

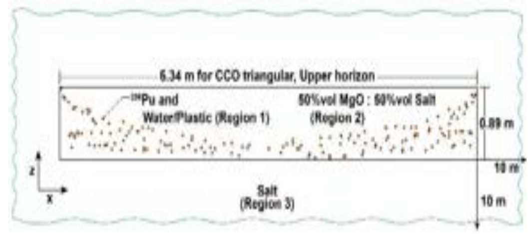
*Pu fissile mass equivalence is the mass of $^{239}Pu$ plus factors for other fissionable masses: For example $0.113 \cdot {}^{238}Pu$, $2.25 \cdot {}^{241}Pu$, $0.9 \cdot {}^{233}U$, and $0.643 \cdot {}^{235}U$.

## Low-Probability Screening Approach Depends on Geomechanical Modeling and Neutron Transport Modeling

Geomechanical modeling of room closure from salt creep predicts spacing of CCOs
—Discussed by Ben Reedlunn



SCALE neutron transporting modeling determines subcriticality of CCO spacing
—Performed by ORNL



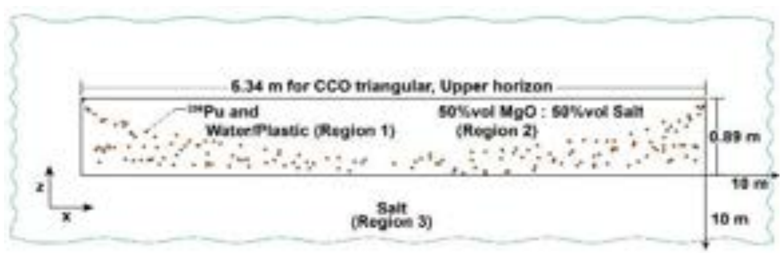



## Outline

- Approach
- ➡ Criticality Study: Modeling neutron transport in compacted CCO array
- WIPP WAC: Derivation of waste acceptance criteria for CCOs with increased fissile content
- Screening Rationale: Key factors for screening out criticality in CCOs

## Criticality model used three material regions

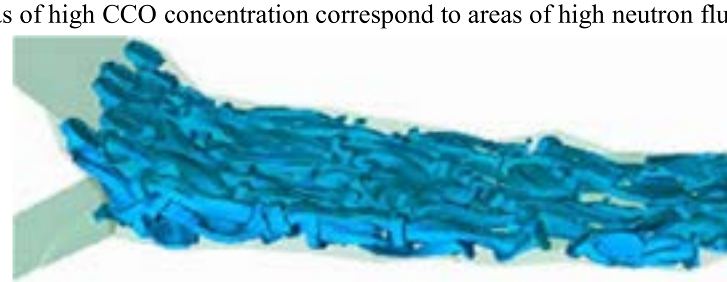
- Region 1: $^{239}$Pu, water, and plastic
- Region 2: Mixture of MgO and WIPP salt
  - Dimensions of Region 2 defined by maximum extent of CCO centers, which changed per geomechanical simulation
- Region 3: 10 m of WIPP salt
- Massive number of CCO simulations run
- Generic analysis that applies to all potential waste streams in CCOs including surplus Pu waste streams from Savannah River Site

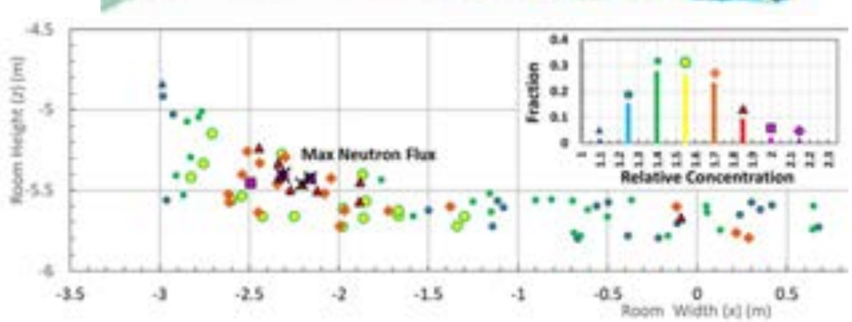




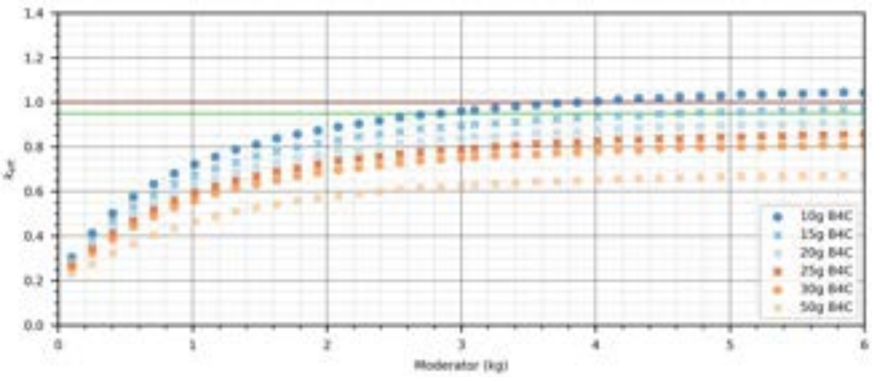

## Wide Variety CCO Spacing and Concentration in WIPP Rooms after Creep Closure

Areas of high CCO concentration correspond to areas of high neutron flux





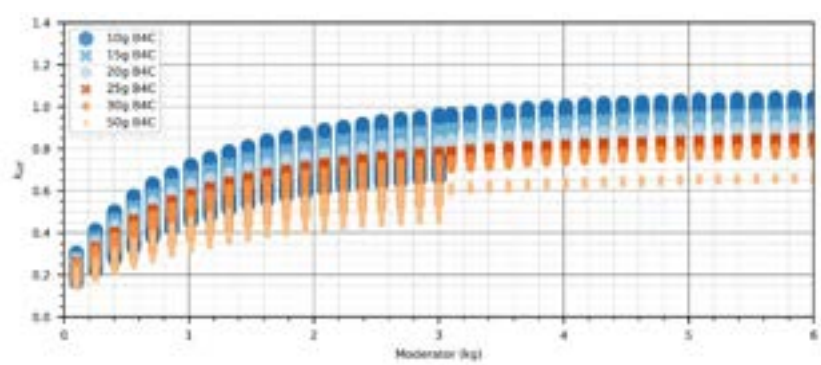
## Boron Carbide Sufficient to Prevent Criticality





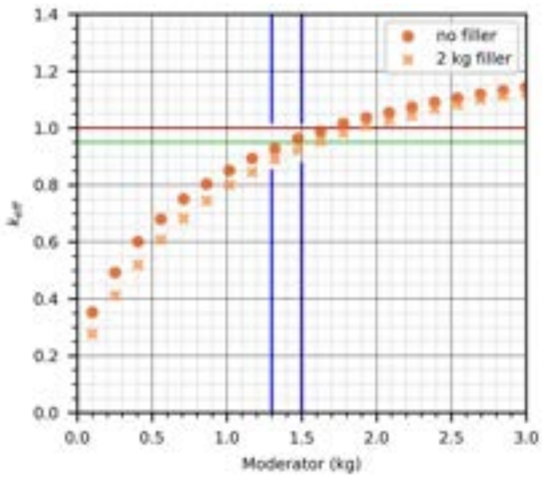

## Boron Carbide Sufficient to Prevent Criticality

- Full range of variation in analysis



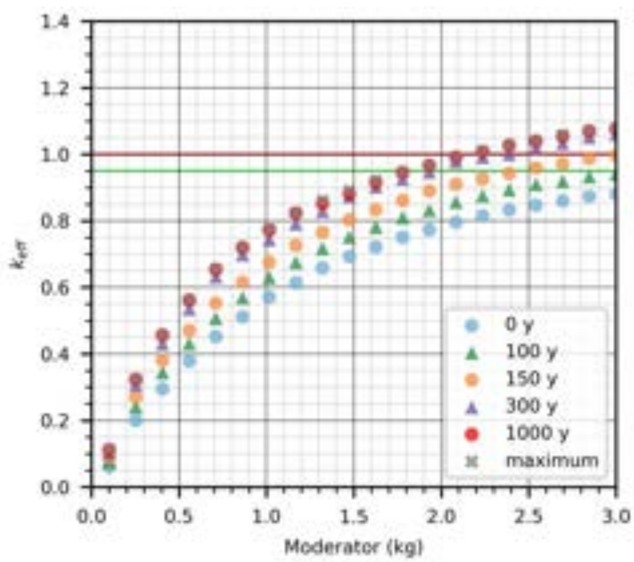
## Limiting Hydrogenous Material Also Prevents Criticality

- Limiting hydrogenous moderator to <1.3 kg prevents criticality after compaction
- Reactivity decreases further if 2 kg miscellaneous filler present

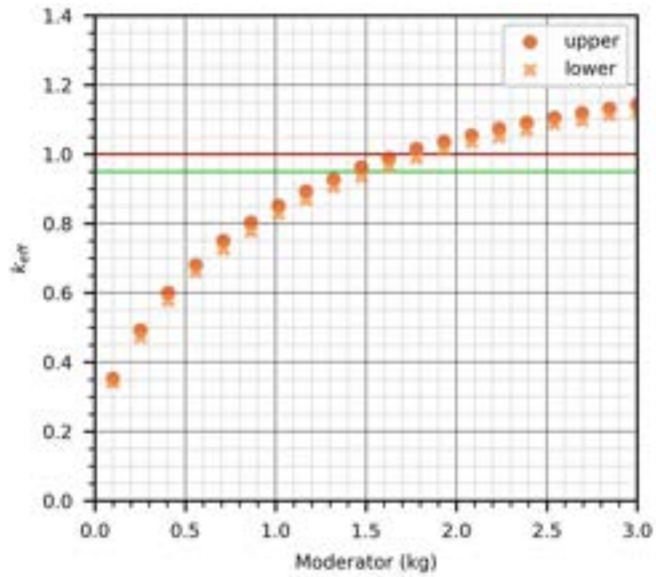





## Room reactivity generally increases monotonically as room creeps closed



## Different Arrangements of Clay Seams in Geologic Strata have only Minor Influence

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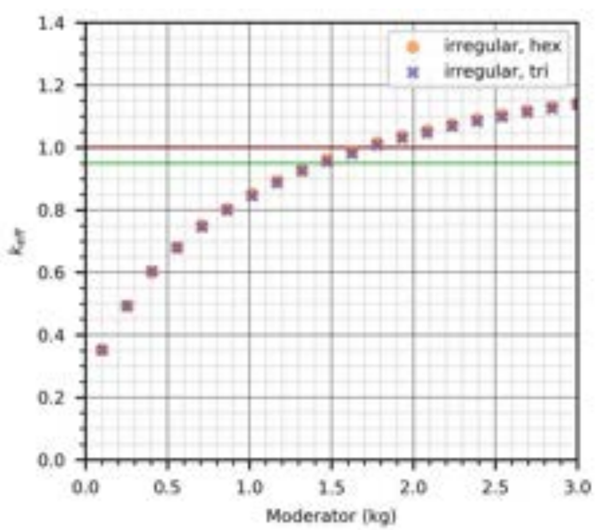
## Initial CCO configuration has only minor influence (hexagonal or triangular)

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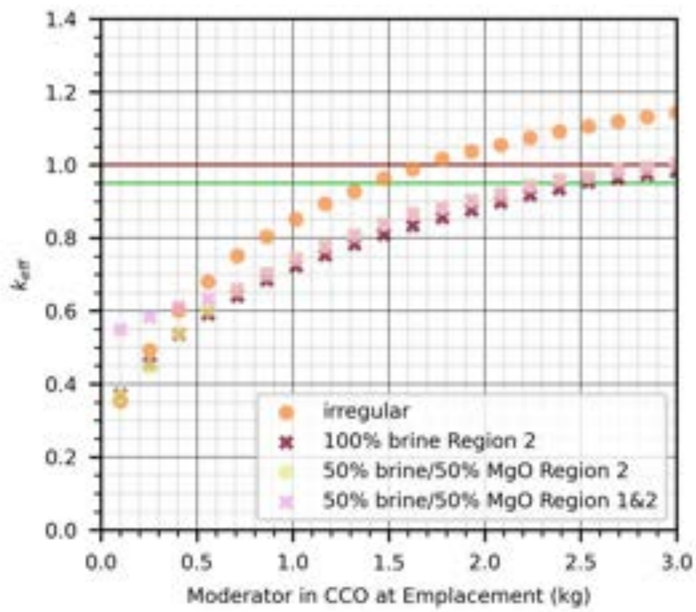
## Brine Around CCOs Reduces $k_{eff}$ by 0.15






## Outline

- Approach
- Criticality Study
- WIPP WAC: Derivation of waste acceptance criteria for CCOs
- Screening Rationale: Key factors for screening out criticality in CCOs

## Supplemental WIPP Waste Acceptance Criteria for CCOs

- Option A applicable to material that has excessive moisture/plastic or lacks pedigree to document necessary acceptable knowledge for disposition
- Options B and C are alternatives for materials with limited moderator
- Options based on generic post-closure criticality safety analysis.
  - $B_4C$ must be well mixed with fissile materials
  - Hydrogenous content includes mass of any organic material and mass of water associated with inorganic material
  - Hydrogenous water/plastic bound by polyethylene plastic
  - Filler must be well mixed with fissile materials and is limited to inorganic, non-hydrogenous materials that is non-fissile and does not contain special reflector.

| Option | Boron Carbide $B_4C$ (g) | Miscellaneous Filler (g) | Hydrogenous Water & Plastic (g) |
|---|---|---|---|
| A | ≥ 10 | -- | <2800 |
| B | -- | -- | ≤ 1300 |
| C | -- | ≥ 2000 | ≤ 1500 |



## Outline

- Approach
- Criticality Study
- WIPP WAC

→ Screening Rationale: Key factors for screening out criticality in CCOs

## Key Factors in Low-Probability Rationale for CCOs

- Rock fall does not cause clustering and create a CCO critical assembly
- Limiting hydrogenous moderator to <1.3 kg sufficient to prevent criticality after compaction of CCOs from salt creep
- Accounting for >2 kg miscellaneous, non-hydrogenous filler and limiting hydrogenous material to <1.5 kg sufficient to prevent criticality in CCOs after salt-creep compaction
- 10 g of $B_4C$ sufficient to prevent criticality in CCOs after room closure from salt-creep
- Brine around CCOs reduces reactivity
- Additional factors are not necessary to control to ensure improbability of post-closure criticality



## Summary of WIPP Post-Closure Criticality Safety Analysis for CCO Disposition

We develop a low probability argument that room closure from salt creep cannot sufficiently assemble a critical arrangement of CCO, provided hydrogenous material is limited and/or $B_4C$ is included in the CCO

- Approach uses improved geomechanical modeling and updated criticality safety analysis to demonstrate that post-closure nuclear criticality events are improbable
- Spacing of CCOs is determined by geomechanical modeling of room closure
- SCALE neutron transporting modeling uses the geomechanical spacing to determine subcriticality of irregular, compacted array of CCOs
- Acceptable knowledge is used to define waste composition and controls for implementing this approach
- Approach supports packaging of contact-handled TRU waste materials in CCOs with up to 380 FGE with no additional constraints on WIPP operations
- Continued use of $B_4C$ is retained as an option for contact-handled TRU wase with much higher limits for water and plastic

# Backup Slides

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## Criticality Evaluation after WIPP Closure Guided by EPA's Probabilistic Framework

- In *WIPP Land Withdrawal Act*, Congress designated EPA as responsible for implementing its post-closure standard at WIPP
- EPA provides three criteria for excluding FEPs, such as criticality, from the performance evaluation: (1) regulatory fiat, (2) low consequence, or (3) low probability of occurring
- WIPP Project currently identifies 245 FEPs and excludes 152 FEPs in WIPP performance assessment
- We develop a low probability rationale that room closure from salt creep cannot sufficiently assemble a critical arrangement of CCO provided hydrogenous material is limited or $B_4C$ is included in the CCO

## Past Approaches to Screening Criticality

- In 1996 Compliance Certification Application criticality was screened out for typical TRU waste packaging (e.g., 55-gallon drums containing debris waste)
  - Analysis was based on 325 g $^{239}$Pu limit in TRUPACT-II (Rechard et al., 2000)
  - PA porosity surface, based on geomechanical modeling of waste monolith, was used to support screening out criticality for compaction of intact TRU drums (Stone 1997)
- In 2019 Compliance Recertification Application (CRA-2019) criticality was screened out for Pipe Overpack Containers (POCs)
  - Analysis was based on higher 1400 g $^{239}$Pu limit in seven pack groupings of POCs for TRUPACT-II transportation container
  - Rationale combined geomechanical modeling (Reedlunn and Bean, 2018) with criticality evaluations (Brickner, 2019) to determine the effect on reactivity from reduced spacing due to room closure from salt creep (Rechard, 2019)



## Updated WIPP Post-Closure Criticality Safety Analysis for Disposal of CCOs

- In CRA 2019 criticality was also screened out for CCOs containing dilute surplus plutonium
  - Analysis based on much higher 2660 g $^{239}$Pu limit in seven pack group of CCOs for TRUPACT-II transportation container
  - ORNL post-closure criticality safety evaluation suggested to blend 50-g $B_4C$ with dilute surplus plutonium contents in each CCO (Saylor and Scaglione, 2018)
  - Used ultra tight packing of intact array of CCOs (i.e., analysis used worst-case analysis)
  - However, EPA allows reasonable analysis rather than worst-case analysis
- Herein, developed geomechanical model that predicts geometry of fissile material after 1000 years that supports a refined CCO post-closure criticality safety assessment
  - Follows approach for POCs in CRA-2019
  - Provides opportunity to dispose a generic waste in the CCO without adding $B_4C$ provided limited moderator (i.e., moisture and plastic)
  - Addresses operational constraints for disposition of surplus plutonium in the CCO through use of Acceptable Knowledge

## Mean Estimate of Probabilities used to Screen Criticality from PA

- EPA Standard for excluding a FEP, such as post-closure criticality at WIPP, uses a *probabilistic approach* (i.e., $<10^{-4}$ over $10^4$ y) and reasoned qualitative discussion as the basis for the exclusion

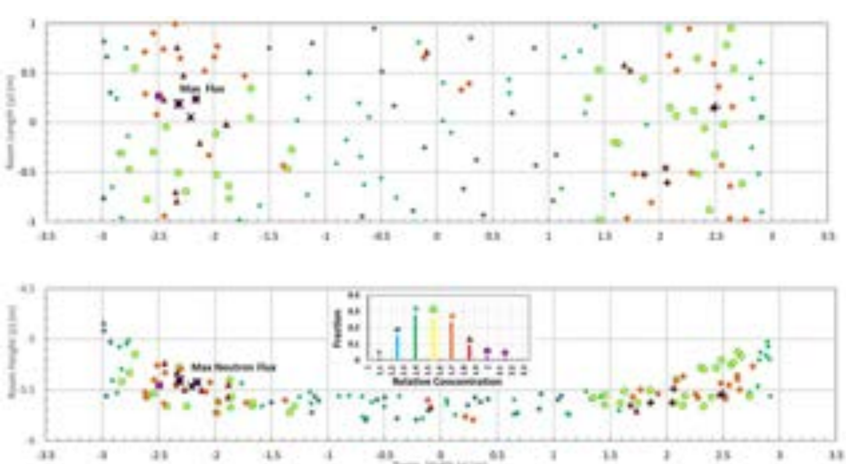
- We provide a mean estimate consistent with reasonable expectation to evaluate compliance with EPA disposal standard 40 CFR 191
  - EPA invokes "reasonable expectation" as the standard of proof for compliance with the Containment Requirements specified in 40 CFR §191.13(a)
  - Reasonable expectation connotes a flexible standard of proof and use of central estimates when encountering unknowns
  - EPA states "…the CCA [compliance certification application] must demonstrate that the *mean* of the population of CCDFs [cumulative complementary distribution functions] meets the containment requirements of §191.13…"

- Use of mean for evaluating the probability of criticality after closure of the repository when personnel are absent, and the nearest humans are separated by 654 m of geologic strata such that consequences are minimal, differs substantially to screening criticality during TRU waste transportation and WIPP operations when humans may be nearby and consequences severe
  - WIPP operations with fissile material (e.g., TRUPACT-II shipments) follow a *rule-based approach* to demonstrate criticality is incredible (ANSI/ANS-8.1).



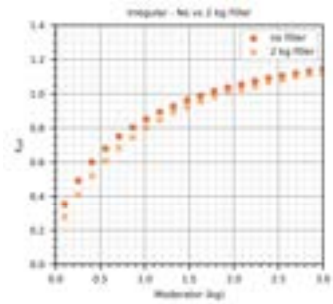
## Wide Variety CCO Spacing and Concentration in WIPP Rooms after Creep Closure

Areas of high CCO concentration correspond to areas of high neutron flux



## Conditions on Criticality Define Supplemental Limits for CCOs for WIPP Waste Acceptance

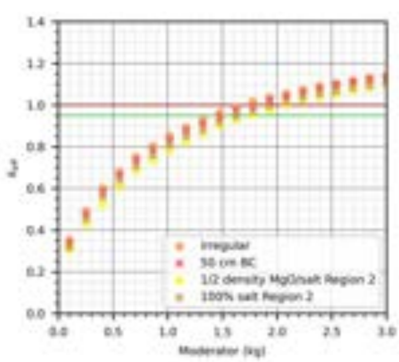
- CCO subcritical with < 1300 g hydrogenous moderator
- Reactivity decreases when adding 2000 g non-hydrogenous filler

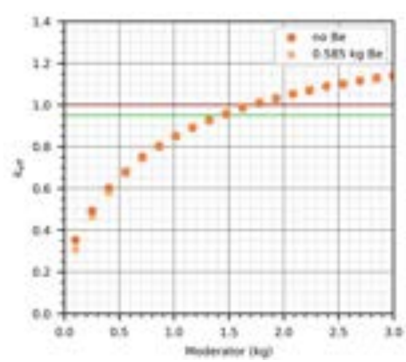


| | | | |
|---|---|---|---|
| A | ≥ 10 | -- | <2800 |
| B | -- | -- | ≤ 1300 |
| C | -- | ≥ 2000 | ≤ 1500 |



## Reactivity and moderator mass not influenced by excess magnesium oxide or presence of beryllium



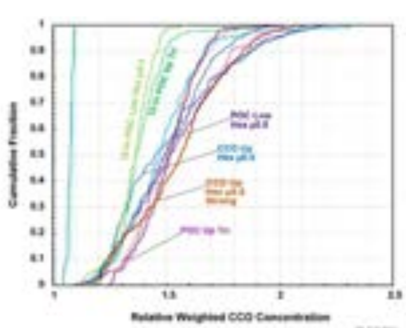
## Using Acceptable Knowledge for Criticality Control

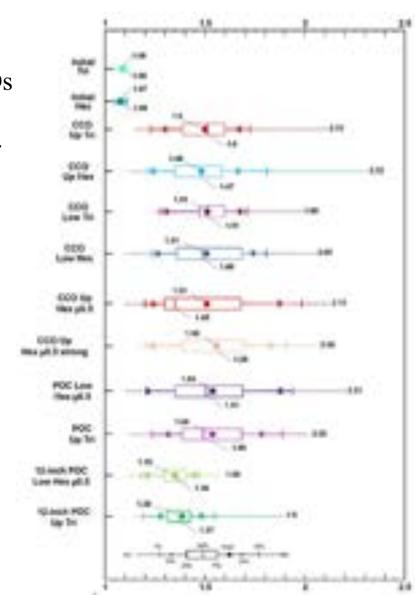
- The updated CCO criticality safety evaluation uses acceptable knowledge to support options for CCOs
- Acceptable knowledge is used extensively to address requirements prescribed by the DSA, TRAMPACs and CRA documents.
- As a point of reference, multiple aspects of waste streams are currently established by acceptable knowledge (e.g., TRUCON chemical list). Examples from CH-TRAMPAC include the following:
  - Residual liquids < 1%.
  - Absence of prohibited items (e.g., explosives, corrosives, and sealed containers greater than 4 liters).
  - Pu FGE mass allowed when special reflectors (i.e., Be) are present – either ≤1% or >1% by mass.
  - Flammable VOCs less than 500 ppm.
  - Locking and bracing of sharp/heavy objects.
  - Manual versus machine-compaction.



## Distribution of CCOs Similar

Geomechanical modeling of CCOs produces a wide variety of deformed spacing between CCOs. *However,* distributions remain similar





# SESSION 3: BREAKOUT

## Uncertainties in Modeling and Verification (BenVaSim 2)

Chair: Oliver Czaikowski (GRS)

# Session 3: BREAKOUT

## Uncertainties in Modelling and Verification

Impulse presentation: Tuanny Cajuhi (BGR)
Chair: Oliver Czaikowski & Larissa Friedenberg (GRS)




# Agenda

Topic 1: Introduction to BenVaSim issues

Topic 2: Impulse presentation by Tuanny Cajuhi

Topic 3: Q&A, Discussion of impulse speech

Topic 4: Other BenVaSim issues…

## Introduction to BenVaSim issues

BenVaSimI
2017 – 2020
02 E 11567A+B

BenVaSimII
2023 – 2026
02 E 12022A+B

Leading organisation: TU Clausthal

Partner organisations:

- Title: Benchmarking for Validation and Verification of THM Simulators with special Regard to Fluid Dynamic Processes in Repository Systems
- Focus: Detailed investigation of basic processes which are included in mostly all THM-coupled simulations, stepwise increase from analytical solutions to complex THM-coupled problems

➢ Improved understanding of simulation codes, processes and their couplings

➢ Improvements in implementations, numerical issues,

➢ Important to have a detailed look into the processes

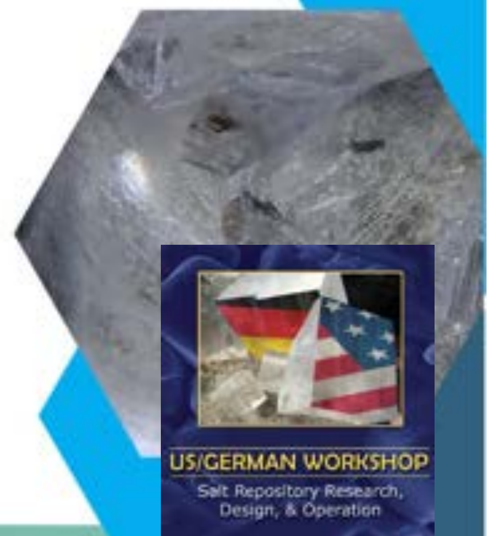


## Impulse presentation

- „Trust & truth in model development"
- Tuanny Cajuhi (BGR)
- Bio:
  - Researcher at the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover, Germany
  - Studied Computational Sciences in Engineering and received her PhD in the field of numerical methods from the University of Technology (TU) Braunschweig, Germany
  - Research interests include coupled thermo-hydro-mechanical phenomena and fracture in porous media, and the connections between experiments, simulations and philosophy

# **Trust and Truth** in model development

Impulse presentation: Tuanny Cajuhi (BGR)




Breakout Session: Uncertainties in Modelling and Verification
Chairs: Oliver Czaikowski & Larissa Friedenberg (GRS)



## Scope & Aims

- Models as instruments we use to think with
- Focus on model adequacy and quality control during the simulation process
- Model interpretation in a context
- Iterative* modeling process and context for action – "good/true enough"
- Epistemology as a whole; not focusing on classic verification and validation (V&V) procedures

## Computer simulation

- Several definitions (narrow, broad, alternative)
- Comprehensive method for studying systems: an entire process [Winsberg 2022]


iterative

- Requires understanding
- Produces understanding

https://www.shutterstock.com/image-vector/process-creative-teamwork-solving-problems-mind-1766876510

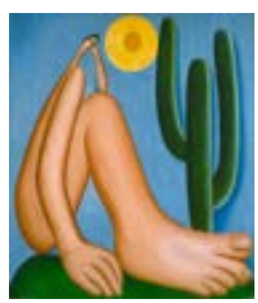
interactive



## Computer simulation: choosing a model

- Science is based on models
- Models are used to grasp reality (think with) [Suárez 2009]
- Models are not mirrors [Hughes 2009, Elgin 2022]
  - Denotation
  - Demonstration (purpose)
  - Inference (manipulation)

- Our objectives
  - set the model's limitations (effective for a purpose) and
  - influence final interpretation.



Abaporu
[Tarsila do Amaral 1928]

O Farol, 1915 Anita Malfatti

O Mamoeiro
[Tarsila do Amaral 1925]

https://www.westwing.com.br/guiar/tarsila-do-amaral/
https://www.wikiart.org/de/anita-malfatti/o-farol-1915

## Discussion & Conclusions

- Felicitous falsehoods are the key to produce scientific understanding
- Accepting them induce action [Cohen 1992]
- Context will never be fully understood, but this should not limit our action.

- "science smoothes curves and ignores outliers […]
  Even the best scientific theories are not true […]
  but where they are successful, they rely on laws,
  models, idealizations and approximations that
  diverge from the truth" [Elgin 2017]

https://www.dreamstime.com/brain-waves-lines-image224188829



## Other BenVaSim issues

Uncertainties in Modelling and Verification:

- **Technical aspects**: implementation of constitutive model, …
- **Numerical aspects**: temporal and spatial discretization, …
- **(Wo)men-made aspects**: input errors, ...
- **Philosophical aspects**: …
- Others?

# SESSION 4: Special Topics

Chair: Jörg Melzer (PTKA)

Nuclear Waste Services

# Progress with Implementation of UK Geological Disposal Facility

**Simon Norris**
**Honorary Professor, University of Manchester**
**Principal Research Manager, NWS**

simon.norris@nda.gov.uk & simon.norris@nuclearwasteservices.uk

# Who we are

Nuclear Waste Services (NWS) is a specialist in the treatment and disposal of nuclear waste. We will build on work delivered over many decades, while adding more essential services for customers in the nuclear energy, defence, industrial, medical, and research sectors.

Our goal is to ensure that waste is managed in a way that protects people and the environment.

**A customer and community focused business with safety at its core**

**A great place to work, where people are respected, included and can perform at their best**

**A centre of excellence to drive and deliver value for the taxpayer**

Part of OneNDA – other companies include Sellafield Ltd, Magnox Ltd.

## Policy for GDF delivery

Local community consent is at the heart of the GDF delivery process and is written into Government policy

- ✓ UK Government policy published 19 December 2018
- ✓ Welsh Government policy published 16 January 2019
- ✓ Scotland is not participating in GDF site selection process (the UK GDF will NOT be sited in Scotland)

To deliver a GDF we need:

1. appropriately packaged waste
2. a suitable site
3. a willing community




# NWS GDF mission:

**To build a Geological Disposal Facility as a permanent solution for the UK's higher activity waste, where there is a suitable site and a willing community.**

**Communities are at the heart of the siting process and no community will get a GDF without a demonstration of its willingness to host one.**

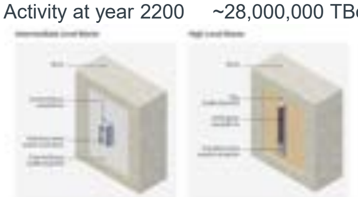
**Safety is also at the heart of all we do. We will not build a GDF unless we are confident of its safety. This requires a lot of scientific & engineering expertise**

# Waste types for the GDF

[2019 Inventory for Disposal]

Volume of waste once packaged:

- Disposal containers ~ 178,000
- LHGW ~ 694,100 $m^3$
- HHGW ~ 78,900 $m^3$
- **Total ~ 773,000 $m^3$**
- Excavation ~10 million $m^3$
- Activity at year 2200 ~28,000,000 TBq



Higher Activity Wastes (HAW) = HHGW + LHGW

GDF = disposal solution for UK's HAW

High heat generating wastes (HHGW)

- High Level Waste (HLW)
- Spent Fuel (SF)
- Mixed Oxide Fuel (MOX)*
- Plutonium (Pu)*
- Highly Enriched Uranium (HEU)*

Low heat generating wastes (LHGW)

- Intermediate Level Waste (ILW, subdivided into Shielded ILW - SHILW - and Unshielded ILW - UILW)
- Some Low Level Waste (LLW, with Shielded SLLW and Unshielded ULLW components)
- Depleted, Natural and Low-enriched Uranium (DNLEU)

**10% of the total packaged waste volume accounts for 16GW(e) New Nuclear Build (NB) with an operating life of 60 years.**

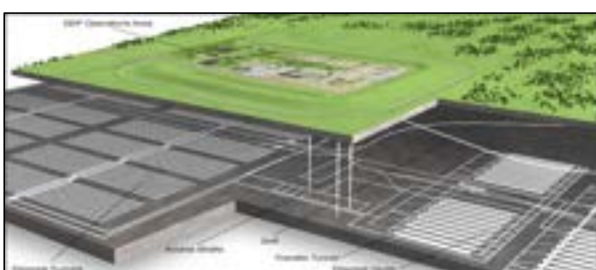
GDF

Nuclear Waste Services

*Special Nuclear Material SNM = MOX + Pu + HEU



# GDF – Onshore / Inshore



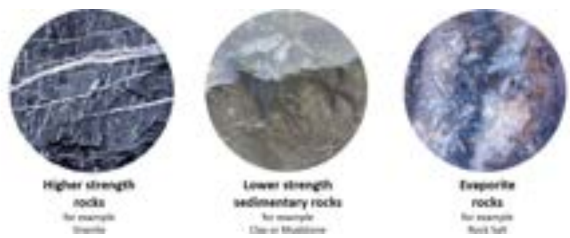
A GDF is a highly-engineered facility specifically designed with the waste and geology in mind, to ensure it is safe, and that it will protect people and the environment for hundreds of thousands of years.

Multiple engineered barriers + deep geological environment working together to isolate and contain the waste => **safety and security over hundreds of thousands of years**

Nuclear Waste Services

# How geology contributes to GDF safety

- An appropriately-sited GDF will provide:
  - Physical separation by a thickness of suitable rock of waste at depth from the surface environment, and therefore from people, flora and fauna (*Isolation*)
  - Stable geological environment through which fluids – water and gas – and any waste-derived radionuclides or non-radiological pollutants move only very slowly if at all (*Containment*)
  - Long or no fluid return times to surface environment from GDF, now and in the future, to 1 million years (*Containment*).
- In siting the GDF, we need to understand the natural system, changes we make to it by building the GDF and emplacing waste, and system evolution to 1 million years.



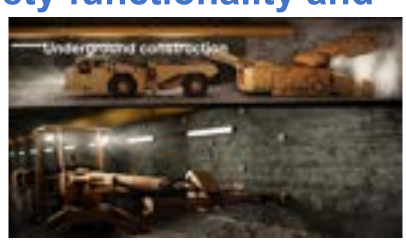

GDF

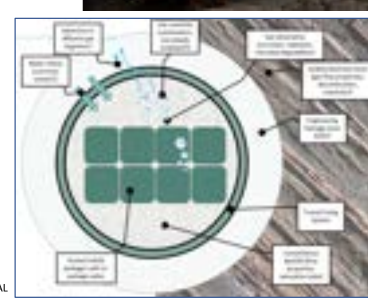
Nuclear Waste Services





# Construction and operations – how to build a GDF, influence of build approach on safety functionality and GDF evolution post-closure

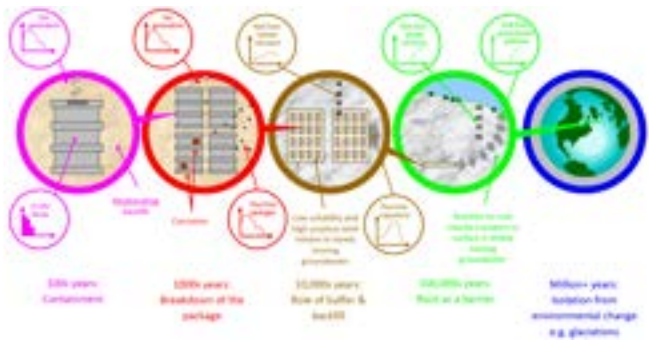




GDF

Nuclear Waste Services

# Evolution of GDF – what matters?



Also consider natural evolution of site, including seismicity, long-term natural climate change and implications of e.g. glaciation, ice-sheet evolution on GDF performance

- **Thermal (T)** – waste & rock temperature evolution. Affects H, M, G, C.
- **Hydrogeological (H)** – desaturation and resaturation of host rock, saturation of EBS and waste (affected by T, M, affects C, G). Is groundwater movement likely?
- **Mechanical (M)** – evolution of vaults, tunnels, waste packages etc. as GDF-related stress field evolves over time (voidage?). Affected by T, C; affects H,
- **Chemical (C)** – evolution of waste chemistry, EBS chemistry, host rock chemistry. Affected by H, T, affects H, M, G.
- **Gas (G)** – gas evolution. Affected by H, T, C, affects H, M.
- **Biological (B)** – influence of microbiology. Affects G, H, affected by T, H, C.
- **THMCGB Coupled Processes**

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# UK Safety Case Context

Generic Disposal System Safety Case:

- Provides evidence that higher activity waste inventory can be disposed of safely
- supports disposal facility siting process
- informs and directs ongoing science and technology programme
- acts as a vehicle for engagement with regulators and other stakeholders
- provides a basis for advice on the disposability of waste packages being conditioned and packaged now
- In the absence of a site and specific disposal facility design, a generic safety case is challenging!


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# UK GDF Siting Process

**As at April 2023**

## Hosting a Geological Disposal Facility can provide a major long-term sustainable community opportunity

A Geological Disposal Facility (GDF):

- Is a nationally significant infrastructure project that can be a catalyst for transforming the socio-economic vitality of a community
- Creates an opportunity that will provide investment over the long term in infrastructure, and support the creation of hundreds of jobs and the development of skills over multiple generations
- Can help develop and deliver the host community's vision for their area
- Can only proceed if the local community provide their explicit consent through a 'Test of Public Support'

## Siting Process

GDF siting factors



## Finding a willing community

We have four communities who want to work with us to explore the implications and benefits of a GDF:

- **Copeland** – two Community Partnerships
  - Mid Copeland formed November 2021
  - South Copeland formed December 2021
- **Allerdale** – Community Partnership formed January 2022

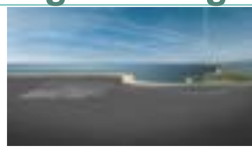
Potential host rock – Mercia Mudstone Group – interbedded mudstone & evaporite sequence

On 1 April 2023, the new Cumberland Council started to begin providing services to residents living in the current Allerdale, Carlisle and Copeland areas.

- **Theddlethorpe** – Community Partnership formed February 2022

Potential host rock – Jurassic clays (akin – but not identical - to host rocks in French and Swiss programmes)

## Finding a willing community



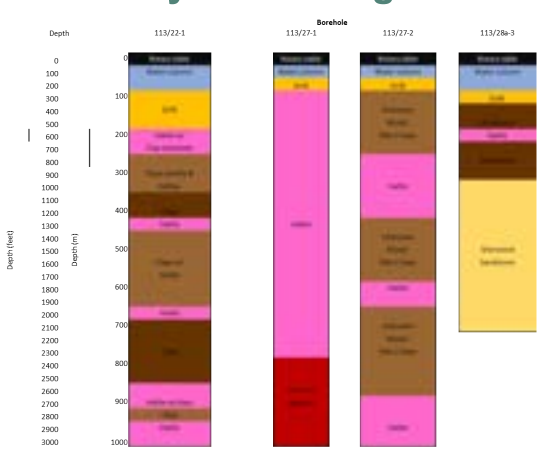
Copeland

Allerdale

Theddlethorpe



## Summary of Existing Information – Boreholes (top 3000ft)




- High lithological complexity
- High lateral variability

## Mercia Mudstone Group – UK analogue core samples
## (Potential Host Rock in Cumbria - Lower Strength Sedimentary Rock)

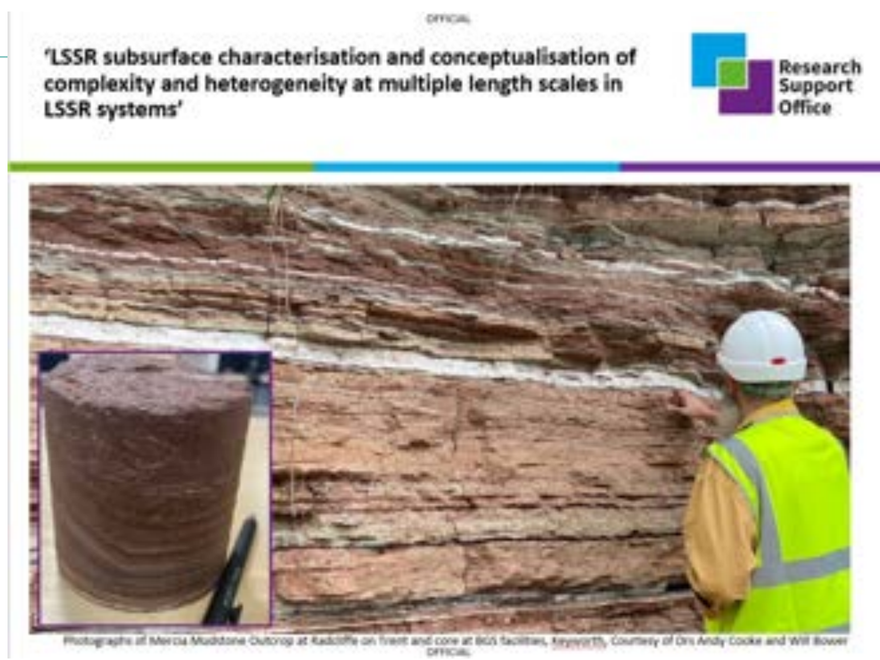
- Complex stratigraphy containing mudstones, siltstones, fine sandstones, halites and other evaporites (e.g. anhydrite). Developing understanding via studying other UK MMG deposits:

Hambleton 302-305 m below ground level (bgl) (North Yorkshire)

Thornton Clevereleys 276-277 m bgl (Blackpool)

Northwich Victoria Infirmary 1 118.3-119.8 m bgl (Cheshire)





# Ancholme Group – UK analogue core samples

## (Potential Host Rock in Lincolnshire - Lower Strength Sedimentary Rock)

- Simpler stratigraphy containing mudstones/siltstones. Potential for high organic content in the Kimmeridge Clay Formation. Developing understanding via studying other UK Jurassic Clay deposits:

**Oxford Clay Formation**
Marchwood 1 ca. 1000 m bgl (Southampton)

**Kimmeridge Clay Formation**
Elm Tree Farm, Kirby Misperton 128.75-129.5 m bgl (Yorkshire)

**Kimmeridge Clay Formation**
Swanworth Quarry 425.5-426.8 m bgl (Dorset)

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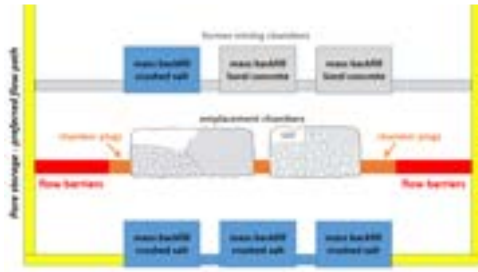
# Current NWS halite-related R&D work programme and future considerations

## NWS funded BGE to undertake literature review

- Provided an overview of each salt repository in Germany and the approach to backfilling in salts (Morsleben, Asse II salt mine, and the former Gorleben exploratory mine)
- Includes use of hydraulic cage concept at Asse II salt mine (create permeable zone to bypass waste emplacement areas)
- Provides an overview of materials employed (crushed salt, magnesia binders, salt concrete)
- Provides an example of a low permeability cement plug/seal system employed at Asse II (i.e. “flow barriers”)

*Backfilling of ILW a Morsleben with dried crushed salt.*




*Hydraulic cage concept applied at Asse II.*

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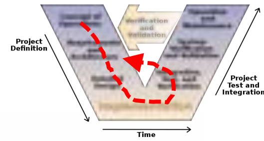
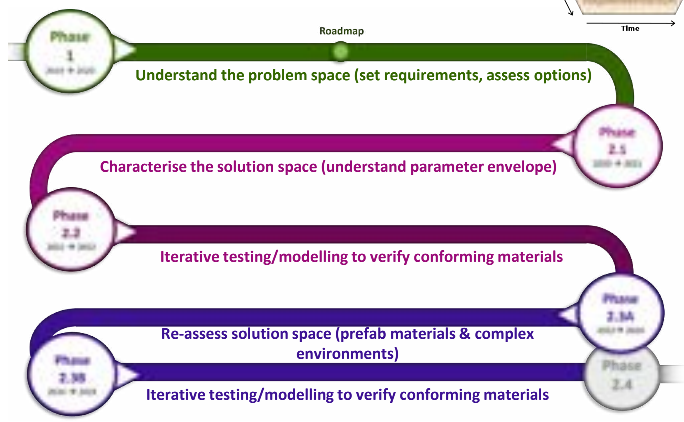
# LHGW Backfill Development in Evaporite

# Backfill Integrated Project (IP)

# Backfill IP: Aim & Execution

*"To ensure a robust understanding of the options available for backfilling the LHGW areas of a GDF at a suitable level of detail for Tranche 2"*

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# Backfill IP – Evaporite Specific Research

- Optioneering concludes that a salt-cement or Mg-based material for local backfill is most suitable in evaporites to ensure chemical compatibility.
- A review has been produced on Germany's experience of backfilling salt formations.
- Developed salt cement backfill formulations, starting initially with NRVB (OPC-hydrated lime-limestone flour), before moving to OPC-limestone flour formulations. Analysed "fresh" properties.
- Currently reviewing backfilling options for interbedded mudstone/evaporite geological environments

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## Laboratory tests

- Experiments to date have focussed on "fresh properties". This includes:
- Flow times (marsh funnel)
- Flow surface angle (channel flow test). greater angle = greater force applied on waste packages
- Bleed (large columns). Measure standing water
- Future work will focus on "Solid properties" – mechanical properties, permeability etc.

*Marsh funnel test to determine flow time*

*Channel flow test to determine surface angle during emplacement*

*Bleed tests in large columns*

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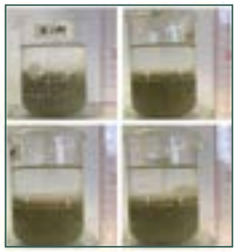
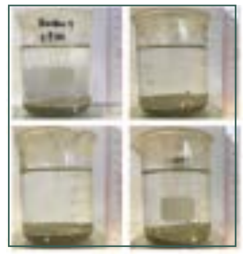
# Bentonite - Salinity Considerations

## Key Concern – Impact of Salinity on Behaviour of Bentonite

- Key issue for Mercia Mudstone Group (MMG) is what the impact of inherent salinity (saline groundwaters) on bentonite safety-related functions would be, were disposal concept to use bentonite.
- Bentonite swelling controlled by electrochemical gradients (i.e. high concentration of cations in interlayer vs low concentration in external pore water.
- Increasing salinity, reduces these gradients, so less draw of water into interlayers).







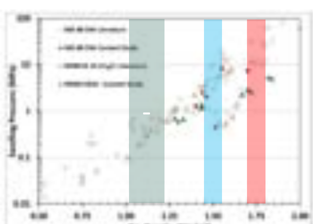
## NWMO results – swelling pressure (optimistic design)

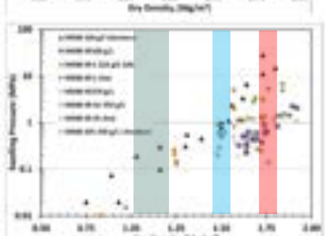
SKB 3-10 MPa (HSR)

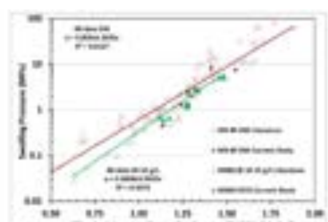
Nagra 0.2 MPa – $\sigma_3$ (LSSR)

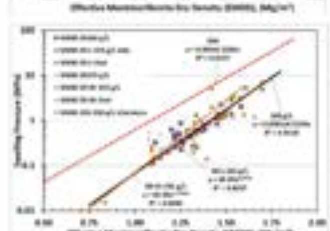
Left figures include MX-80 and 70:30 MX-80: sand mix

Right figures – normalised against montmorillonite content









Pellets GBM Blocks

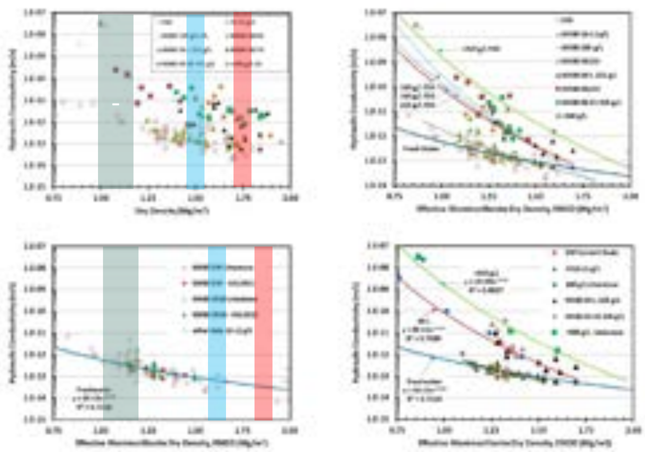
## NWMO results – hydraulic conductivity (optimistic design)

SKB $10^{-12}$ m/s (HSR)

Nagra $10^{-11}$ m/s (LSSR)

Left figures include MX-80 and 70:30 MX-80: sand mix

Right figures – normalised against montmorillonite content



Pellets GBM Blocks

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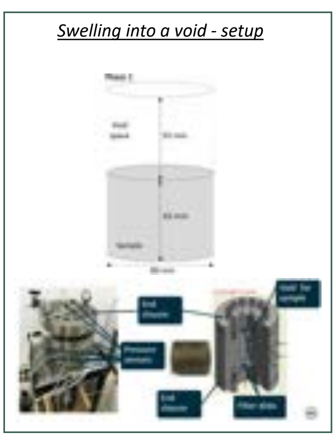
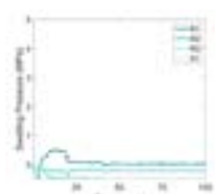
## BGS results- swelling into large void (pessimistic design)



- NWMO = No gap (ideal scenario)
- BGS = gap representing technical void
- Very important to build up datasets from independent teams, via a variety of experimental setups to ensure underpinning is robust

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## The Story So Far for NWS: Bentonite - Salinity Summary

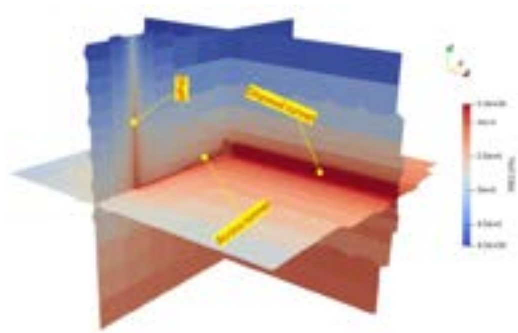
- In ideal scenario (no engineered gaps), the NWMO results indicate bentonite could potentially be used in a UK GDF in Mercia Mudstone Group
- However, research commissioned by the Canadian regulator shows on average 40% lower swelling pressures than NWMO, so there is uncertainty
- In pessimistic scenario (large engineered gaps), the BGS results indicate highly compacted blocks (1.7 $Mg/m^3$) disintegrate/turn into sludge and do not swell
- There is uncertainty and ambiguity in results available so far.
- No work published on the combined impact of temperature and salinity, which are likely to compound and have a greater impact on bentonite swelling.
- Investigations tend to focus on MX-80 bentonite, but there a number of bentonites and they may behave differently



# Fate of Gases in Evaporites

## Gas migration modelling

- NWS is undertaking a series of gas migration models at various scales.
- Aiming to underpin safety arguments in a range of potential host rocks, relating to:
  - Flammability hazard during GDF operations
  - Pressurisation after closure
  - Release of carbon-14
- Models will also help to underpin design decisions (elicitation of System Requirements).
- Conceptual models for gas migration through evaporites and the associated parameterisation for flow models will be reported.

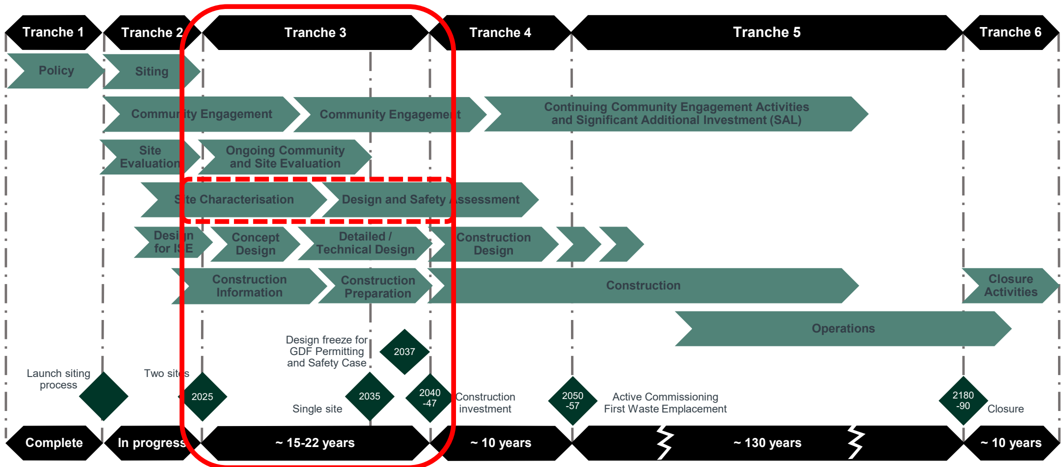




## Summary of UK GDF Siting Process

1. A multi £billion major infrastructure project that will live within a community for over 100 years – huge opportunity to think long-term
2. NWS is committed to working closely with local communities, local authorities and place leaders on this project.
3. Community involvement and support in this consent-based process is essential – must have both a suitable site and a willing community
4. Community visions, developed locally, will shape the project and significant additional investments. Chance to maximise positive impacts in green regeneration and sustainable growth.

# GDF Overarching programme reminder




GDF



ISE. Initial Site Evaluation

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# Thank you

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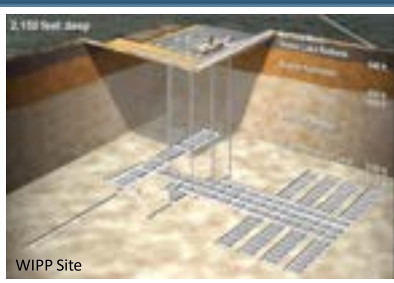
Visit the RSO website
research-support-office-gdf.ac.uk
Email: rwm_rso@comms.manchester.ac.uk

# How to compare different sealing concepts?

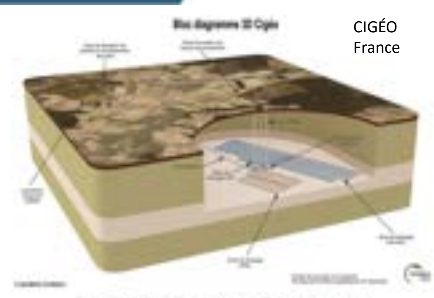

Philipp Herold, Victoria Burlaka, Martin Neuhaus, Hannes Räuschel
BGE TECHNOLOGY GmbH

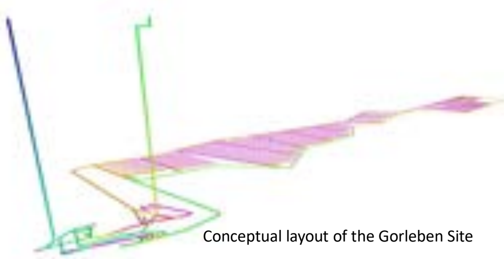
1

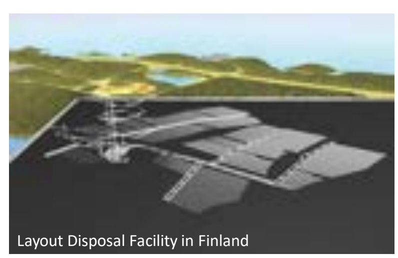
## Surface Connections



WIPP Site


CIGÉO France


Conceptual layout of the Gorleben Site


Layout Disposal Facility in Finland

2

## Arguments for Shaft or Ramp

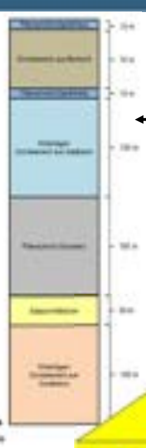
- Decision how to design surface connection is mainly driven by operational and geological/site-specific aspects:
  - depth and shape of the repository
  - geology of the overburden
  - production rate/time
  - expected duration of operating
  - time horizon until production starts (cost factor)
  - running costs for machinery/personnel
  - transport frequency and size of the goods

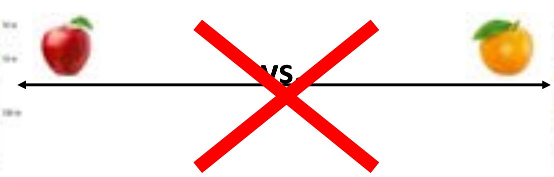
- For GDF, long-term-related aspects and the sealing are relevant as well
- Only limited consideration within the design of the surface connections
- A simplified method how to compare different sealing concepts would support the decision process and allows a comparison of "apples and oranges"



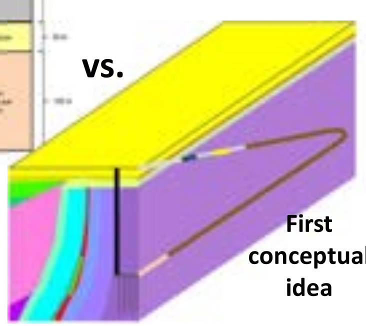
## Conceptual Designs in Salt

Shaft sealing concept for domal formations, based on RESUS project

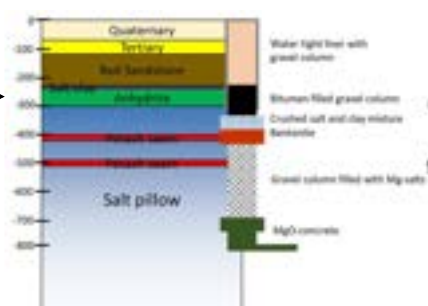





vs.

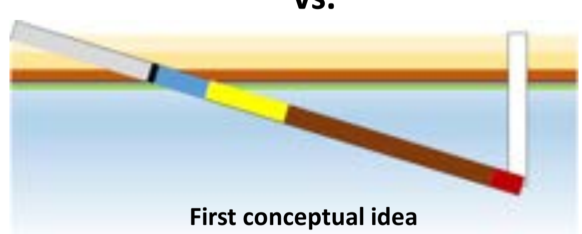


First conceptual idea



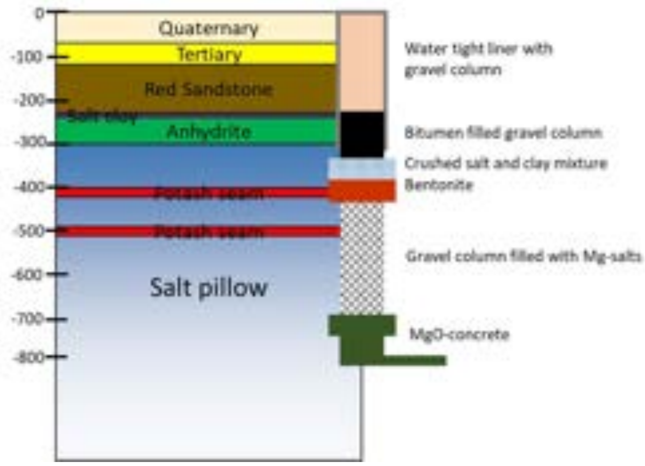

Shaft sealing concept for bedded formations, based on ELSA2 project

vs.



First conceptual idea

# Indicators




**Sequence of elements:**

- Depends on the geological conditions and expert judgement of the designer
- Difficult to access with simplified indicators

**Robustness:**

- Sensitivity of the barriers to internal and external impacts
- Assessment possible in combination with the performance targets

**Sealing capacity:**

- Seals within surface connections have to limit potential flow into or out of the underground facility
- Tightness/penetration time/flow time can be evaluated

**Retention capacity:**

- Different sealing materials provide different retention capacities (e.g. sorption) against different nuclides
- E.g. smectite mass of bentonite as first indictor
- How to assess concrete?

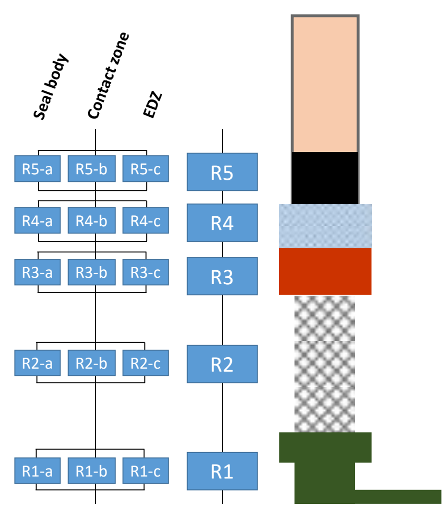
**Technical feasibility:**

- Constructability of the sealing elements
- Have to be considered in the design, shouldn`t be part of the assessment



# Sealing Capacity

- Sealing capacity of a shaft/ramp can be described by the hydraulic resistance of the construction
- Assuming Darcy flow, properties of the solution and the seal define the resistance:
  - Viscosity of the solution
  - Permeability
  - Length
  - Cross-section
- Different sealing elements are combined in series
- Seal body, contact zone, and EDZ can be represented by parallel circuits




Example: Shaft sealing concept for bedded formations, based on ELSA2 project

# Sealing Capacity

- Time until solution passes the full sealing:

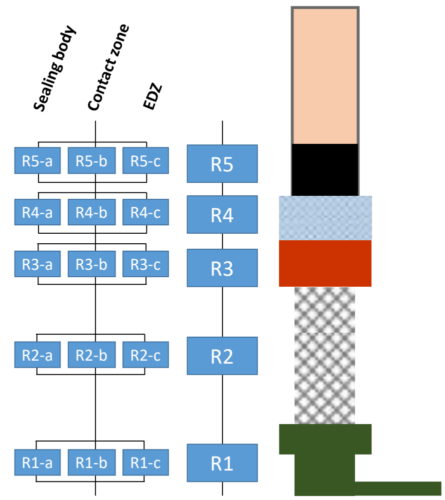
$$t_B = \frac{R}{\Delta p} * \sum_{i}^{N} L_i * A_i * \eta_{eff,i}$$

- Compared with an assessment period, the ratio can indicate the performance:

$$\frac{t_B}{t_{limit}} < 1$$

- The assessment period is specific to the shaft/ramp seal

*„The maximum functional period of the sealing system is limited by the occurrence of the next ice age, which, according to long-term geological forecasts, will occur in about 50,000 years."* (Müller-Hoeppe et al., 2012)

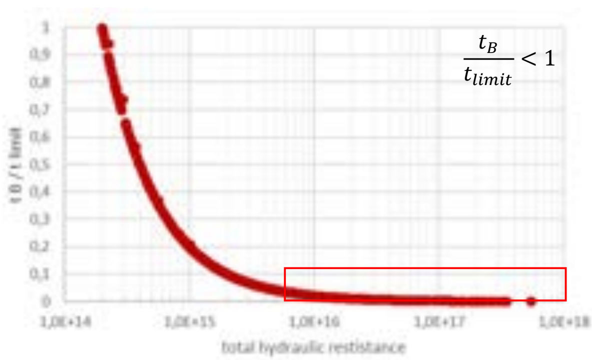


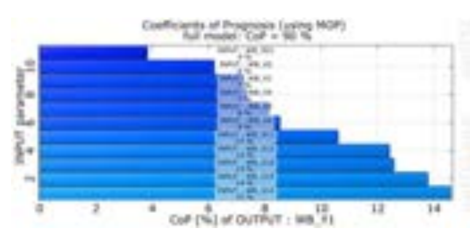

Example: Shaft sealing concept for bedded formations, based on ELSA2 project

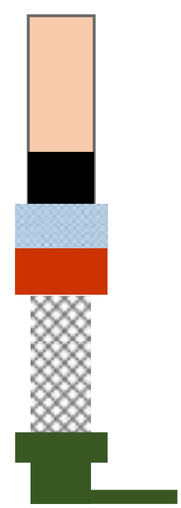


# Sealing Capacity

- Variation of parameters allows a comparison of <u>configurations</u> of the sealing system and identifies the significant impacts
- Configuration = a defined set of parameters (e.g. exact length of all the elements)





Example: Shaft sealing concept for bedded formations, based on ELSA2 project

➢Further increase of the total resistance without significant impact on the performance

➢Especially relevant for a ramp with larger available sealing length

# Retention Capacity

**In general:**

- Solids can absorb substances from their environment (sorption)
- Ability of sorption depends on the material properties and environmental conditions

**Example:**

- Bentonite is a mixture of different minerals, especially the smectites provide sorption capacity
- Smectite mass represents a simple indicator for the comparison of different sealing structures

**Problem:**

- Concrete provides a retention capacity but without smectite
- CSH, Afm, and AFt as most important phases
- Ability of sorption varies with environmental conditions and degradation of the concrete
- Kd value of relevant radionuclides can be used



# Retention Capacity

$RF_i$ = Retention Factor of a specific material and for specific nuclides

$$RF_{IxCs} = \frac{Kd_{Iod} + Kd_{Cäsium}}{\sqrt{I}}$$

$m_i$ = Mass of the sorbent material in the respective sealing element

Basic indicator for Bentonite:

$$MI = \frac{M^S_{Smektit}}{M^R_{Smektit}}$$

Additional materials have to be considered

$$x^{S,R}_{Rück} = \frac{\sum_{i=1}^{n} m_i^{S,R} \cdot RF_i}{n}$$

$$MI_R = \frac{x^S_{Rück}}{x^R_{Rück}}$$

$MI_R > 1$ Shaft is better
$MI_R < 1$ Ramp is better

Assessment Factors

Final Indicator

# Robustness of the Design

**Assessment of the design:**

- How complex is the sealing system?
- Is redundancy given?

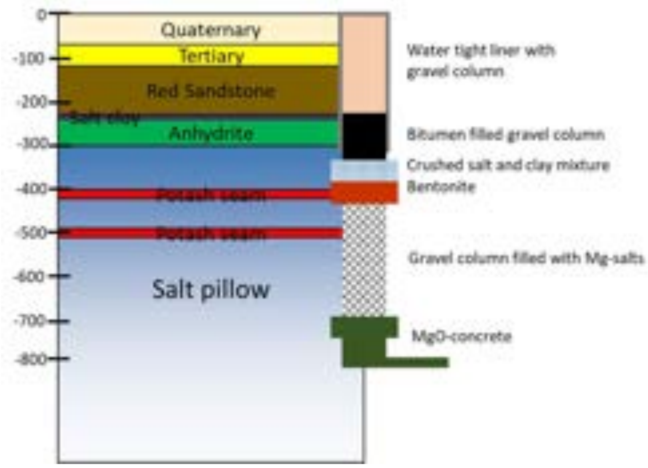
Numbers from 1 to 4:

(1) Simple designs without redundancy

(2) A series of identical sealing elements

(3) Same sealing elements but in different designs

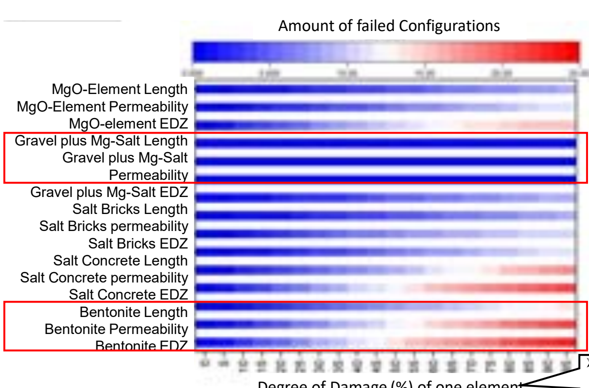
(4) Different sealing materials in different designs of the elements ✓






# Robustness against Changes

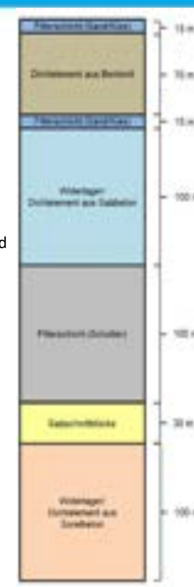
- Safety case and performance assessment of sealing systems also include alternative scenarios
- What if one or more sealing elements fail or properties change?




- The sealing concept (right) is one possible configuration
- Changes in length and permeability (performance targets) are possible and can be represented by different configurations
- "Damages" to these performance targets are possible
- Assessment of robustness is possible for sealing capacity and retention capacity

What if?

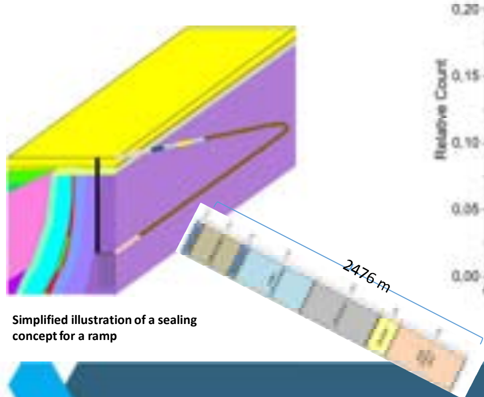
- **For every parameter, a defined range of possible damages is considered, e.g. a certain length or a defined change of permeability**
- **100% damage does not mean total damage of the element!**



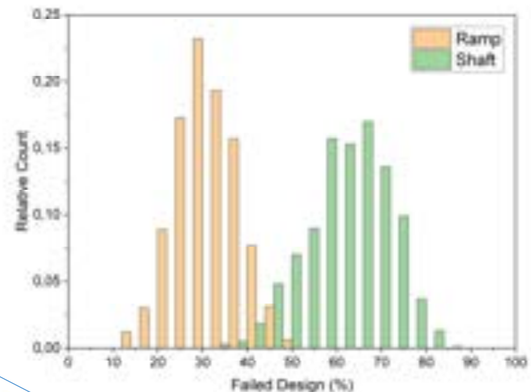
**Example: Shaft sealing concept for domal formations, based on RESUS project**

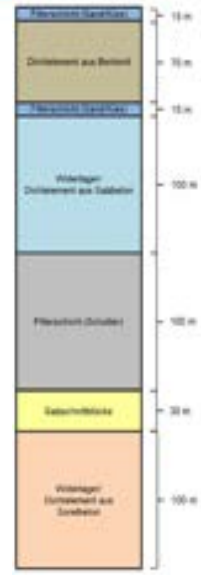
# Robustness against Changes

- What if several elements or components are damaged at the same time?
- How to compare shaft and ramp?




Simplified illustration of a sealing concept for a ramp



Example: Shaft sealing concept for domal formations, based on RESUS project



# Robustness against Changes

- Combination of failures

Damage Configurations

| | 1 | 2 | 3 | ... | $N_D$ | | |
|---|---|---|---|---|---|---|---|

Sealing Configurations

| Sealing Configuration # | $k_1$ | $k_2$ | ... | $k_{N_D}$ | $L_1$ | $L_2$ | ... | $L_{N_D}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | $10^{-19.5}$ | $10^{-17.1}$ | ... | $10^{-1\ .6}$ | 104 | 105 | ... | 28 |
| 2 | $10^{-17.8}$ | $10^{-1\ .5}$ | ... | $10^{-1\ .4}$ | 160 | 89 | ... | 24 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $N_D$ | $10^{-1\ .0}$ | $10^{-17.3}$ | ... | $10^{-15.1}$ | 81 | 95 | ... | 21 |

# Robustness against Changes

- Combination of failures

Damage Configurations

Sealing Configurations

| | 1 | 2 | 3 | ... | $N_D$ | | |
|---|---|---|---|---|---|---|---|

| Damage Configuration # | $k_1$ | $k_2$ | ... | $k_{N_D}$ | $L_1$ | $L_2$ | ... | $L_{N_D}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 27 % | 49 % | ... | 38 % | 7 % | 8 % | ... | 66 % |
| 2 | 73 % | 87 % | ... | 23 % | 2 % | 76 % | ... | 27 % |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $N_D$ | 68 % | 65 % | ... | 88 % | 24 % | 89 % | ... | 28 % |



# Robustness against Changes

- Combination of failures

Damage Configurations

Sealing Configurations

| | 1 | 2 | 3 | ... | $N_D$ | | Normalized sum of damage configurations to fail a sealing configuration |
|---|---|---|---|---|---|---|---|
| 1 | ✓ | ✗ | ✓ | ... | ✗ | $\frac{\sum}{N_d}$ | 0.83 |
| 2 | ✗ | ✓ | ✓ | ... | ✗ | | 0.57 |
| 3 | ✓ | ✗ | ✗ | ... | ✓ | | 0.73 |
| ... | ... | ... | ... | ... | ... | | ... |
| $N_S$ | ✗ | ✓ | ✗ | ... | ✓ | | 0.97 |
| | $\frac{\sum}{N_S}$ | | | | | | |
| Normailzied sum of failed sealing configurations | [illegible] | 0.54 | 0.93 | ... | 0.73 | | |

„In 83% of the damage configurations, the sealing configuration 1 fails“

„Because of damage configuration 1, 81% of the sealing configurations fail“

# Robustness against Changes

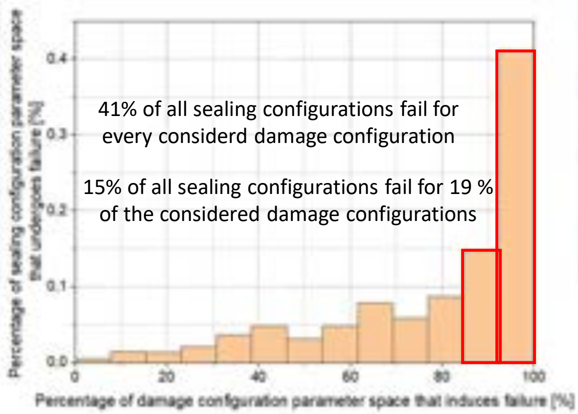
- Combination of failures

Damage Configurations

Sealing Configurations

| | 1 | 2 | 3 | … | $N_D$ | | Normalized sum of damage configurations to fail a sealing configuration |
|---|---|---|---|---|---|---|---|
| 1 | | | | | × | | 0.83 |
| 2 | | | | | × | | 0.57 |
| 3 | | | | | ✓ | | 0.73 |
| … | | | | | … | | … |
| $N_S$ | | | | | ✓ | | 0.97 |
| | | | | | | | |
| Normailzied sum of failed sealing configurations | | | | | 0.73 | | |

$\frac{\sum}{N_d}$






# Robustness against Changes

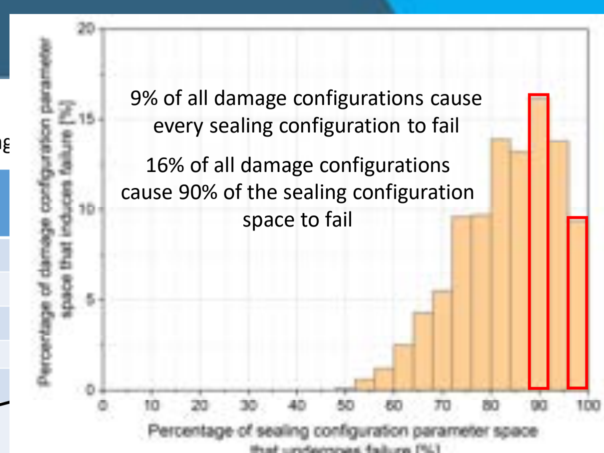
- Combination of failures

Damag

Sealing Configurations

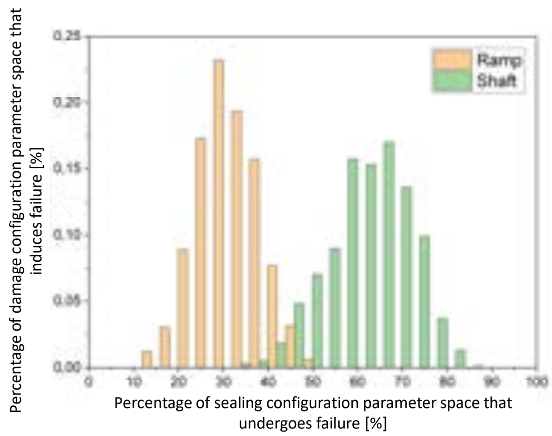
| | 1 | 2 | 3 | … | $N_D$ |
|---|---|---|---|---|---|
| 1 | ✓ | × | ✓ | | |
| 2 | × | ✓ | ✓ | | |
| 3 | ✓ | × | × | | |
| … | … | … | … | | |
| $N_S$ | × | ✓ | × | | |
| | | | | | |
| Normailzied sum of failed sealing configurations | 0.81 | 0.54 | 0.93 | … | 0.73 |

$\frac{\sum}{N_S}$



# Robustness against Changes

• Combination of failures – comparison between two sealing system




- The same damage system was used with both a ramp system and a shaft system
- The more left the distribution, the less of the sealing configuration space is damaged
  - → left is better
- In this example:
  - For the ramp system, fewer configurations fail when exposed to every possible damage configuration compared with the shaft system
  - → Ramp is more robust
  - The robustness difference can be traced to the larger dimensions of the configuration parameter space of the ramp system, which allows for more configurations with a higher sealing capacity and hence robustness
- With this method, it is possible to compare the potential of different sealing systems, without knowing the exact design
- With this method, it is possible to identify an exact design



# Resumee

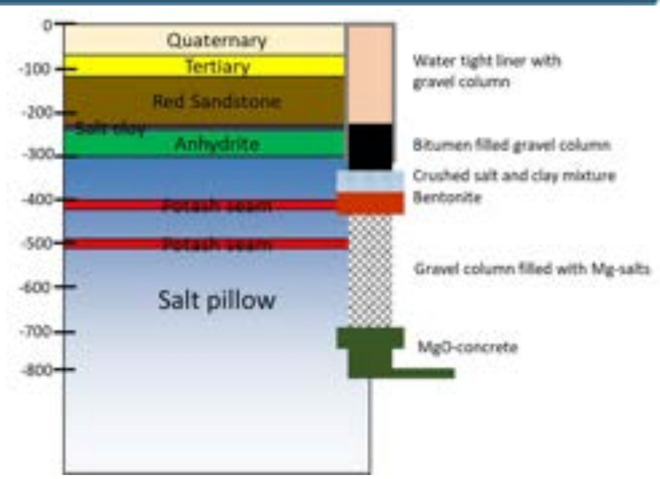
**Sequence of elements:**

- Depends on the geological conditions and expert judgement of the designer
- Difficult to access with simplified indicators

→ Indicator Robustness of Design

**Robustness:**

- Sensitivity of the barriers to internal and external impacts
- Assessment possible in combination with the performance targets




**Sealing capacity:**

- Seals within surface connections have to limit potential flow into or out of the underground facility
- Sealing capacity or tightness evaluated based on hydraulic resistance

**Retention capacity:**

- Different sealing materials provide different retention capacities (e.g. sorption) against different nuclides
- Indicator combines different materials but complex in application

**Technical feasibility:**

- Constructability of the sealing elements
- Have to be considered in the design, shouldn`t be part of the assessment

# Summary

- Within the design process of surface connections, long-term related aspects seem to be subordinated, however:
  - Site-specific and operational (safety) related aspects are relevant
  - LT related aspects are more complex in the evaluation

- A simplified method how to compare different sealing concepts would support the decision process

- Sealing capacity, retention capacity, and robustness are indicators with different complexities in their application

- Not just suitable for the comparison of shafts and ramps or “apples and oranges” 

- The method also allows a comparison of possible configurations within a single sealing system

# US/German Workshop on Salt Repository

Research, Design & Operation 2023


## Update on WIPP Microbiology Research

**Julie Swanson, Adrianne Navarrette, Jandi Knox, Hannah Kim**
**Actinide Chemistry & Repository Science Program**
**Los Alamos National Laboratory-Carlsbad Operations**

**LA-UR 23-26216**



## Current Focus of Microbiology Research

### Viability and Activity Studies

### Bioassociation Studies

### Gas Generation

**The assumptions are that all organisms will survive, be active and mobile, and have the potential to transport actinides.**

## Important definitions in the context of a salt-based repository setting

- Habitability
  - The capability of an environment to support life, whether or not life exists there
  - What are the boundary conditions for a habitable space?

- Viability and survivability
  - The ability to remain alive or continue to exist versus the act of remaining alive, usually in the context of extreme conditions

- Activity
  - Proliferation



## Microbial (halophile) viability and activity under repository conditions

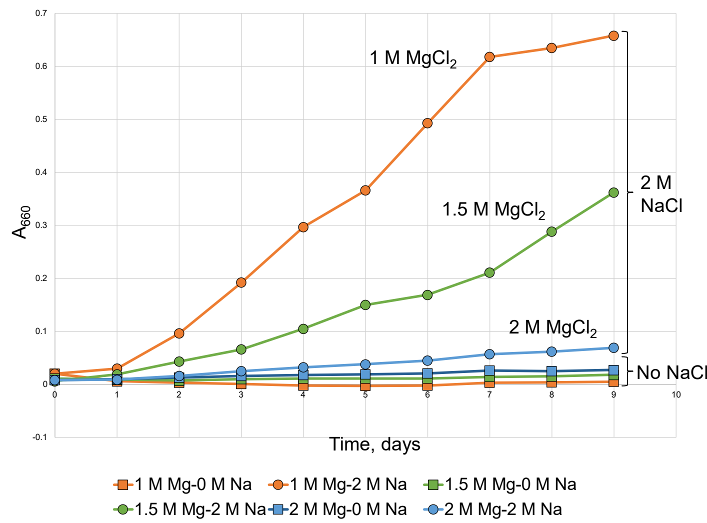
- Growth Assays

- Agar Gelation Assays

- Proposed 3D Window of Habitability

## *Halobacterium* sp. growth assays

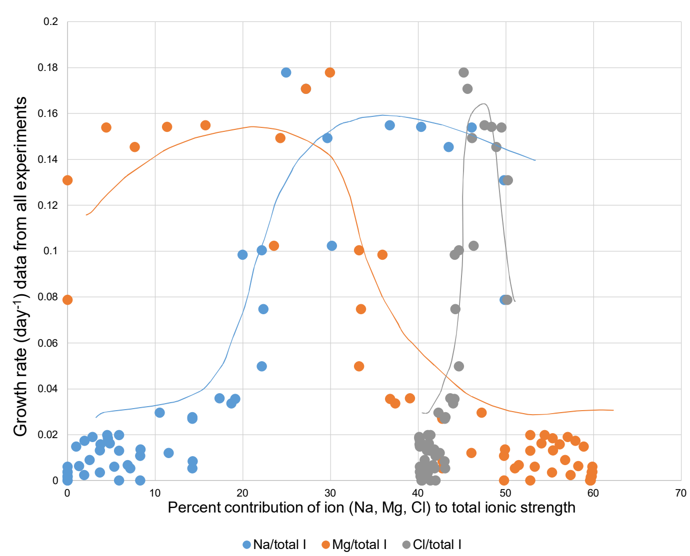
- Test conditions:
  - Representative haloarchaeon
  - Variable ionic strength:
    - [NaCl] 0-3 M
    - [$MgCl_2$] 1, 1.5, 2 M
  - Constant ionic strength:
    - [NaCl] 3.4 and 5 M
    - [$MgCl_2$] variable





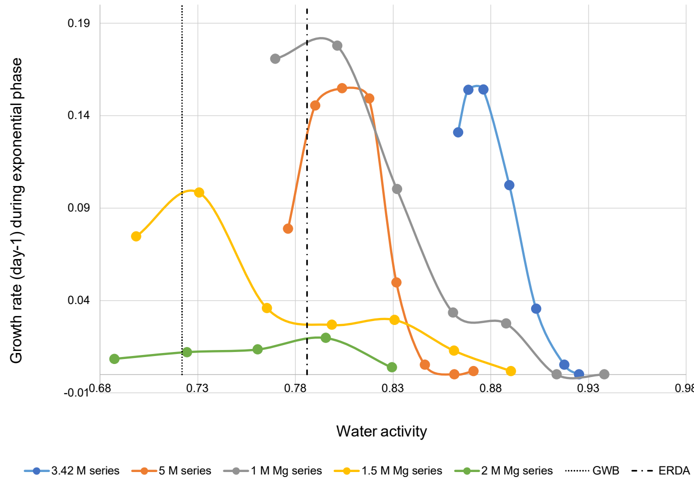

## *Halobacterium* sp. Growth Assays

- **Results:**
  - **Positive correlation of growth with [NaCl] and negative correlation of growth with [$MgCl_2$]**
  - **Correlation with $Na^+$ content is strongest**



## *Halobacterium* sp. Growth Assays

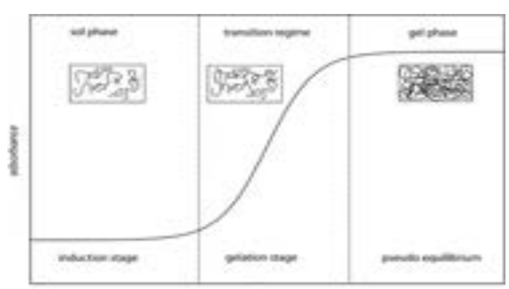
- **Results:**
  - **Water activity is not the chief determinant of halophile growth**
  - **Growth rate is more dependent on $Na^+$ and $Mg^{2+}$ content**






## Agar Gelation Assays

- **<u>Chaotropicity</u> leads to disorder of biopolymers, e.g. protein structure**
- **<u>Kosmotropicity</u> counters chaotropicity**
- **Agar gelation temperature: indirect measure of chaotropicity (effects on hydrogen bonding within agar)**

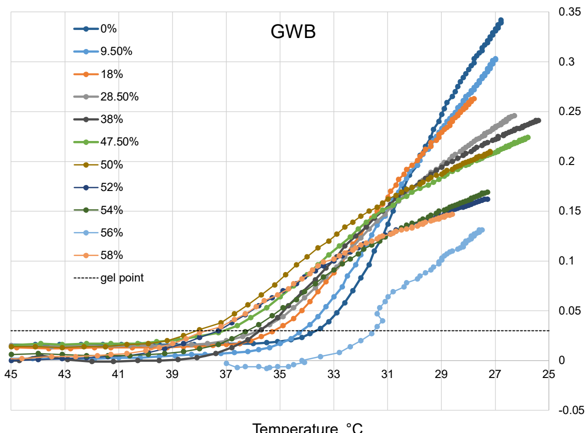


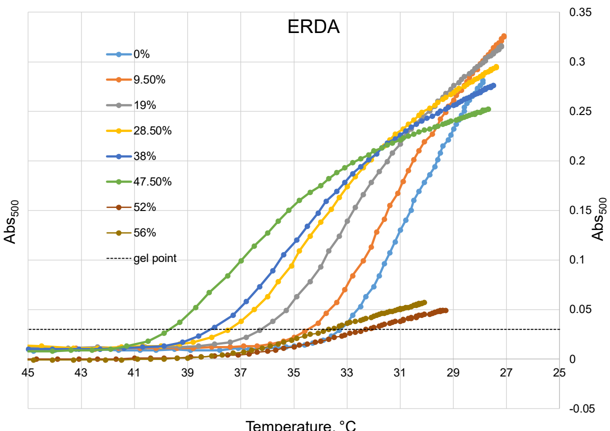
Nordqvist D and TA Vilgis. 2011. *Food Biophysics* 6 : 450

- **Test conditions:**
  - **1.5 % (w/v) Noble agar**
  - **Growth media**
  - **Basal salts only**
  - **Dilutions of GWB, ERDA**
  - **Heat agar to dissolution, monitor absorbance versus temperature and time**

## Results of Agar Gelation Assays

- Between 10-50% of full strength GWB or ERDA, curve shifts to left = less chaotropic
- Above 50% of full strength, curve shifts back to right:
  - Gelation temperatures decrease = more chaotropic
  - Gelation rates decrease = more chaotropic

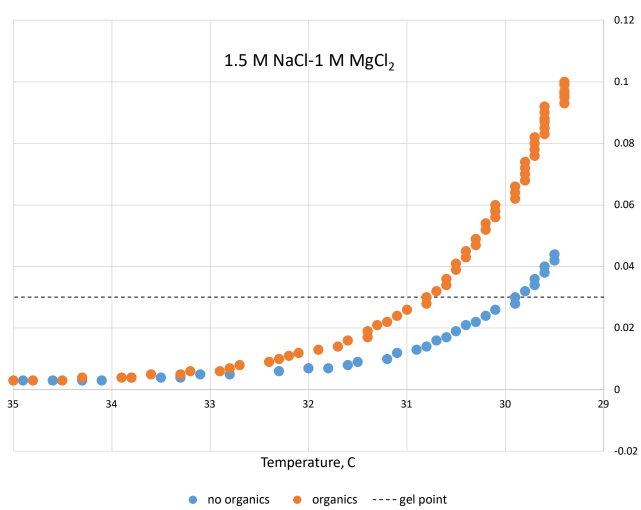




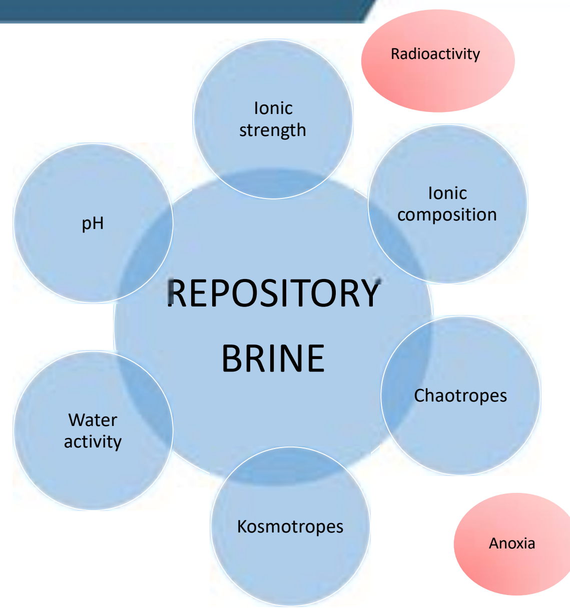

## Results of Agar Gelation Assays

- **Addition of organics to brine increases gelation temperature = lowers chaotropicity**
- **Increased temperature increases water activity, but decreased temperature mitigates chaotropicity**



## WIPP Repository Conditions and Calculation of a “Habitability Index”

- **Brine Matrix**
  - **Ionic strengths between 6-8 M**
  - **Ionic composition:**
    - **Chaotropes:**
      - **$Mg^{2+}$, $Cl^-$, $Ca^{2+}$, $Li^+$, borate, $Br^-$**
    - **Kosmotropes:**
      - **$Na^+$, $K^+$, $SO_4^{2-}$**
  - **Water activity:**
    - **0.703 – 0.735 (0.722) GWB**
    - **0.780 – 0.732 (0.787) ERDA**
  - **pH ~7-8; or $pC_{H+}$ ~ 9-9.5**
- **“Habitability Index” = (sum of chaotropes)/(sum of kosmotropes), or “log(C/K)”**



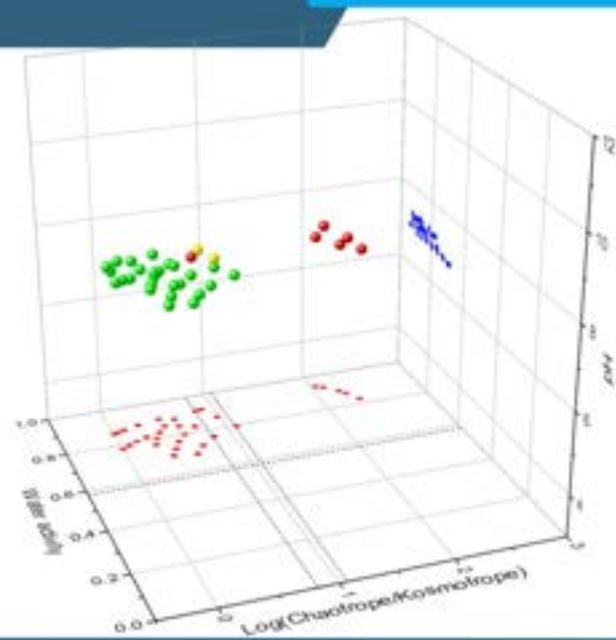



## Growth Media

- **Green = growth**
- **Red = no growth**
- **Yellow = minimal growth**

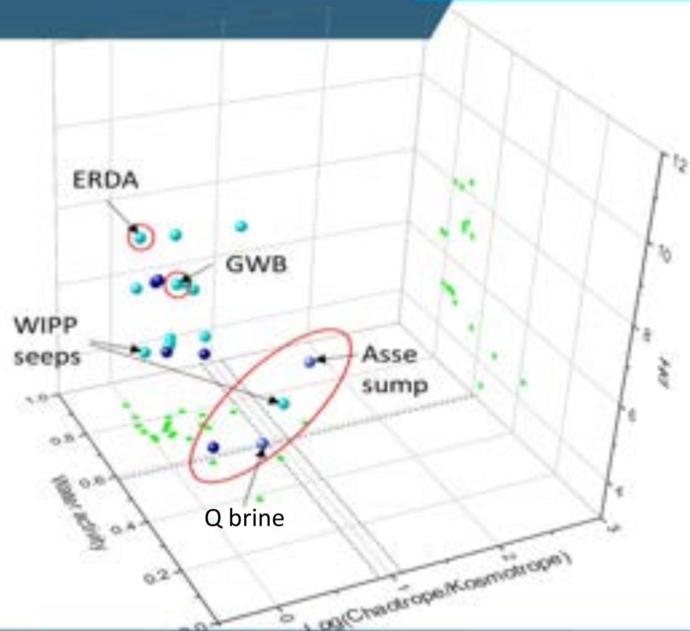
- **Lack of growth due to insufficient $Na^+$ to counter $Mg^{2+}$ effects**

- **Reminder:**
- **These results are for an extreme halophile**
- **Most bacteria require $a_w$ > 0.91-0.95**



## Salt Mine Brines

- Cyan = WIPP brines and seeps[1,2]
- Light blue = Asse[3], Q[4]
- Royal blue = Boulby salt mine/UK[5]

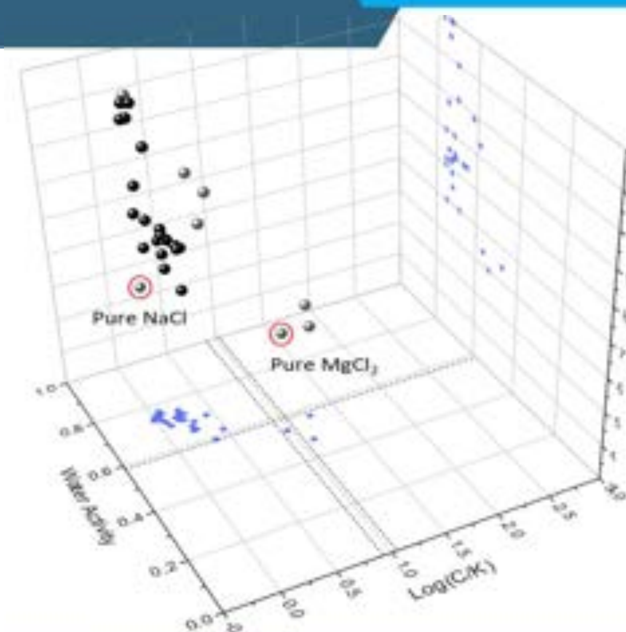



[1]Stein CL and JL Krumhansl. 1988. *Geochimica et Cosmochimica Acta* 52: 1037-1046
[2]personal sampling efforts
[3]Zirnstein & Arnold, unpublished (ABC-Salt )
[4]Thies A and JW Schulze. 1996. *Materials and Corrosion* 47: 146-153
[5]Megaw J et al. 2019. *FEMS Microbiology Letters* 366



## Reacted Cement-Brines

- Black[1] = WIPP brines + Portland cement at varying cement/brine ratios ± MgO
- Gray[2] = simulated cemented wastes ± nitrates



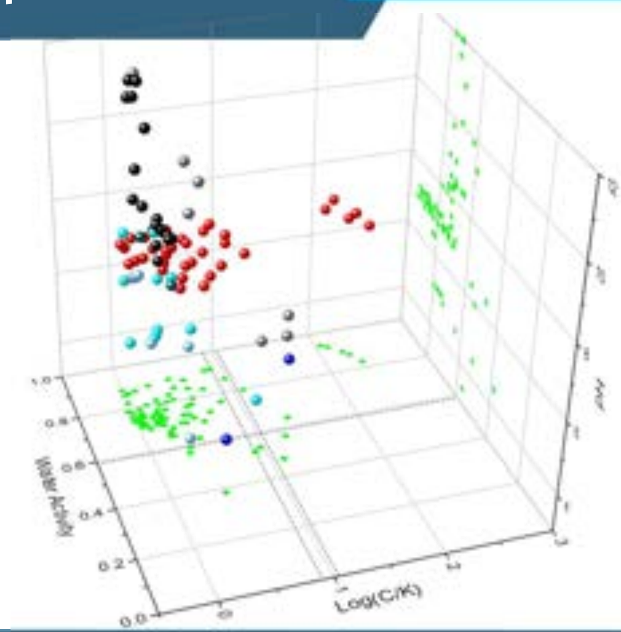

[1]Lucchini J-F et al. 2015. LANL Report LCO-ACP-22
[2]Kienzler B. et al. 2000. *Nuclear Technology* 129: 101-118

## Region of Habitability for a Halophile

- Constrained by:
- pH extremes
- High $Mg^{2+}$ (> 1.5 M) and $Ca^{2+}$
- Insufficient $Na^+$ (< 2 M) or $K^+$
- High nitrate

- Synthetic WIPP brines do not fall outside of region of habitability, but brine seeps do

- Asse and Q brines fall outside of region






## Bioassociation Studies: Experimental Conditions

- Neodymium used as analog for An(III)

- Organisms: isolates from incubations of WIPP halite at varying [NaCl]
  - 3 haloarchaea (*Halobacterium* sp., 2 unidentified)
  - 4 bacteria (*Chromohalobacter* sp., *Salinicoccus* sp., *Nesterenkonia* sp., *Thalassobacillus* sp. spores)

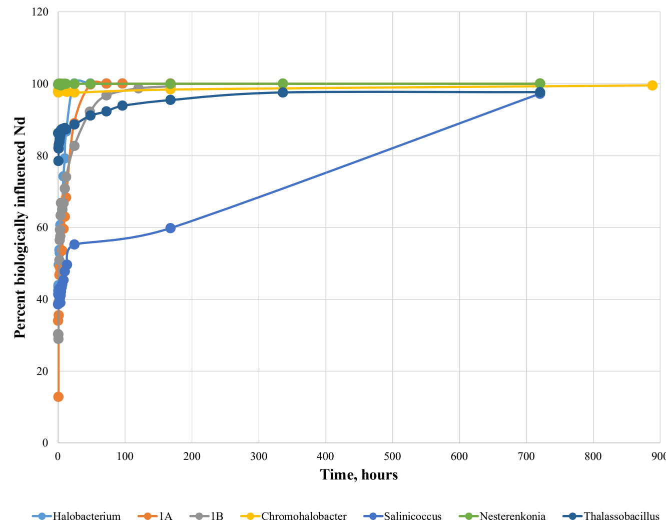
- All tested in simple NaCl solutions at optimum concentration

- Subset tested in WIPP brines (GWB, ERDA at 90% of full strength)

- Batch tests lasting ~1 month

## Results in NaCl Solutions

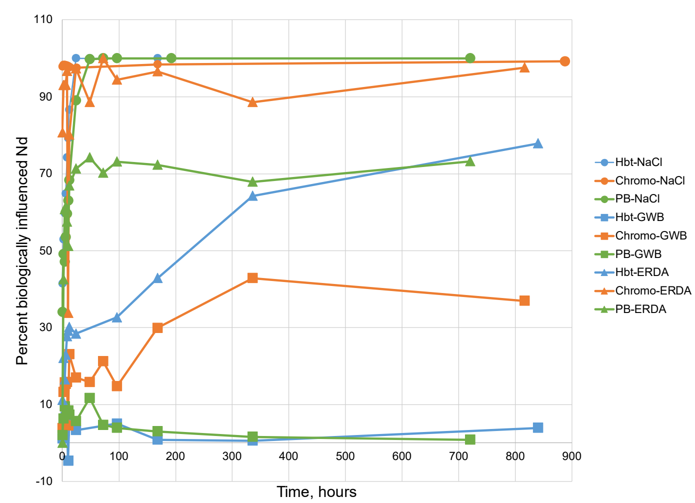
- Extent of biological influence at t = 0 varies (range 13-100%) and weakly correlates with [NaCl] (i.e., higher [NaCl] → less initial influence)
- Over time, biological influence reaches 100% in all experiments = No Nd left in solution
- Mechanism of Nd loss over long-term is different from initial loss
- All cells sediment to bottom of test tubes, if not in constant motion





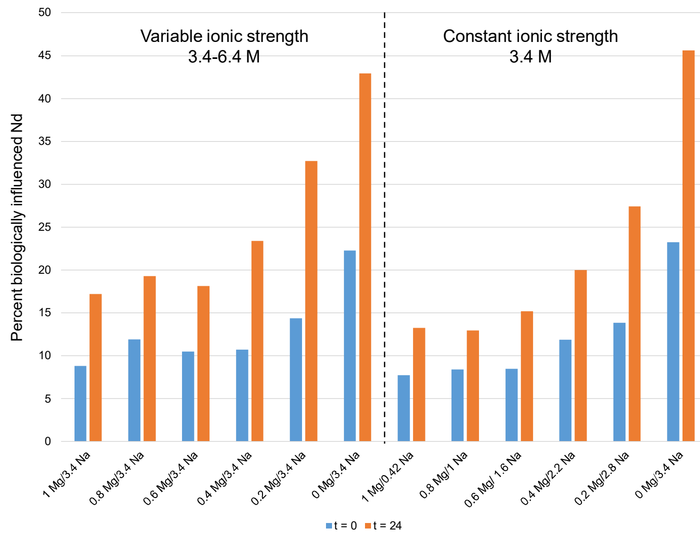

## Results in WIPP Brines

- Little to no influence of organisms on Nd solubility when in GWB
- Moderate influence of organisms in ERDA (more similar to NaCl)
- Greatest influence in simple NaCl solutions



## Cation Competition/$Mg^{2+}$ Effects

- $Na^+$ competition can explain variation at t = 0 (in simple NaCl solutions)
- $Mg^{2+}$ competes with Nd for available binding sites at cell surfaces
- This explains findings at early time points where surface sorption is likely mechanism of Nd loss
- Also explains the lack of apparent influence in GWB
- Data suggest minimal biological influence at [Mg] > 0.6 M






## Other $Mg^{2+}$ Effects

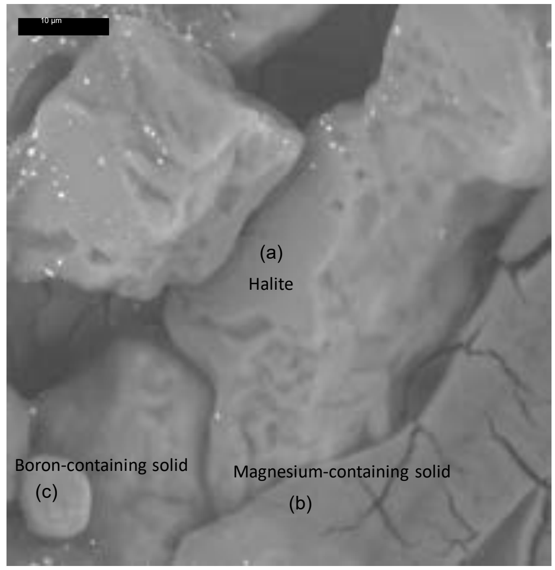
- Loss of surface layer (S-Layer) structure
  - $Mg^{2+}$ stabilizes S-layer (within a range specific to each organism)
  - Loss of S-layer results in changes to cell morphology
    - High $Mg^{2+}$ content (without other ions) results in large, rounded cells = increased surface area
    - Exposure to WIPP brines results in smaller coccoid cells = decreased surface area

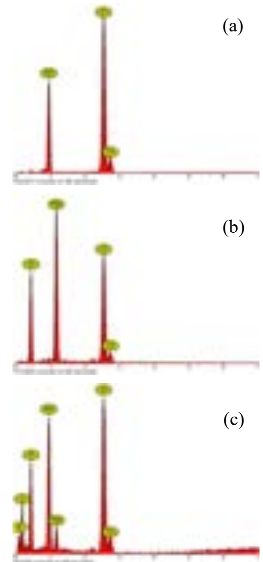
- S-layer shedding with associated Nd would appear as increased biological influence
- Shed S-layers can mineralize along with associated metals

## Biologically-Induced Precipitation of Nd?

- Sorbed onto organism that is trapped in precipitated salt?
- As salt precipitate?
- As mineral precipitate?

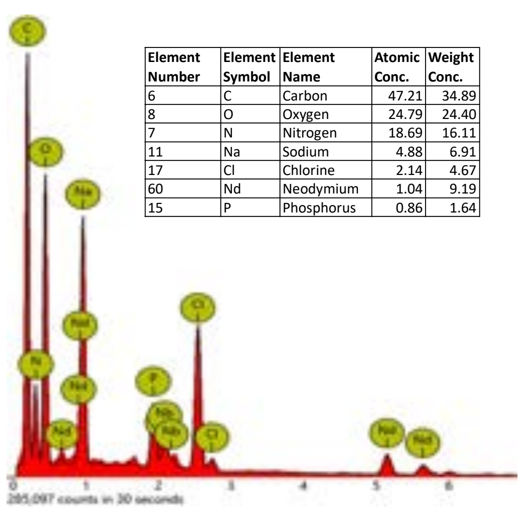
NEED EVIDENCE



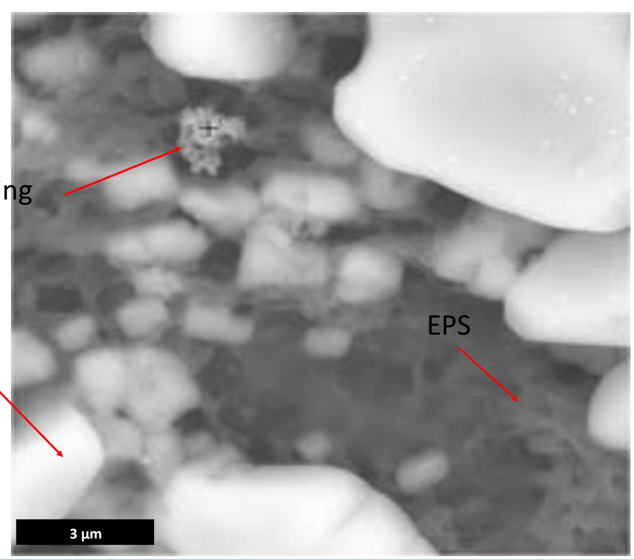



## Entrapment of Nd Within Extracellular Polymeric Substances (EPS)



| Element Number | Element Symbol | Element Name | Atomic Conc. | Weight Conc. |
|---|---|---|---|---|
| 6 | C | Carbon | 47.21 | 34.89 |
| 8 | O | Oxygen | 24.79 | 24.40 |
| 7 | N | Nitrogen | 18.69 | 16.11 |
| 11 | Na | Sodium | 4.88 | 6.91 |
| 17 | Cl | Chlorine | 2.14 | 4.67 |
| 60 | Nd | Neodymium | 1.04 | 9.19 |
| 15 | P | Phosphorus | 0.86 | 1.64 |

***Chromohalobacter* sp. in NaCl**



## Microbial Activity and the Degradation of Cellulosics: Natural Analogue Case Study

- **Archaeological site in Salzkammergut region of Austria—Bronze and Iron Age salt mines**
- **Discovery of a wooden staircase buried in salt, now ~3100 years old**
- **Presence of halophilic organisms on stairs, but…**
- **No deterioration until stairs were removed from site and fungal mycelia grew**


Piñar et al., 2016. PLoS ONE 11: e0148279

"The structure and stability of the wooden staircase were fully intact at the time of its discovery, due to the suppression of common wood-decaying fungi by the salt".



**Thanks to Anderson Ward, DOE-CBFO Compliance Certification Manager, for his support of this work, thanks to my teammates, and**

**THANK YOU FOR YOUR ATTENTION!**
**QUESTIONS?**

# Update on ABC-Salt VII Workshop

*(15-16 June 2023, Santa Fe, USA)*

INSTITUTE FOR NUCLEAR WASTE DISPOSAL (INE)

**13th US/German Workshop on Salt Repository Research, Design & Operation**

**Santa Fe, New Mexico June 20-23, 2023**


*Marcus Altmaier*
*(marcus.altmaier@kit.edu)*




## ABC-Salt Workshop Series

**ABC-SALT**: **A**ctinide and **B**rine **C**hemistry in a **Salt** based repository.

- **ABC-SALT workshop series organized under NEA-SC frame.**
- **Previous meetings held (organized KIT-INE / LANL-CO):**
- **2010 Carlsbad, 2011 Karlsruhe, 2013 Santa Fe, 2015 Heidelberg, 2017 Ruidoso, 2019 Karlsruhe, 2023 Santa Fe**.

## ABC-Salt Scope

**ABC-SALT workshops consist of presentations (mainly oral) and focus upon:**

- **Overview talks on current repository projects** (USA, Germany)
- **Actinide/radionuclide chemistry in brines** (solubility, redox, inorganic and organic complexation, aggregation, sorption, chemical analogy, …)
- **Brine chemistry and brine evolution** (oceanic salt system, sorel, …)
- **Iron chemistry, corrosion** (kinetics, secondary phases, …)
- **Microbial effects in brines** (microbial activity, $CO_2$-production, …)
- **Thermodynamic databases and modeling studies** (data selection, data Pitzer fitting approaches, data gaps, modeling constraints…)



## ABC-Salt VII overview

# ABC Salt Meeting VII

*Santa Fe – NM, USA*

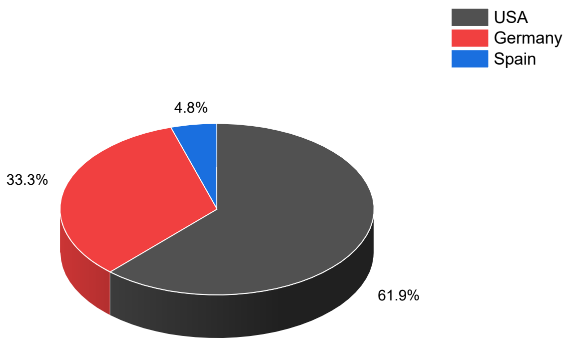
*15-16 June 2023*

Los Alamos NATIONAL LABORATORY · KIT Karlsruher Institut für Technologie · Sandia National Laboratories · BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

**Organizers:** **Juliet Swanson (LANL-CO), Ugras Kaplan (LANL-CO)**
Support: Marcus Altmaier (KIT-INE), Chammi Miller (SNL)

# ABC-Salt VII - participation

**Total: 38 participants**
**15 groups**



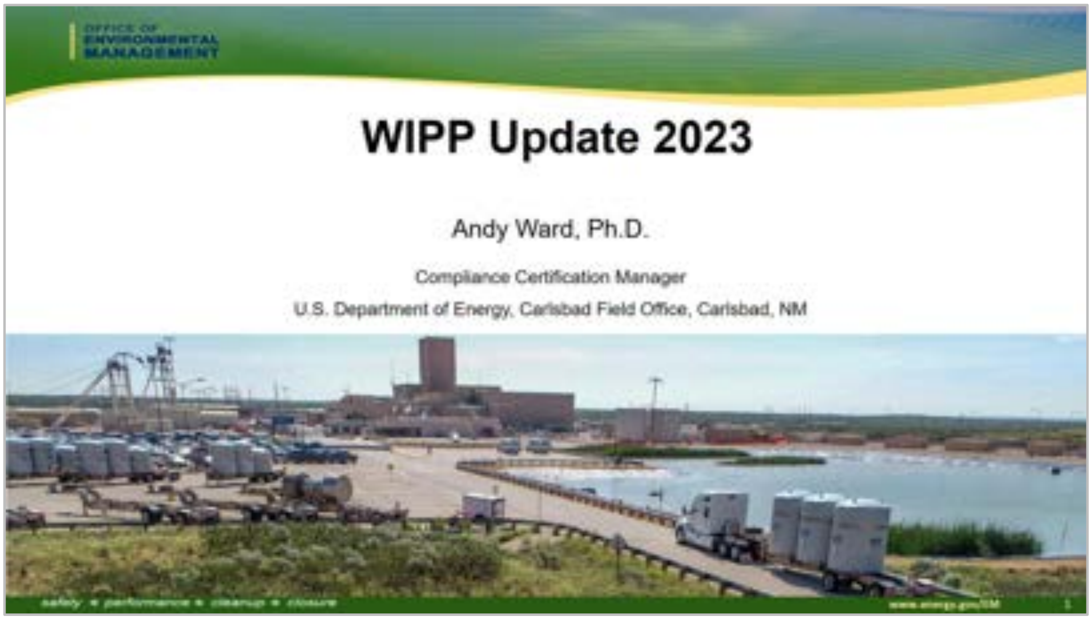

**Amphos[21]** (ESP)
**BGE** (GER)
**CTAC** (USA)
**DOE** (USA)
**EPA** (USA)
**Florida Internat. University** (USA)
**GRS** (GER)
**HZDR** (GER)
**KIT-INE** (GER)
**LANL** (USA)
**New Mexico State University** (USA)
**SC&A Inc.** (USA)
**SNL** (USA)
**TU Freiberg** (GER)
**University of Notre Dame** (USA)



# ABC-Salt VII agenda

- Brine Chemistry
- Microbiology
- Fe Corrosion
- Actinide Chemistry
- Modeling studies and related thermodynamic databases

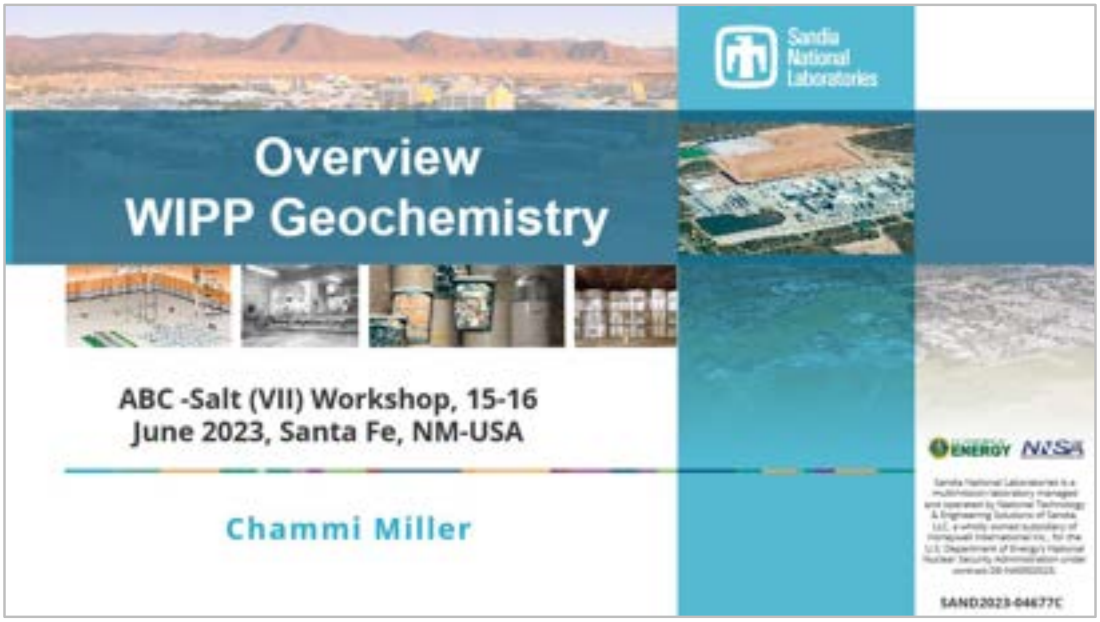
## Examples – Program Overviews





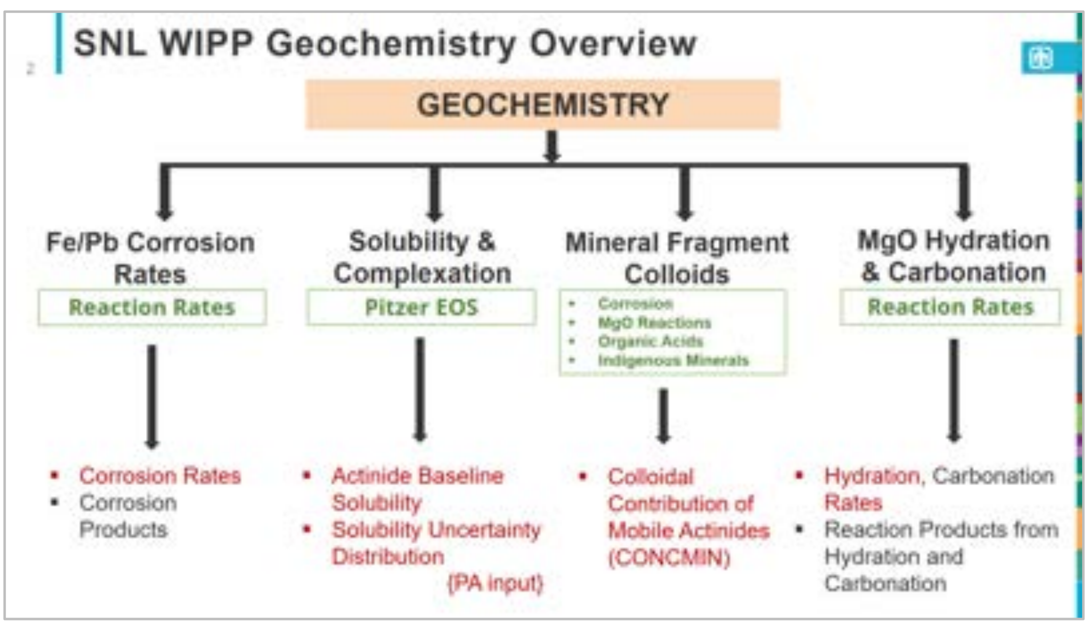

## Examples – Program Overviews

## Examples – Program Overviews

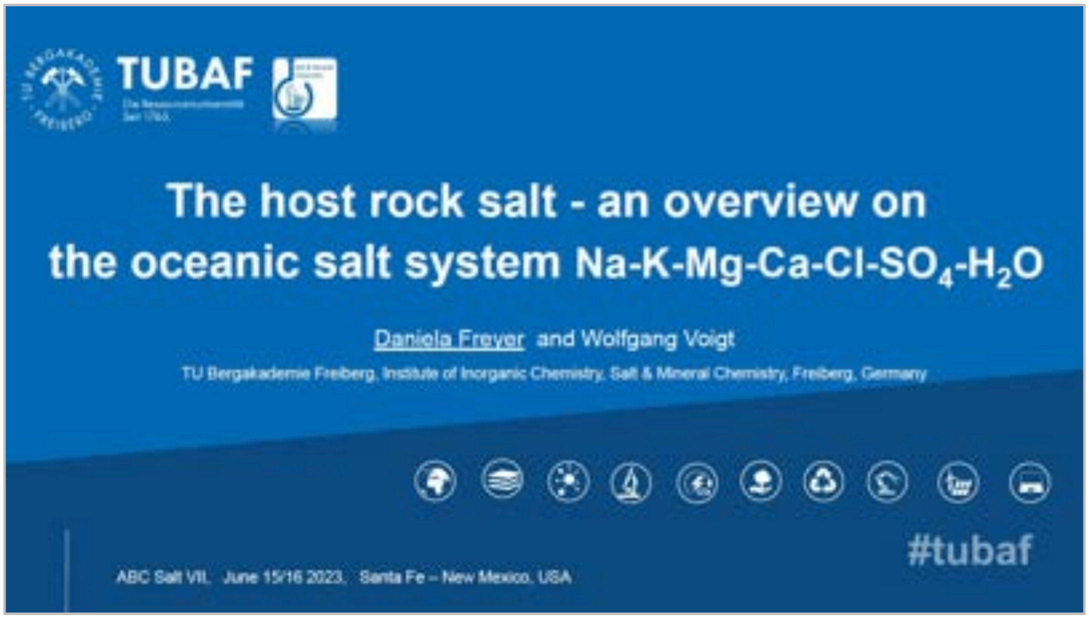





## Examples – Program Overviews



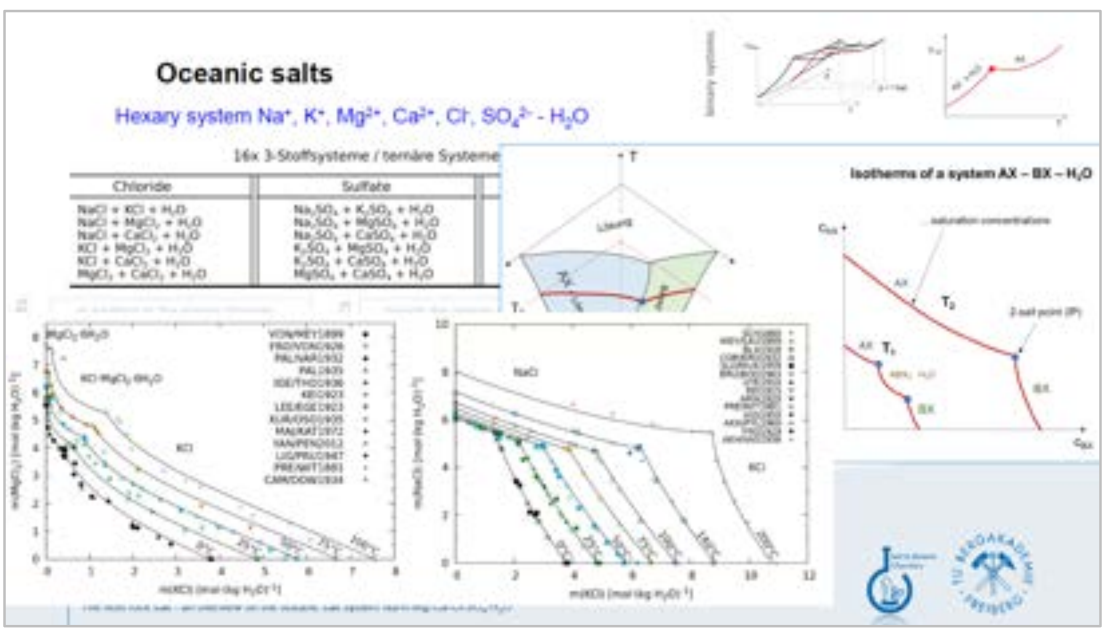
## Examples – Oceanic Salt System







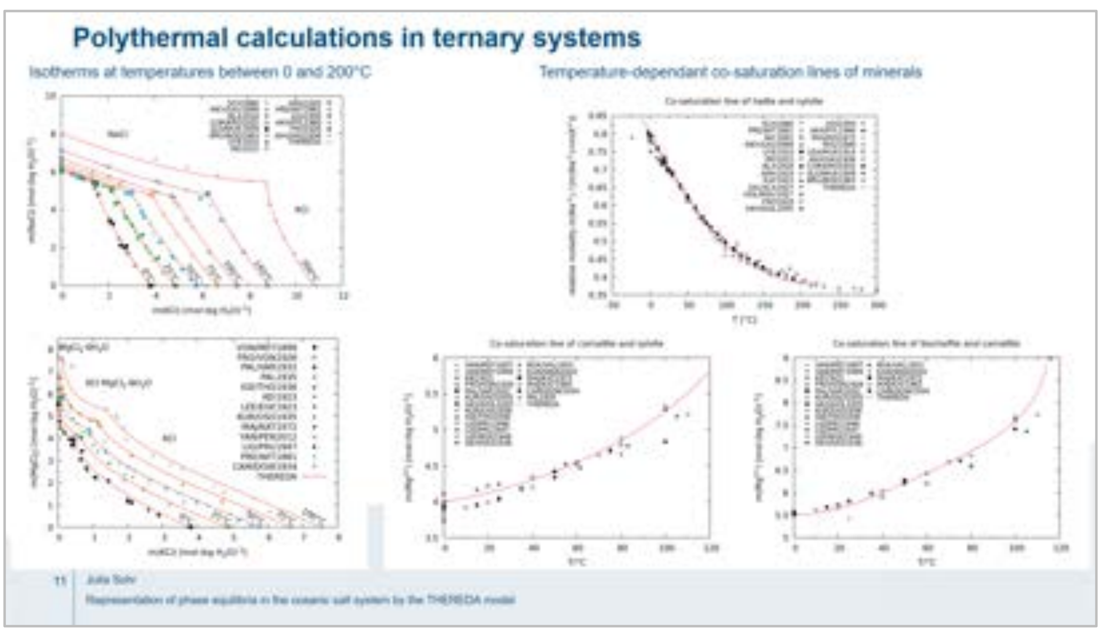
## Examples – Oceanic Salt System



## Examples – Oceanic Salt System




## Examples – Oceanic Salt System



# Examples – Iron Chemistry and Corrosion

KIT
Karlsruhe Institute of Technology

## Stainless steel corrosion and actinide uptake by corrosion products under anoxic and highly saline conditions

N. Finck[1], N. Morelová[1], M.L. Schlegel[2], J. Lützenkirchen[1], D. Schild[1], S. Reguer[3], K. Dardenne[1], H. Geckeis[1]

[1]KIT-INE, Karlsruhe, Germany
[2]Université Paris Saclay, Gif-sur-Yvette, France
[3]Synchrotron SOLEIL, Saint-Aubin, France

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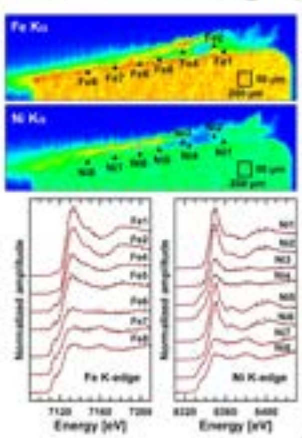
# Examples – Iron Chemistry and Corrosion

## Fe & Ni *K*-edge µXANES




| Point of interest | Results of linear combination fitting (mol%) |
|---|---|
| | Fe K-edge |
| Fe1 | 96(3) % α-$Fe_2O_3$ + 4(3) % CrFeNi-LDH |
| Fe2 | 92(3) % α-$Fe_2O_3$ + 8(4) % CrFeNi-LDH |
| Fe4 | 26(2) % steel + 74(2) % Cr-doped $Fe_3O_4$ |
| Fe5 | 36(2) % steel + 64(2) % Cr-doped $Fe_3O_4$ |
| Fe6 | 74(2) % steel + 26(2) % Cr-doped $Fe_3O_4$ |
| Fe7 | 84(2) % steel + 16(2) % Cr-doped $Fe_3O_4$ |
| Fe8 | 80(2) % steel + 20(2) % $NiFe_2O_4$ |
| | Ni K-edge |
| Ni1 | 100% CrFeNi-LDH |
| Ni2 | 100% CrFeNi-LDH |
| Ni3 | 37(7) % steel + 33(3) % $NiFe_2O_4$ + 31(3) % CrFeNi-LDH |
| Ni4 | 36(3) % steel + 29(4) % $Ni(OH)_2$ + 31(3) % $NiFe_2O_4$ |
| Ni5 | 49(5) % $Ni(OH)_2$ + 34(14) % NiO + 23(10) % $NiFe_2O_4$ |
| Ni6 | 53(16) % $Ni(OH)_2$ + 47(7) % $NiFe_2O_4$ |
| Ni7 | 86(2) % steel + 14(2) % $NiFe_2O_4$ |
| Ni8 | 85(2) % steel + 15(2) % $NiFe_2O_4$ |

- Steel
- Oxides
  - $Cr_{2-x}Fe_xO_3$
  - NiO
- Spinel type compounds
  - Cr-doped $Fe_3O_4$
  - $NiFe_2O_4$
- Hydrous compounds
  - CrFeNi-LDH
  - $Ni(OH)_2$

Finck et al. (2023) Corros. Sci. 220, 111265

12 19.06.2023 Nicolas Finck – ABC-salt VII workshop, Santa Fe, NM, USA KIT-INE, Radiochemistry, Secondary Phases

## Examples – Iron Chemistry and Corrosion

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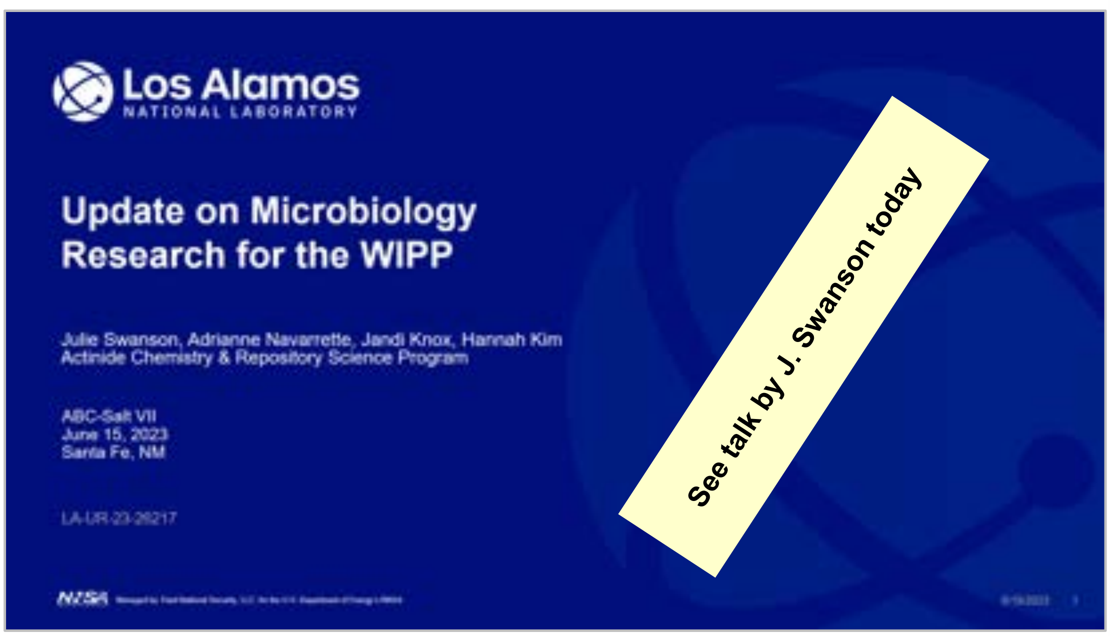
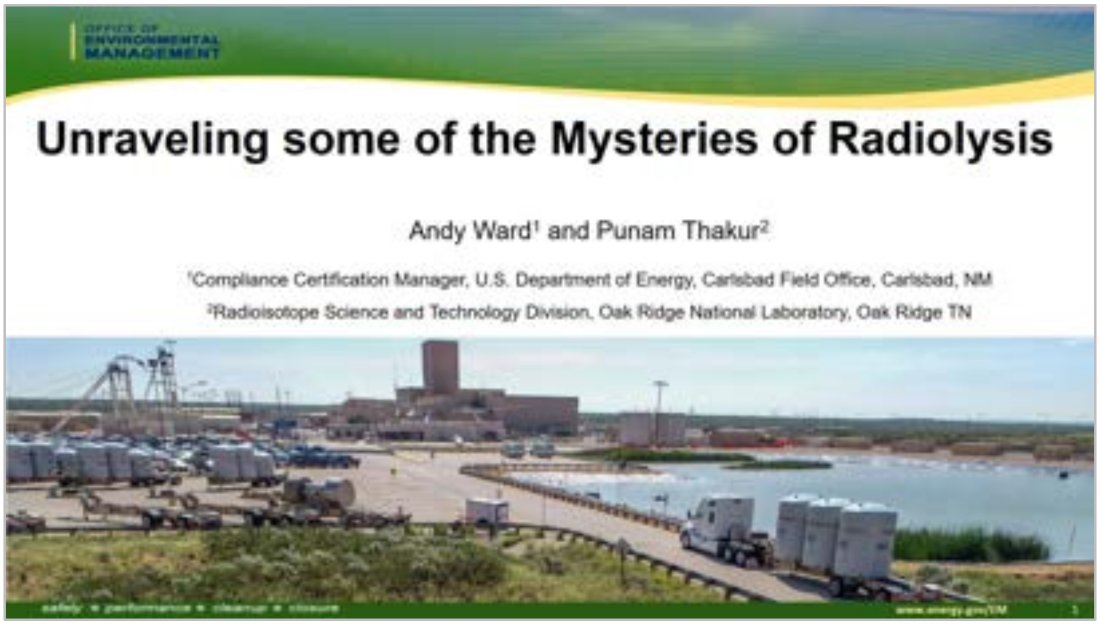
## Examples - Microbiology

KIT
Karlsruhe Institute of Technology

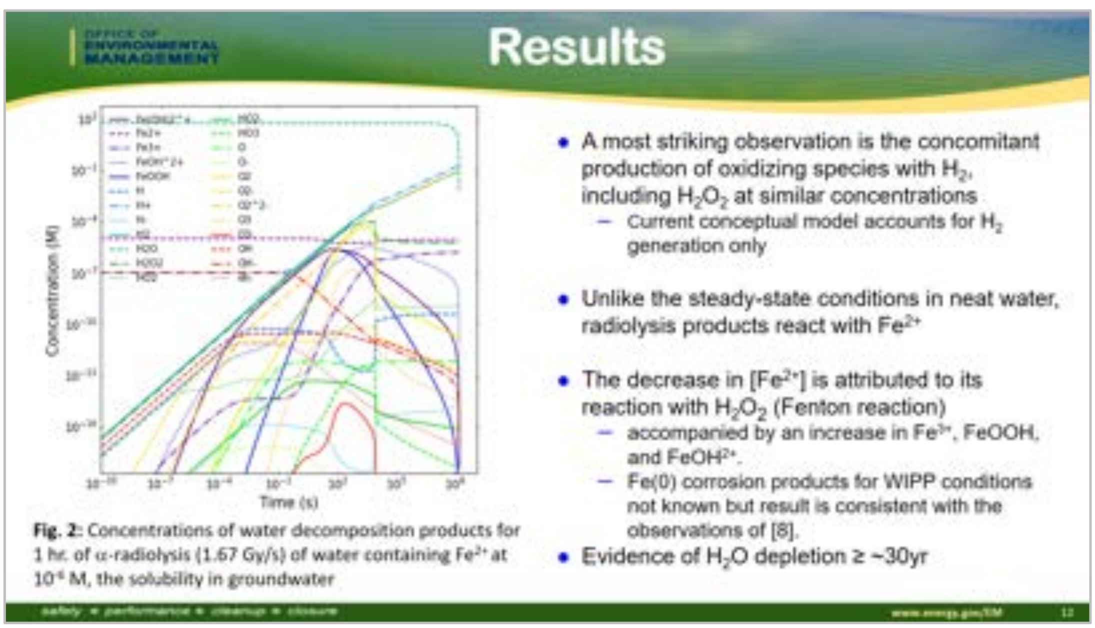


## Examples - Radiolysis






## Examples - Radiolysis



## Examples – Actinide Chemistry

**An(III) and An(IV) solubility limits and source terms in generic saline NaCl, $MgCl_2$ and $CaCl_2$ solutions in absence and presence of organic ligands**

Fellhauer, D.[1]; Meier, R[1].; DiBlasi, Ph. Müller; N. A.[1]; Gaona, X.[1]; Altmaier, M.[1]

*[1]Karlsruhe Institute of Technology, Institute for Nuclear Waste Disposal, P.O. Box 3640, 76021 Karlsruhe, Germany*

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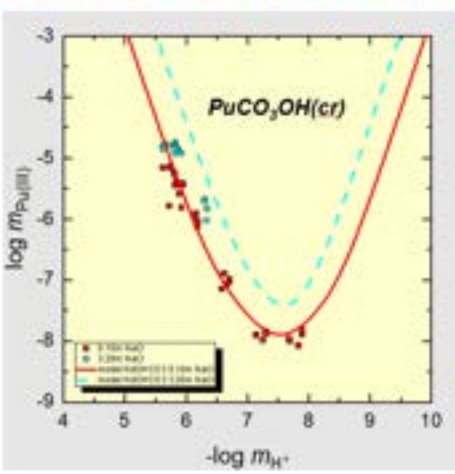
## Examples – Actinide Chemistry

**Pu(III) solubility and speciation in carbonate containing NaCl solutions**



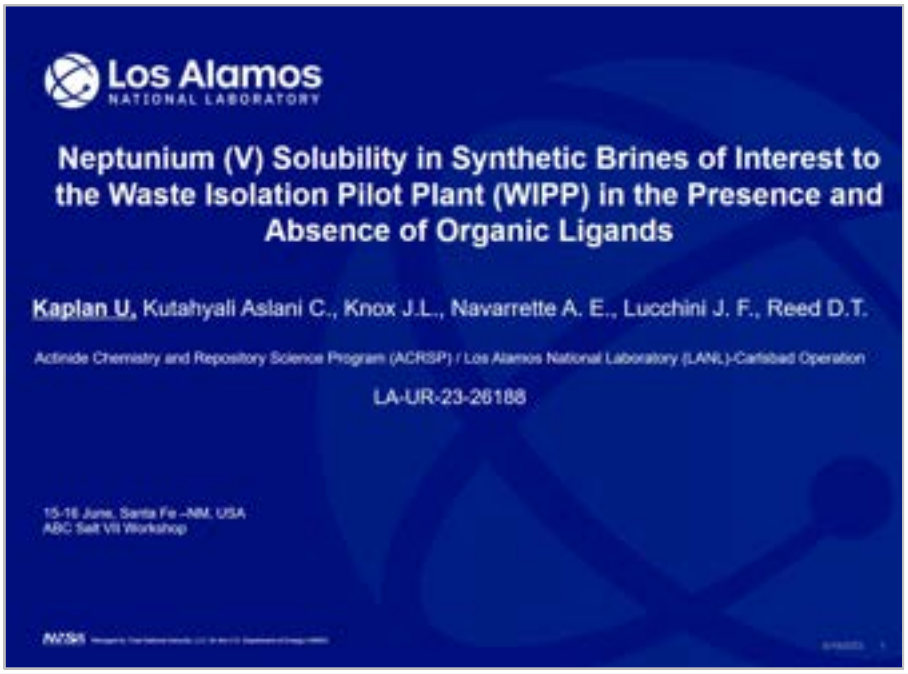

**SEM-EDX**

- First systematic ***solubility study*** in 0.1-5.0 M NaCl solutions + 1% $CO_2$ (ongoing)

⇒ results are in good agreement with the chemical-thermodynamic ***model for Nd(III)/Am(III)***

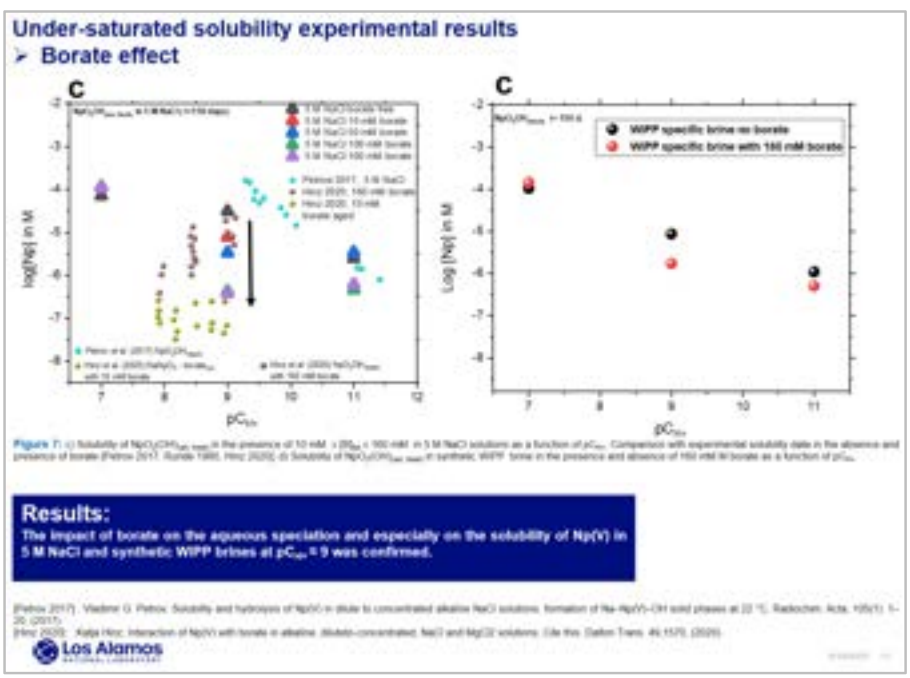
⇒ significant impact on ***Pu(III) solubility estimations*** in reducing, carbonate containing systems

# Examples – Actinide Chemistry






# Examples – Actinide Chemistry



## Examples – Actinide Chemistry

*Actinide and Brine Chemistry in a Salt Repository Workshop VII*
June 15–16, 2023

# Plutonium Redox Chemistry in the Presence of Citrate

Matthew B. Comins,[1] Amy E. Hixon,[1] Jeremy Beam,[2] Adrianne Navarrette,[2] Ugras Kaplan,[2] Jef Lucchini [2]

(1) University of Notre Dame, Notre Dame, IN, 46556, USA
(2) Los Alamos National Laboratory–Carlsbad Operations, Carlsbad, NM, 88220, USA

Los Alamos National Laboratory
University of Notre Dame

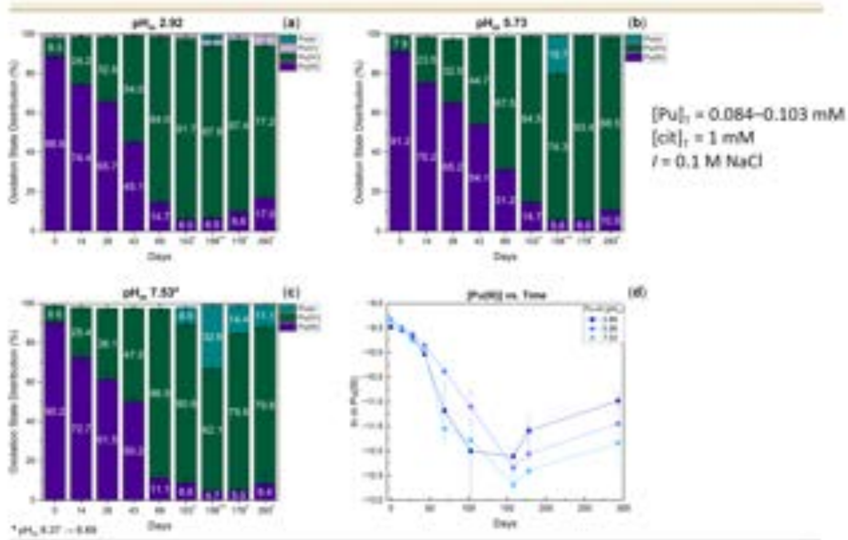
LA-UR-23-26015



## Examples – Actinide Chemistry

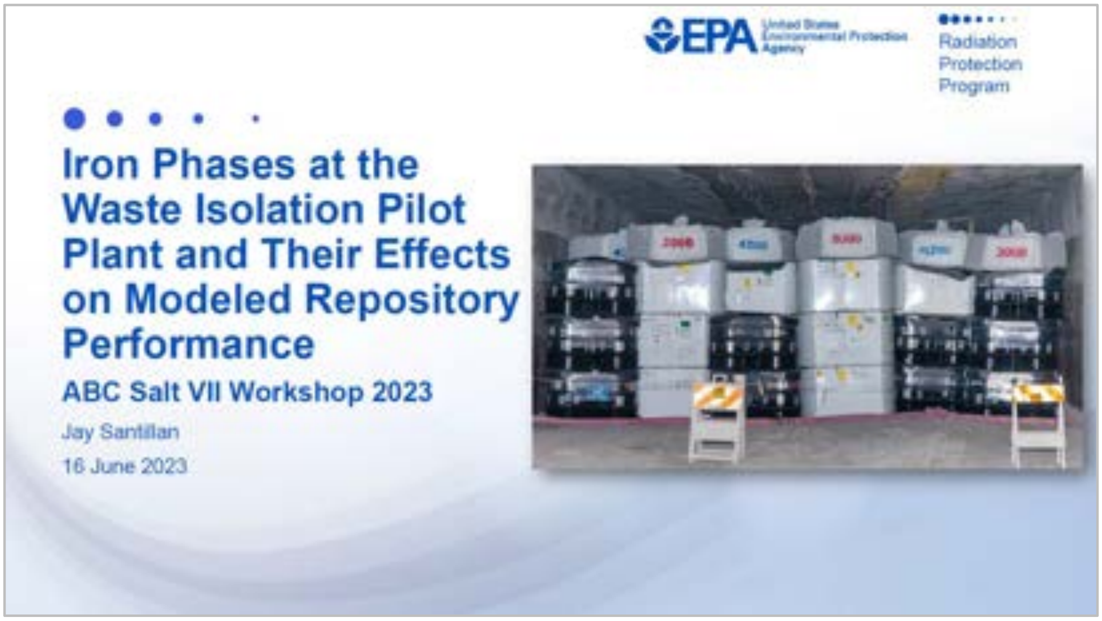
### Pu(III)-cit vs. Time (OSA)

University of Notre Dame



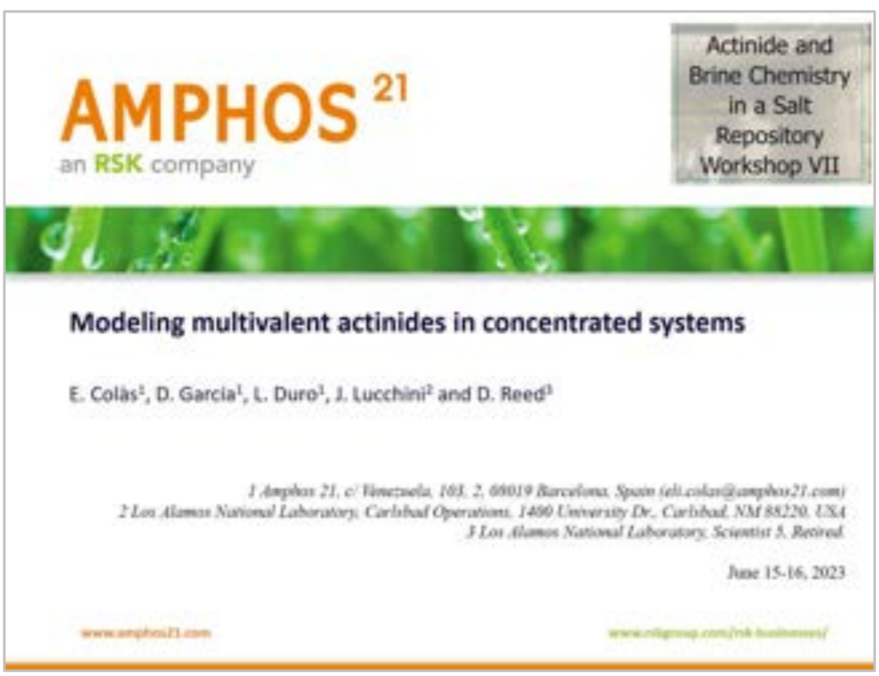

$[Pu]_T$ = 0.084–0.103 mM
$[cit]_T$ = 1 mM
$I$ = 0.1 M NaCl

## Examples – Thermodyn. Databases + Modelling






## Examples – Thermodyn. Databases + Modelling



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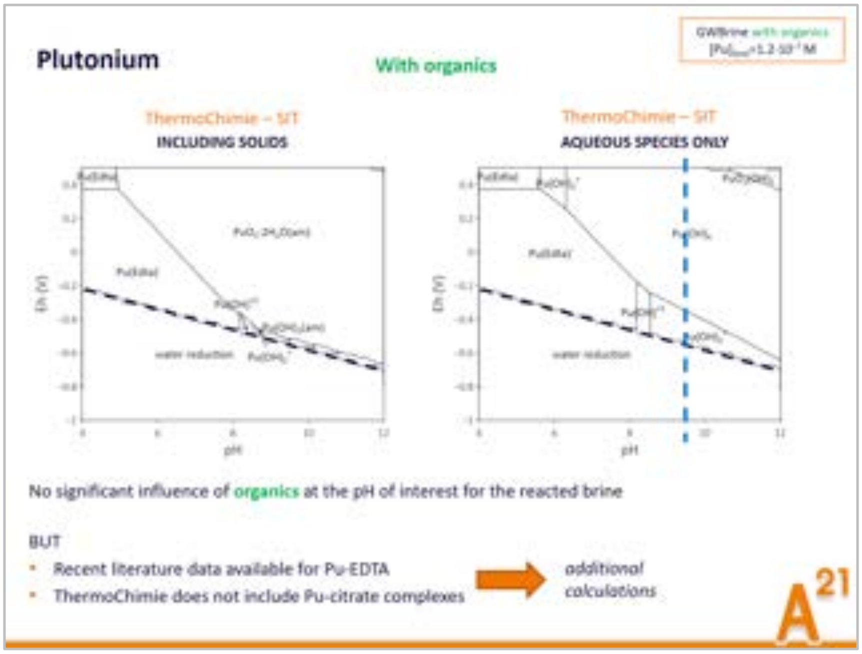


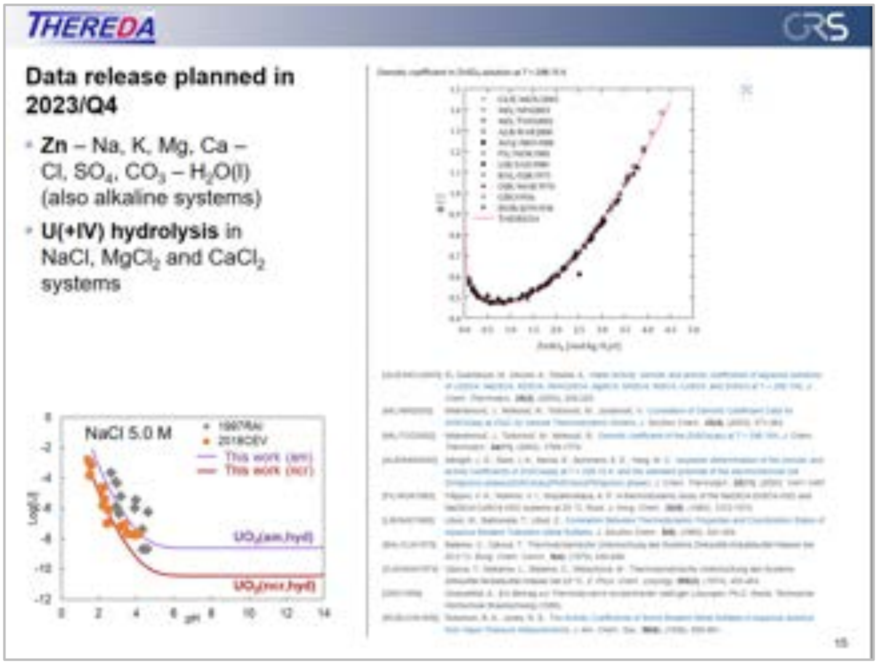




## Examples – Thermodyn. Databases + Modelling

## Examples – Thermodyn. Databases + Modelling

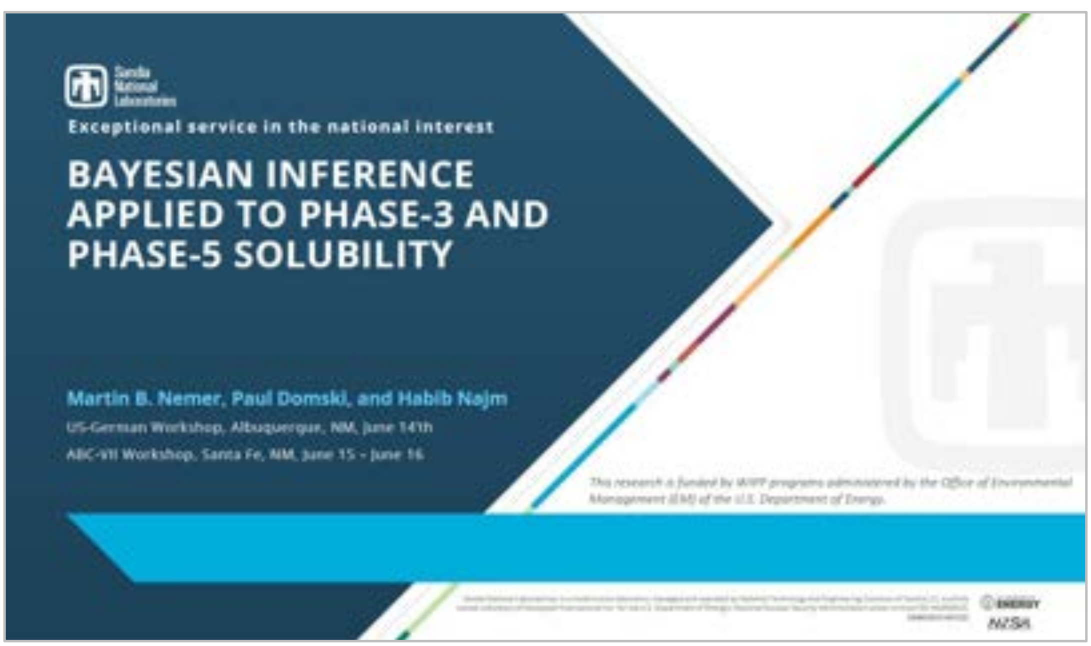
Karlsruhe Institute of Technology






## Examples – Thermodyn. Databases + Modelling

Karlsruhe Institute of Technology



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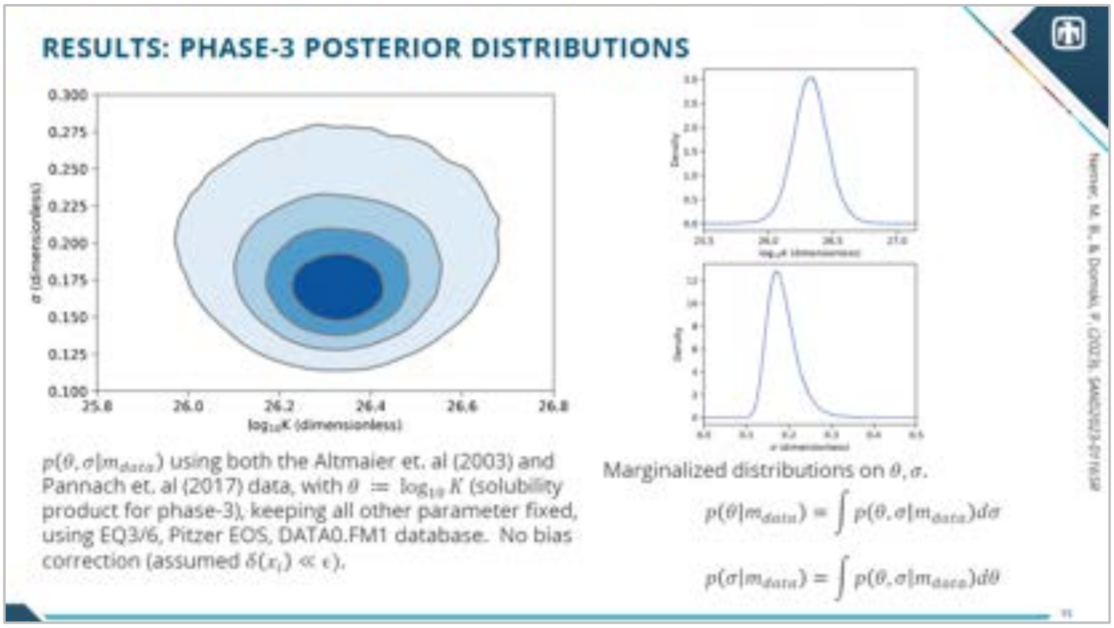




## Summary / outlook

**Main observations from ABC-Salt VII:**

- Excellent technical presentations spanning a broad range of relevant topics.
- Active discussions and networking between participants and groups.
- Mutual interest in taking action towards more cooperation, i.e. regarding the topic of thermodynamic data(bases).
- Actinide-brine-chemistry topics remain a lively and important research field – good decision to have re-started ABC-Salt series after the Covid break.

- **ABC-Salt organized on bi-annual basis (within NEA-Salt Club).**
- *Discussion ongoing if future proceedings will be published within NEA-SC.*

- **ABC-Salt VIII: organized by KIT-INE in Germany in 2025** (same org. team).

# Thanks for your attention !

*Thanks to Don Reed for past input into the ABC-Salt Workshop Series*

# US/German Workshop on Salt Repository
Research, Design, & Operation 2023

## Laboratory investigations on crushed salt by TUC and modeling benchmark results in KOMPASS II


Svetlana Lerche
Uwe Düsterloh
TU Clausthal


Santa Fe, Juni 20-23, 2023


1



## KOMPASS II

Compaction of crushed salt for safe containment

**(07.2021 - 06.2023)**


Supported by:

Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection


*project partner*

GRS, BGR, BGE TEC, Sandia National Laboratories, COVRA, IfG Institut für Gebirgsmechanik GmbH Leipzig, Universiteit Utrecht, TU Clausthal

***Overview-Presentation on 22.06.2023 ‚KOMPASS Summary & Outlook MEASURES' by Larissa Friedenberg (GRS)***



2

# Agenda

**Intro**

**Long-term strategy** for the experimental investigations

**Main part**

1. **Laboratory investigations** in the framework of **KOMPASS II**
2. **Modeling benchmark** on long-term test **TUC-V2**

**Outlook**

Long-term **tests planned** for the follow-up project **MEASURES**

KOMPASS II

3

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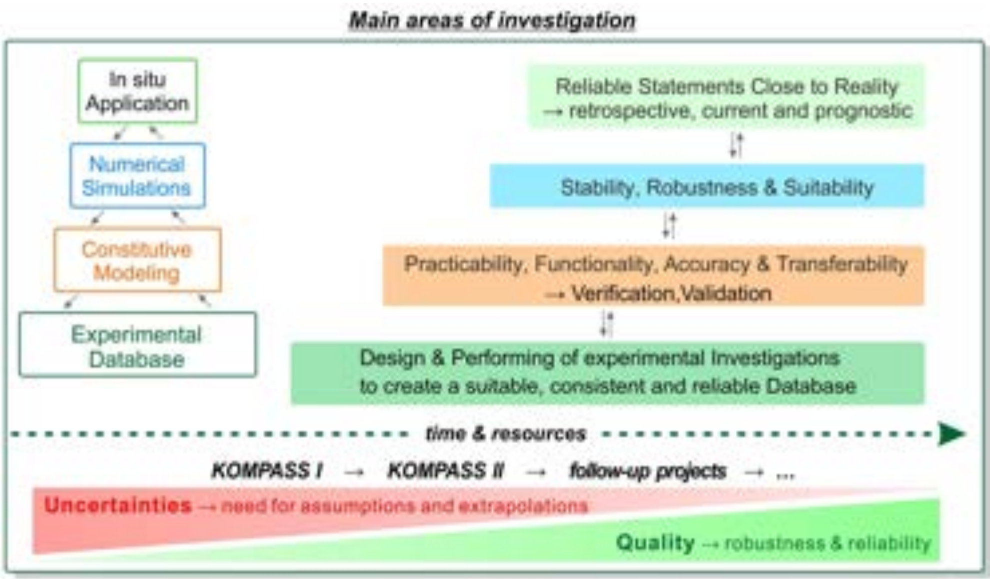
KOMPASS II

4

## Intro: Long-term strategy for the experimental investigations

TU Clausthal





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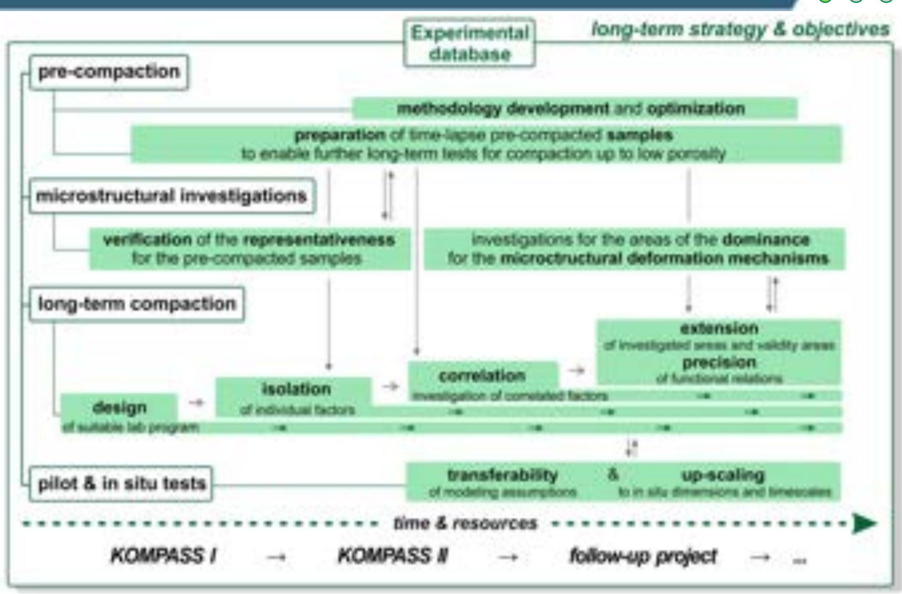
TU Clausthal



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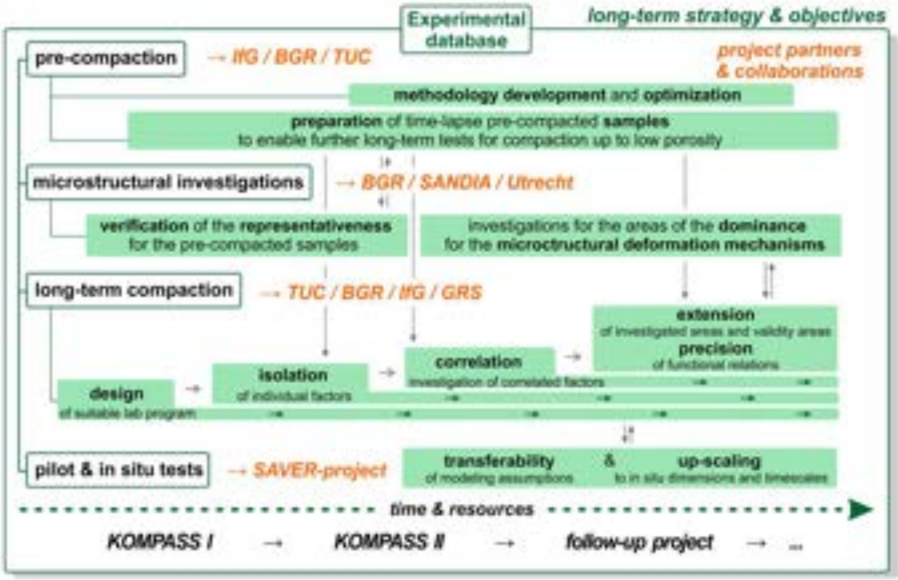
TU Clausthal





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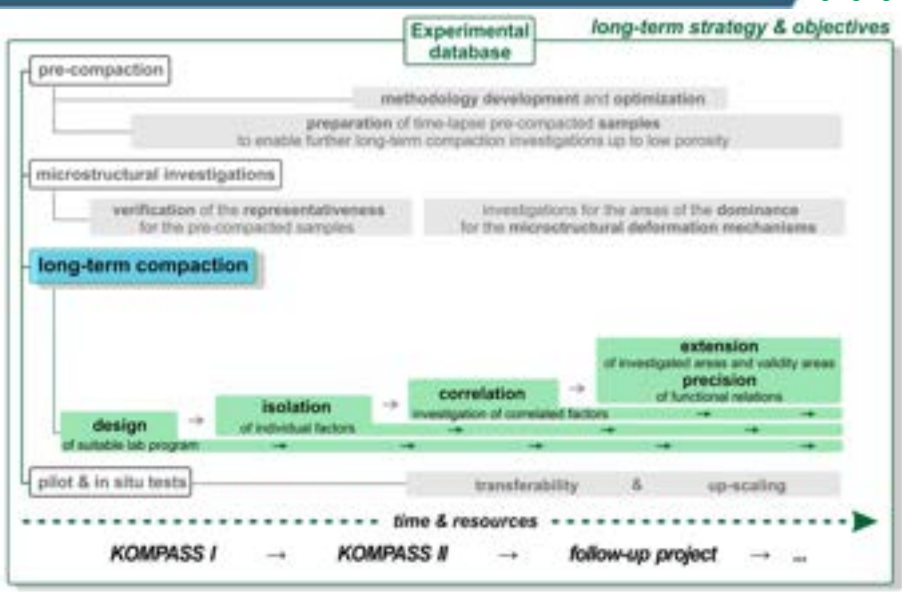
TU Clausthal



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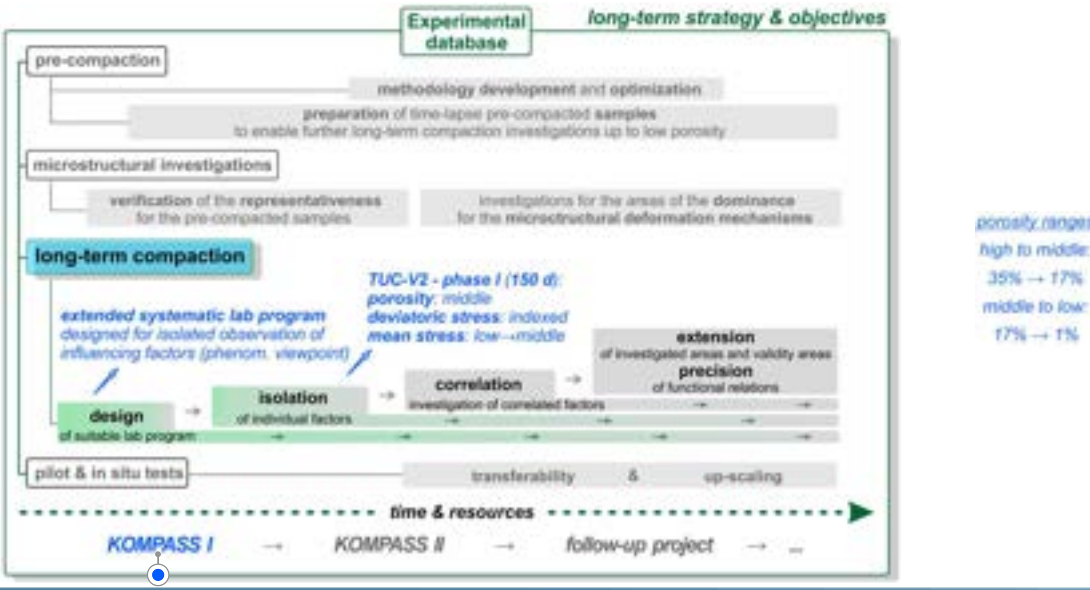






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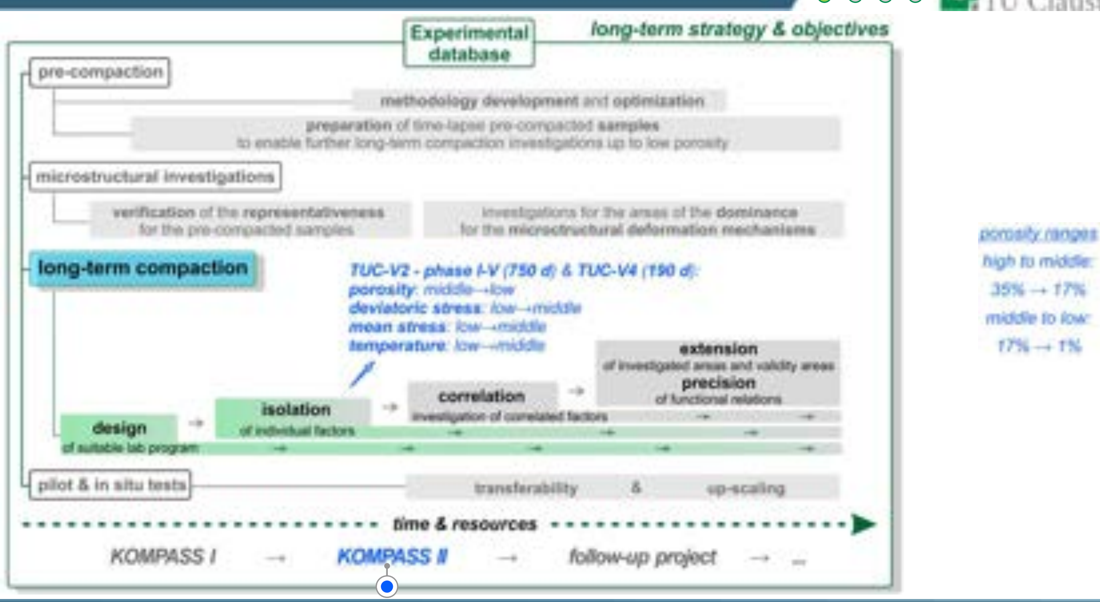
TU Clausthal



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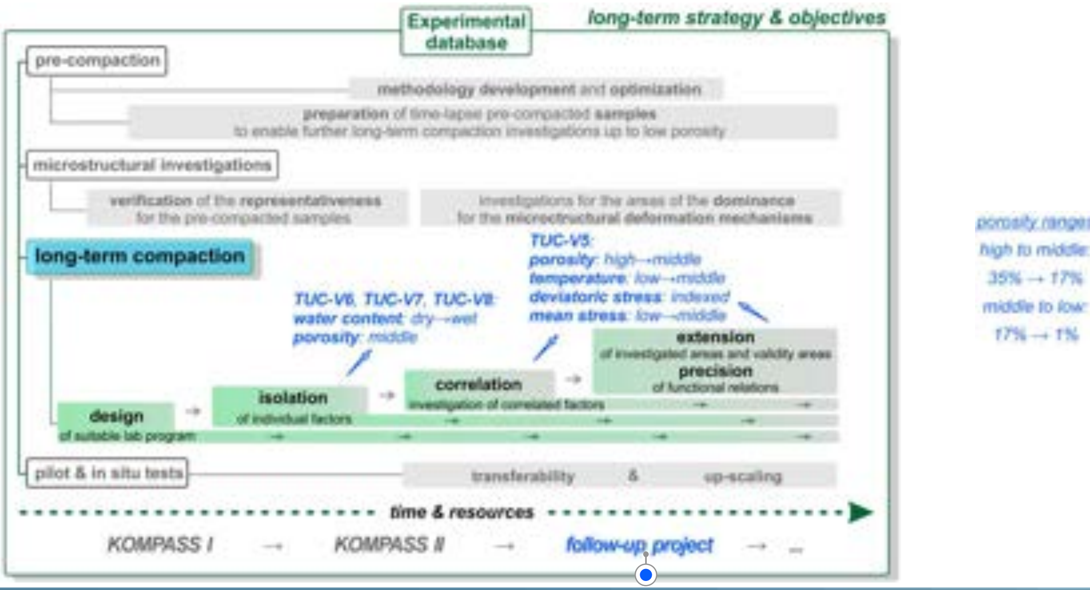
TU Clausthal





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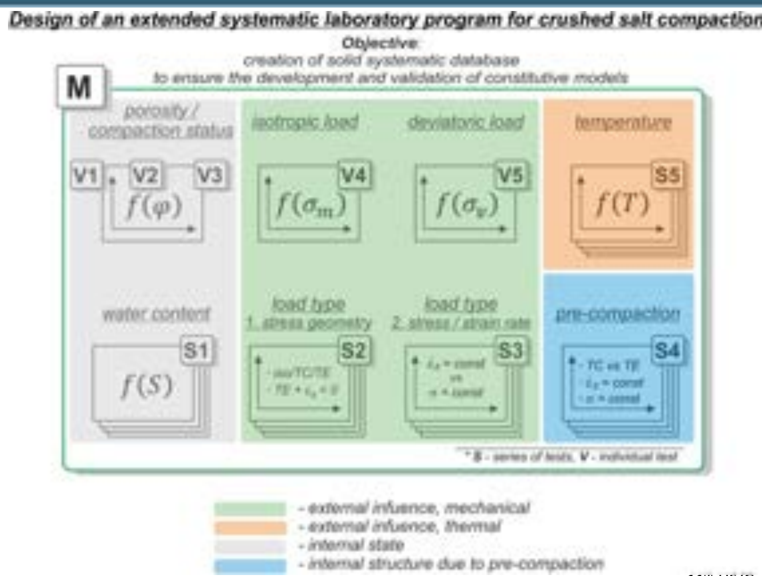
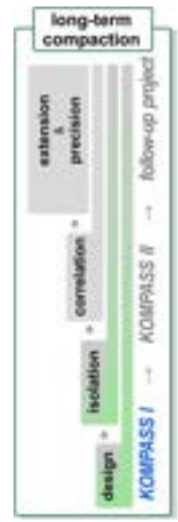
**Outlook**

Long-term **tests planned** for the follow-up project **MEASURES**

KOMPASS II

## Laboratory investigations in the framework of KOMPASS I

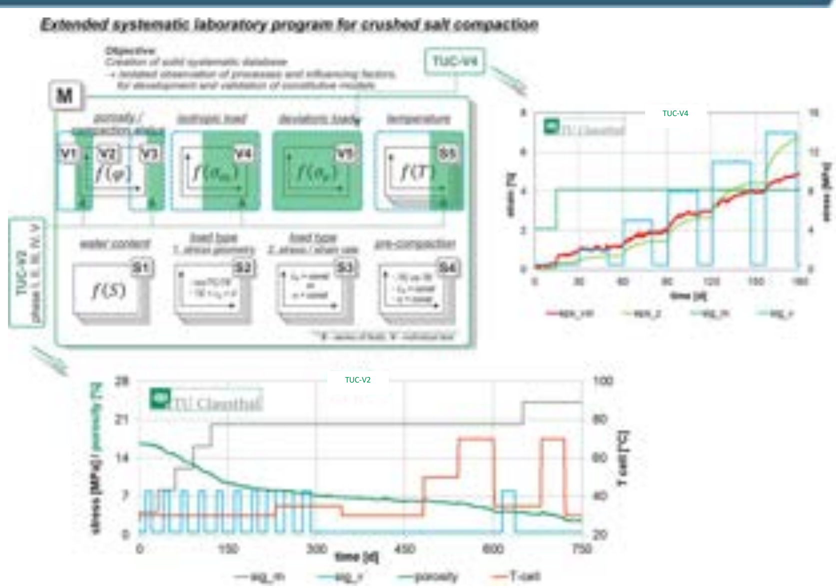


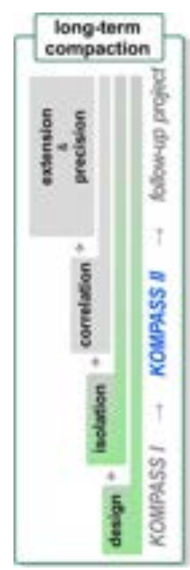




*11th US/German Workshop, 2021*



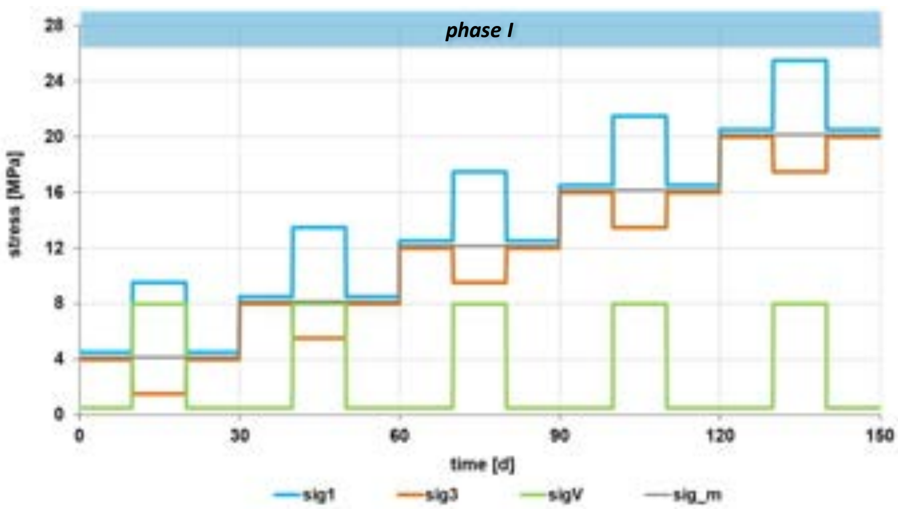
## Laboratory investigations in the framework of KOMPASS II



## Laboratory investigations in the framework of KOMPASS II

**Long-term compaction test TUC-V2**
**Phase I → 5 isotropic load steps with deviatoric load phases (one level)**







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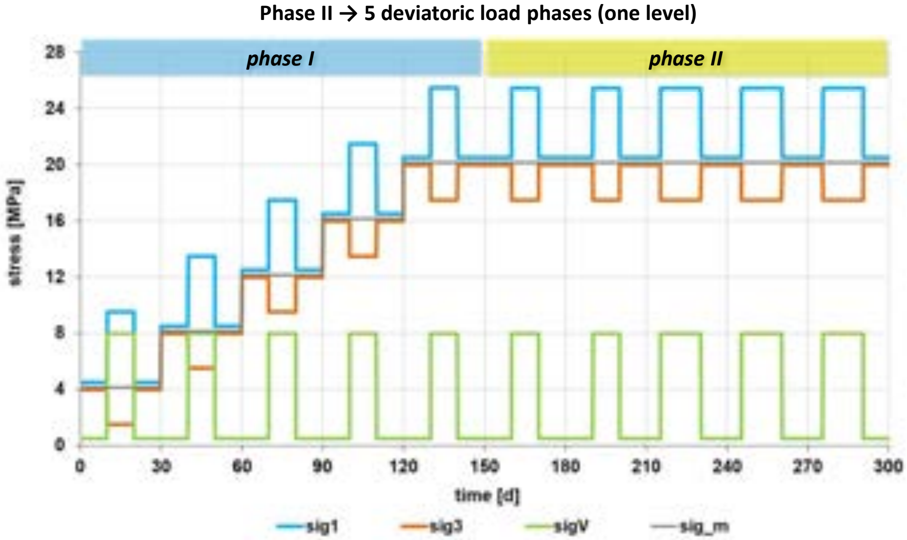
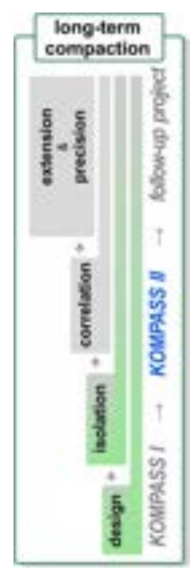
## Laboratory investigations in the framework of KOMPASS II

**Long-term compaction test TUC-V2**
**Phase II → 5 deviatoric load phases (one level)**

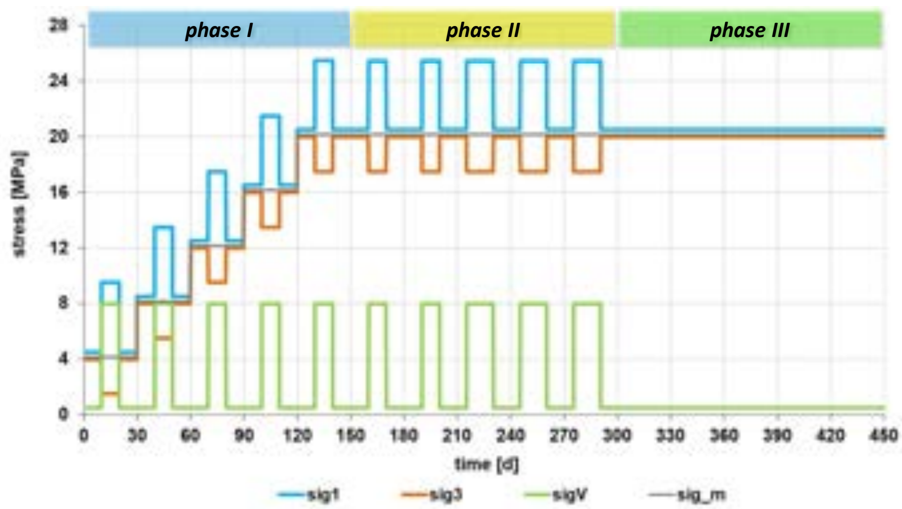


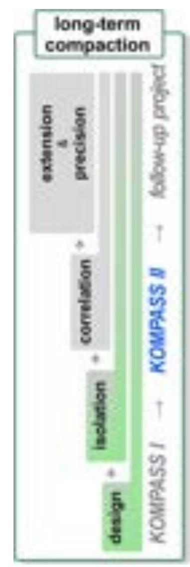



# Laboratory investigations in the framework of KOMPASS II

TU Clausthal

**Long-term compaction test TUC-V2**
**Phase III → long term behavior under constant load**



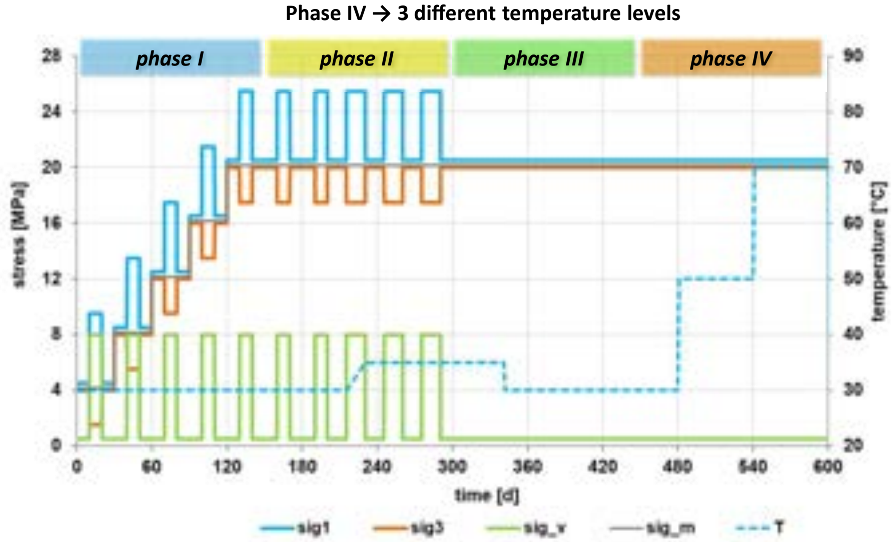



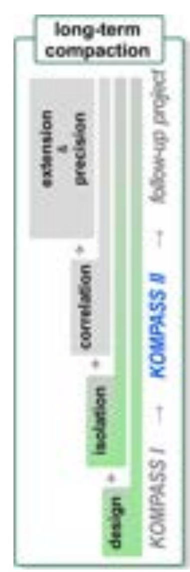



# Laboratory investigations in the framework of KOMPASS II

TU Clausthal

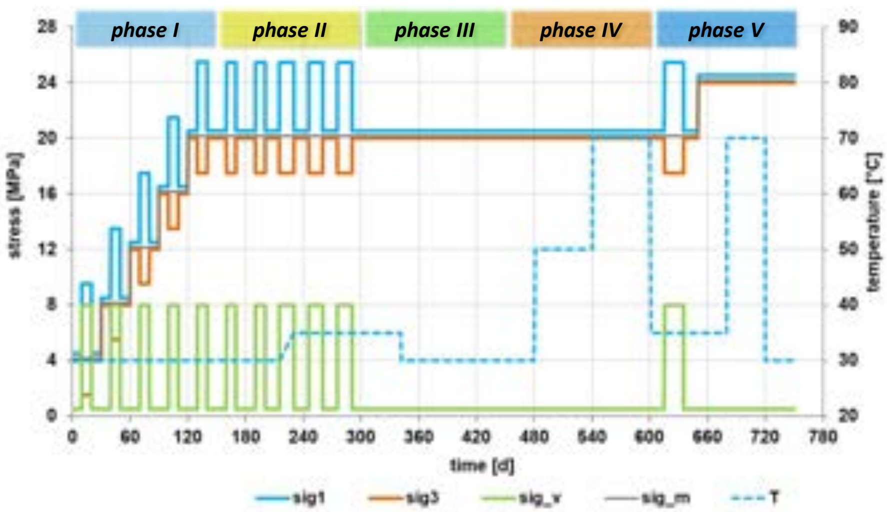
**Long-term compaction test TUC-V2**
**Phase IV → 3 different temperature levels**



## Laboratory investigations in the framework of KOMPASS II

**Long-term compaction test TUC-V2**
**Phase V → repeated activation of investigated factors for low porosity**





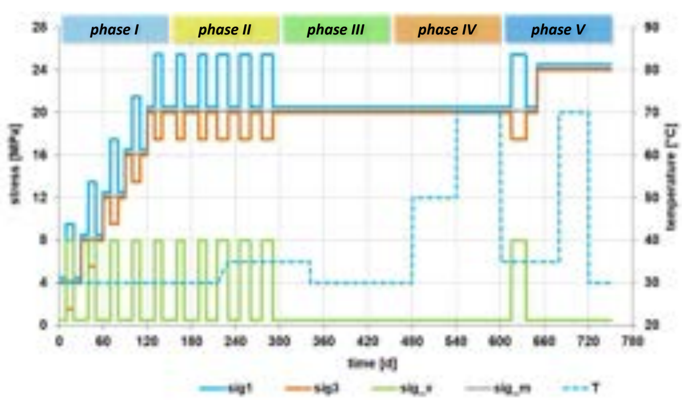


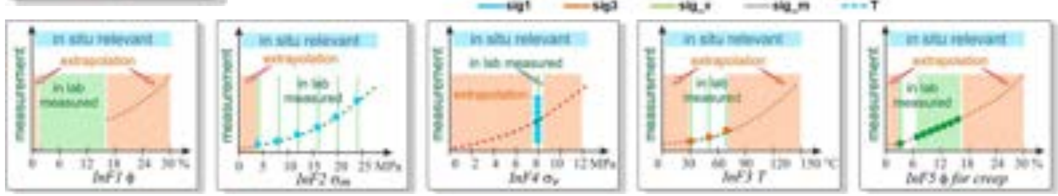
## Laboratory investigations in the framework of KOMPASS II

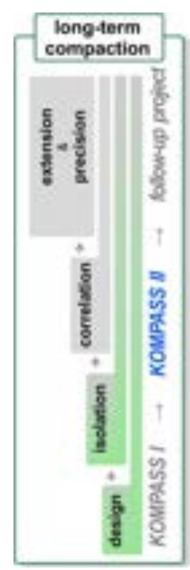
**Influencing factors**
- *InF1* = $\phi$ *for compaction*
- *InF2* = $\sigma_m$
- *InF3* = *T*
- *InF4* = $\sigma_v$ (!)
- *InF5* = $\phi$ *for creep*

**Boundary conditions B/C**
material: Sondershausen
isotropic & deviatoric phases
- 6 levels of $\sigma_m$
- 3 levels of *T*
- 1 level of $\sigma_v$, 11 phases

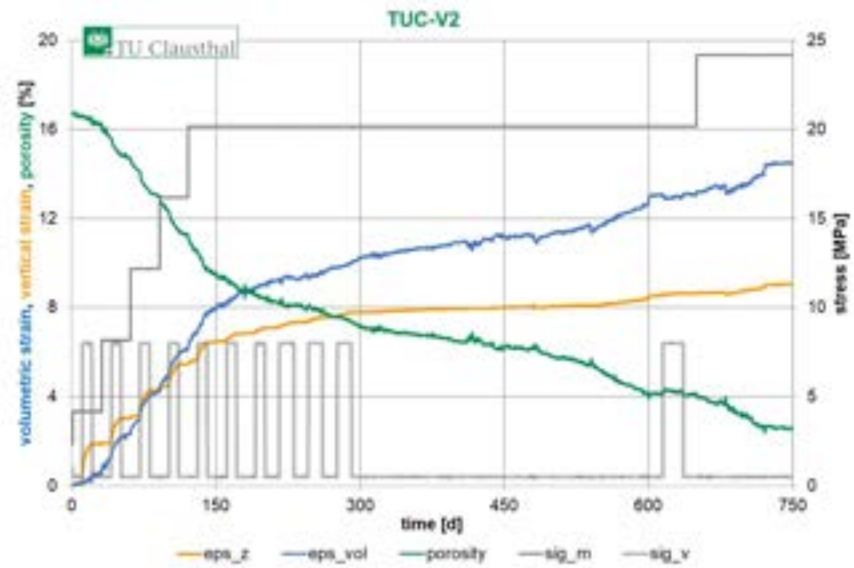
**Investigated areas/ranges**
- $\phi$ → 16.7% – 3% (!)
- $\sigma_m$ → 4/8/12/16/20/24 MPa
- *T* → 30/50/70 °C
- $\sigma_v$ = 8 MPa
- w = 0.5%
- t = 750 d (!)



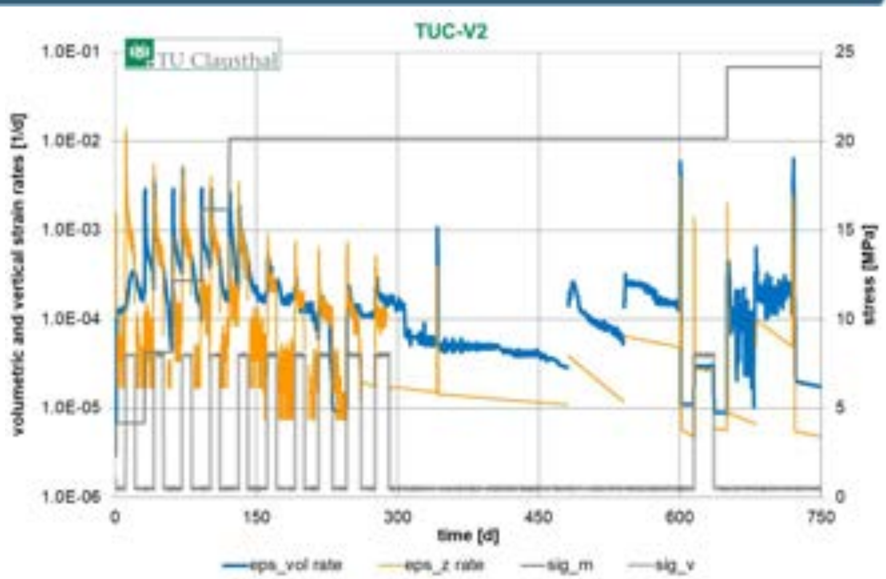
## Laboratory investigations in the framework of KOMPASS II

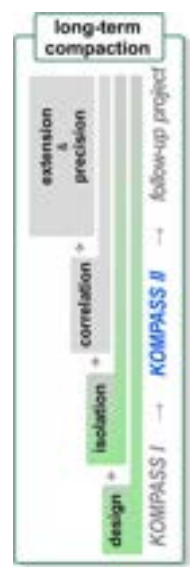






## Laboratory investigations in the framework of KOMPASS II



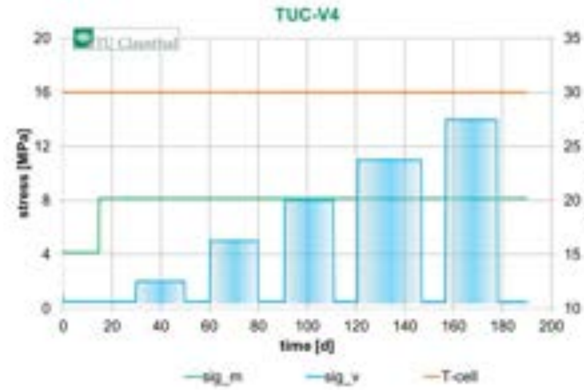
# Laboratory investigations in the framework of KOMPASS II

TU Clausthal

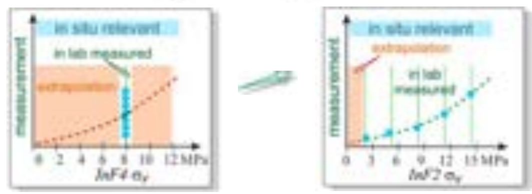
**Influencing factors**
- $InF1 = \phi$
- $InF2 = \sigma_v$

**Boundary conditions B/C**
material: Sondershausen
isotropic & deviatoric phases
- 5 levels of $\sigma_v$
- 2 levels of $\sigma_m$
  → comparable to TUC-V2

**Investigated areas/ranges**
- $\phi$ → 16.7% ~ 12.4%
- $\sigma_m$ → 2/5/8/11/14 MPa (!)
- $T$ = 30 °C
- w = 0.5%
- t = 190 d




TUC-V2



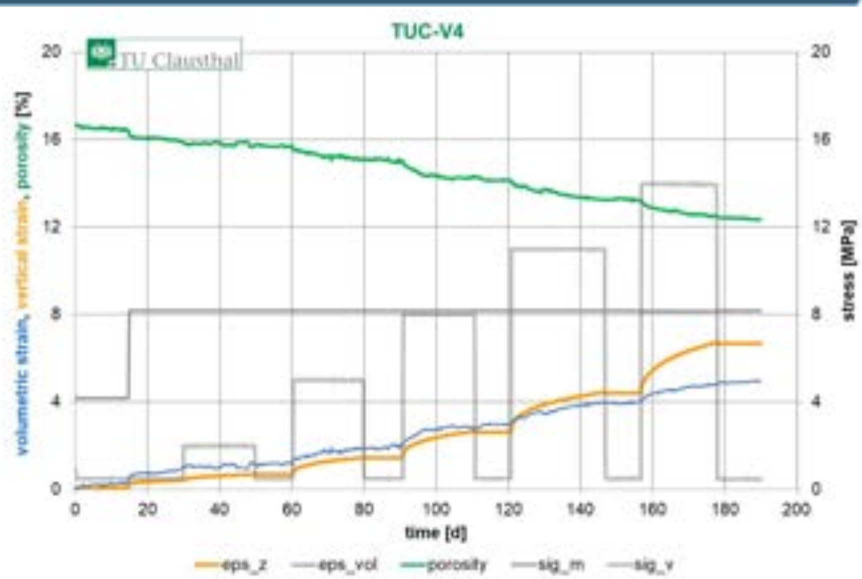

TUC-V4

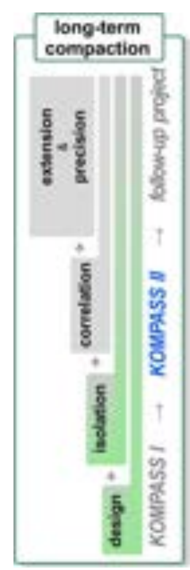




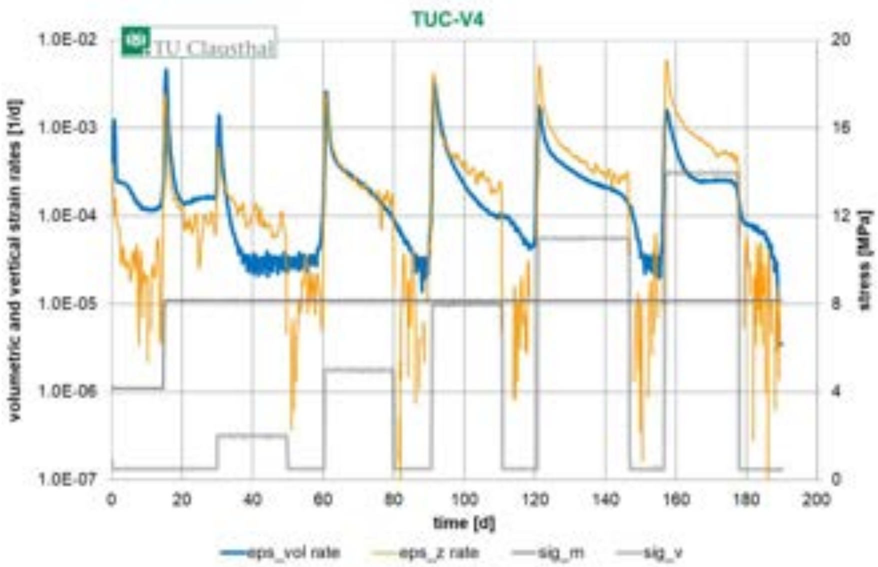

# Laboratory investigations in the framework of KOMPASS II

TU Clausthal



## Laboratory investigations in the framework of KOMPASS II









# Agenda

**Intro**

**Long-term strategy** for the experimental investigations

**Main part**

1. **Laboratory investigations** in the framework of **KOMPASS II**
2. **Modeling benchmark** on long-term test **TUC-V2**

**Outlook**

Long-term **tests planned** for the follow-up project **MEASURES**

KOMPASS II

## Modeling benchmark on long-term test TUC-V2

**Involved modeling approaches**

| microstructurally based modeling approaches | | | phenomenological approaches | | |
|---|---|---|---|---|---|
| Olivella/Gens | CS3 | Callahan | Hein/Korthaus | EXPO-COM | C-WIPP-IfG |



## Modeling benchmark on long-term test TUC-V2

**Involved modeling approaches**

| microstructurally based modeling approaches | | | phenomenological approaches | | |
|---|---|---|---|---|---|
| Olivella/Gens | CS3 | Callahan | Hein/Korthaus | EXPO-COM | C-WIPP-IfG |

*model **optimized** in the framework of KOMPASS II* (Olivella/Gens)

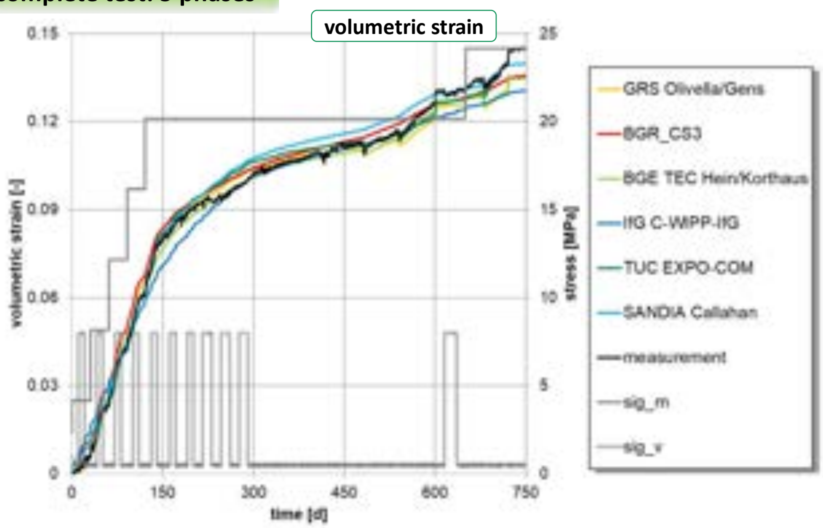
*__new__ model, __developed__ in the framework of KOMPASS II* (EXPO-COM)

*model **optimized** in the framework of KOMPASS II* (C-WIPP-IfG)

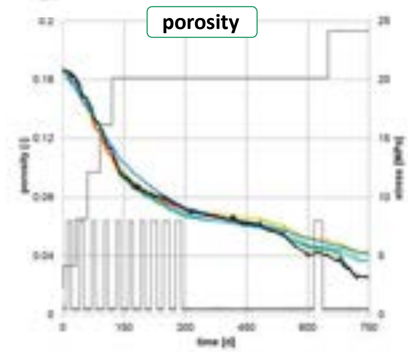
# Modeling benchmark on long-term test TUC-V2

TU Clausthal

**complete test: 5 phases**




**In general**
relatively good agreement
with measurements
for all models



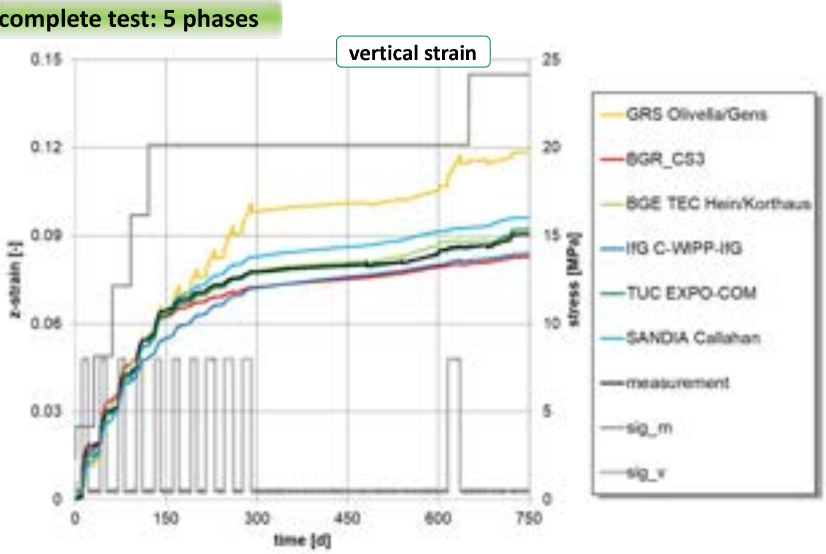


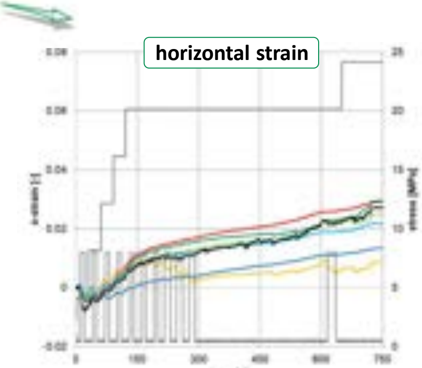



# Modeling benchmark on long-term test TUC-V2

TU Clausthal

**complete test: 5 phases**



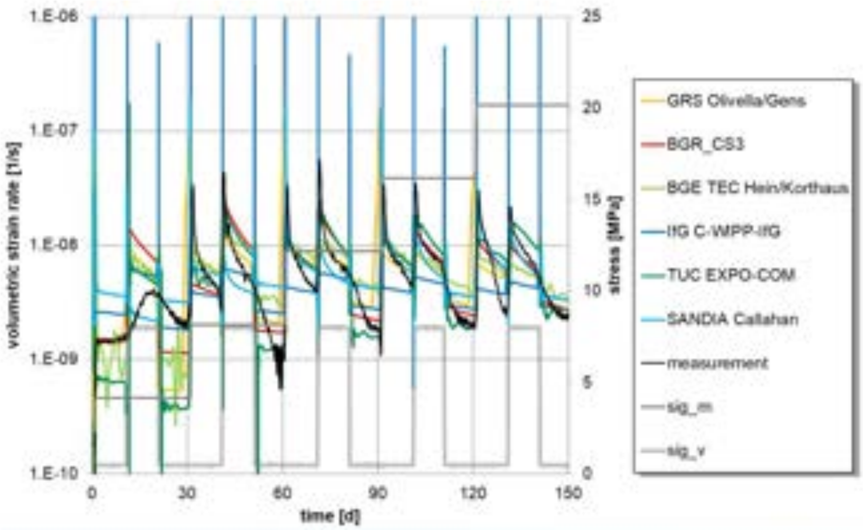
# Modeling benchmark on long-term test TUC-V2

**Phase I**

Investigated effects
on compaction creep:
- f(porosity)
- f(mean stress)
- f(deviatoric stress)

Criteria for evaluation
of the successful
reproduction of the
reaction of the sample:
- reaction: Yes/No
- magnitude
- development

**volumetric strain rate**




**Detailed analysis**
**by strain rates**
**&**
**phase by phase**



TU Clausthal

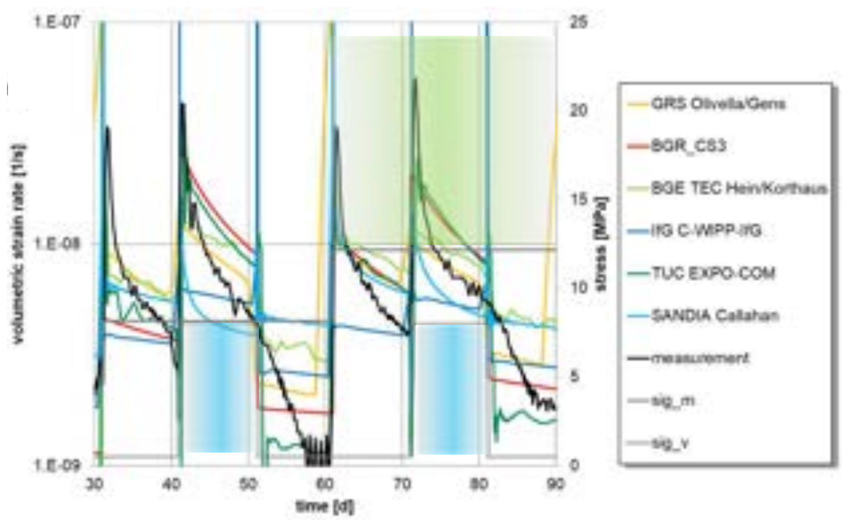
# Modeling benchmark on long-term test TUC-V2

**Phase I**

Investigated effects
on compaction creep:
- f(porosity)
- f(mean stress)
- f(deviatoric stress)

Findings:
- mean stress level change: moderate scattering
- activation of deviatoric load: slightly larger scattering
- development of the strain rate within each stress level (curve progression shape): mostly appropriate by Callahan

**volumetric strain rate**



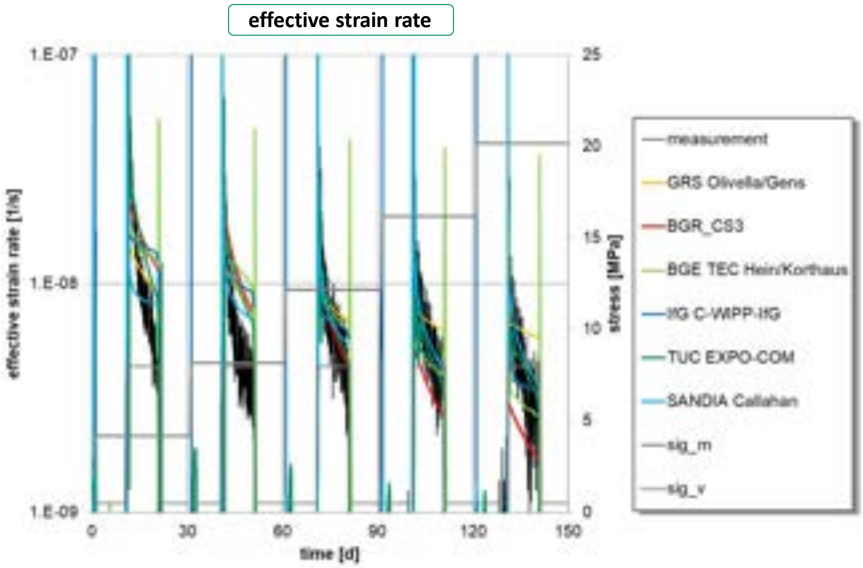
## Modeling benchmark on long-term test TUC-V2



**Phase I**

Investigated effects
on volume-true creep:
- f(porosity)

Findings:
- magnitude of the effective strain rates correctly reproduced, minor scattering







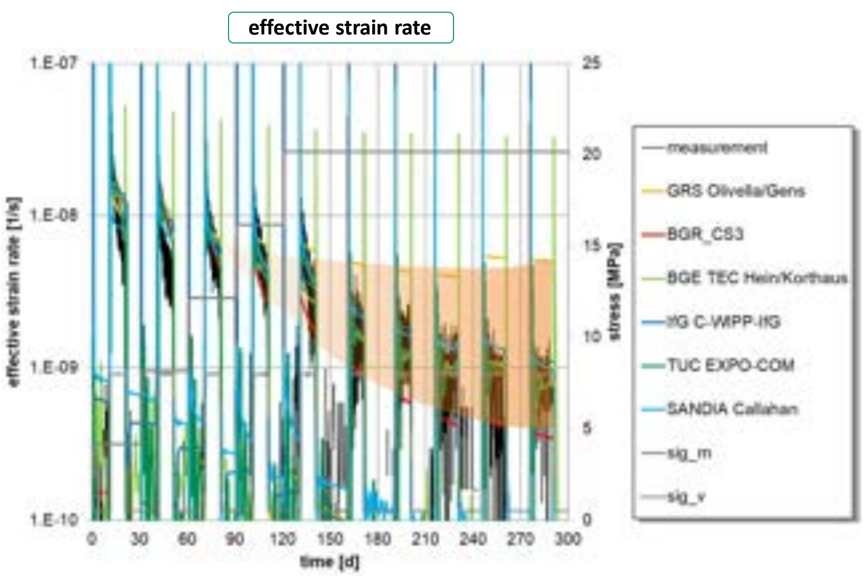

## Modeling benchmark on long-term test TUC-V2



**Phases I & II**

Investigated effects
on volume-true creep:
- f(porosity)

Findings:
- magnitude & development: significant increase of differences between models as well as of deviation from measurements



## Modeling benchmark on long-term test TUC-V2

TU Clausthal

### Phase V

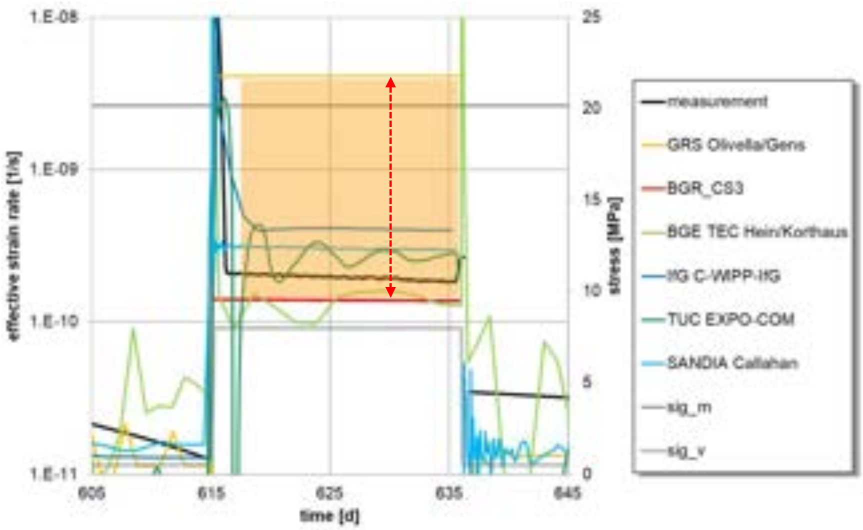
Investigated effects
on volume-true creep:

- f(porosity)

Findings:

- magnitude:
  → low porosity reached:
  creep ability similar to **rock salt** to be expected
  → still large deviation from measurement results for some models

**effective strain rate**






## Modeling benchmark on long-term test TUC-V2

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### Phases IV & V

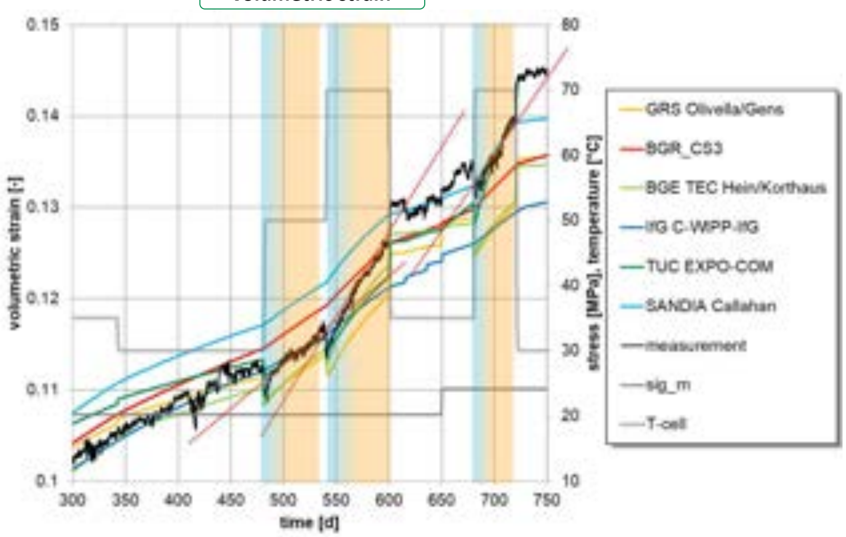
Investigated effects
on compaction creep:

- f(temperature)

Findings:

- T change 30°C to 50°C:
  compaction rate change reproduced relatively well in all models
- T change 50°C to 70°C:
  → underestimations in all models: slight to significant
  → best agreement by EXPO-COM, Olivella/Gens & Hein/Korthaus
- T change 35°C to 70°C:
  → large scattering of results: underestimations as well as overestimations
  → best agreement by Callahan

**volumetric strain**



# Modeling benchmark on long-term test TUC-V2

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**Phases IV & V**

Investigated effects
on compaction creep:

- f(temperature)

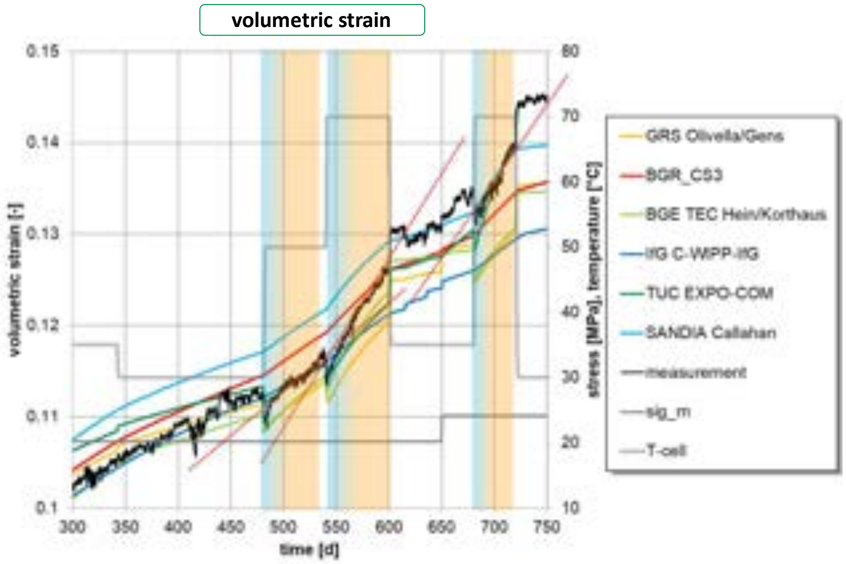
Findings:
almost all models are affected by the heterogeneity of the representation of the compaction behavior as a function of temperature

→ understanding for areas of dominance for microstructural deformation mechanisms relevant

→ extension of the laboratory investigated area sufficient

⬇

**MEASURE**






# Modeling benchmark on long-term test TUC-V2

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**Modeling Benchmark Summary**

Reached **Milestones**, detected **Shortcomings** and **Outlook** Points

- Experiment **TUC-V2** enables

  **development**, **validation** and **parameter determination** of investigated influencing factors:

  mean stress, deviatoric stress (indexed), temperature, porosity (middle to low)

- **Detailed comparative analysis** of the **benchmark results** allows

  to **detect** the **shortcomings** and the **advantages** of individual modeling approaches

- Detected **shortcomings, gaps in understanding** and **in database**

  **can be removed** by the planned investigations within the follow-up project **MEASURES**

# Agenda

Intro

**Long-term strategy** for the experimental investigations

Main part

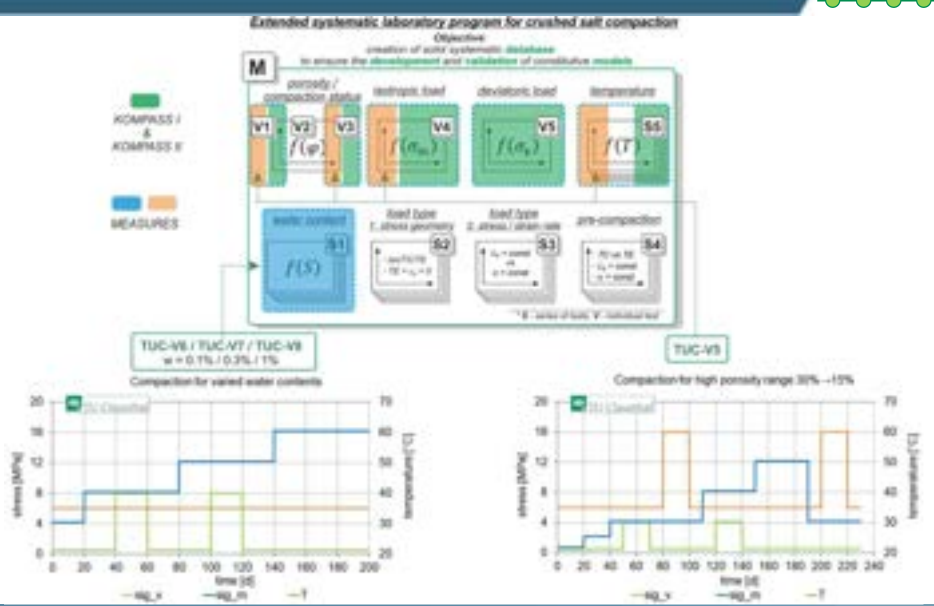
1. **Laboratory investigations** in the framework of **KOMPASS II**
2. **Modeling benchmark** on long-term test **TUC-V2**

Outlook

Long-term **tests planned** for the follow-up project **MEASURES**

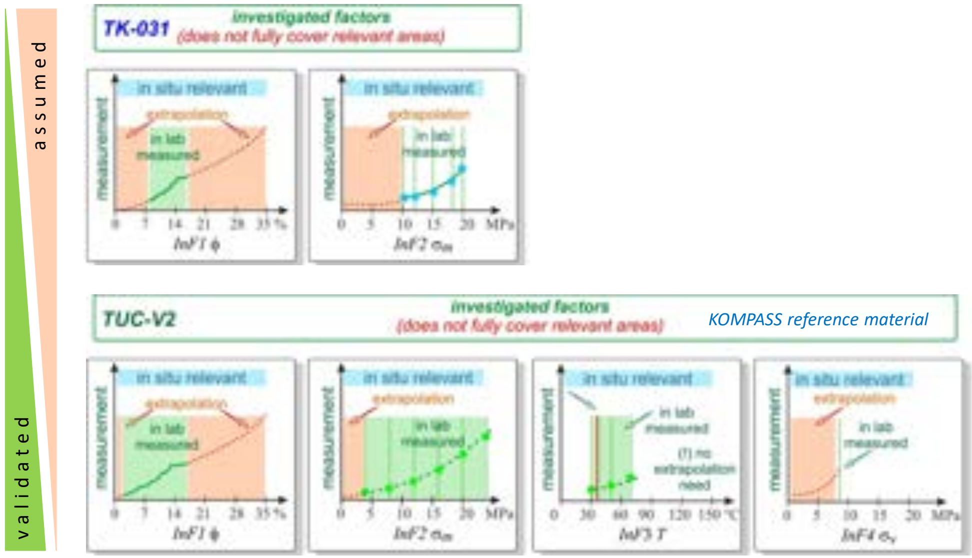


## Long-term tests planned for the follow-up project MEASURES



## Long-term tests planned for the follow-up project MEASURES

TU Clausthal




→ KOMPASS I

→ KOMPASS II



## Long-term tests planned for the follow-up project MEASURES

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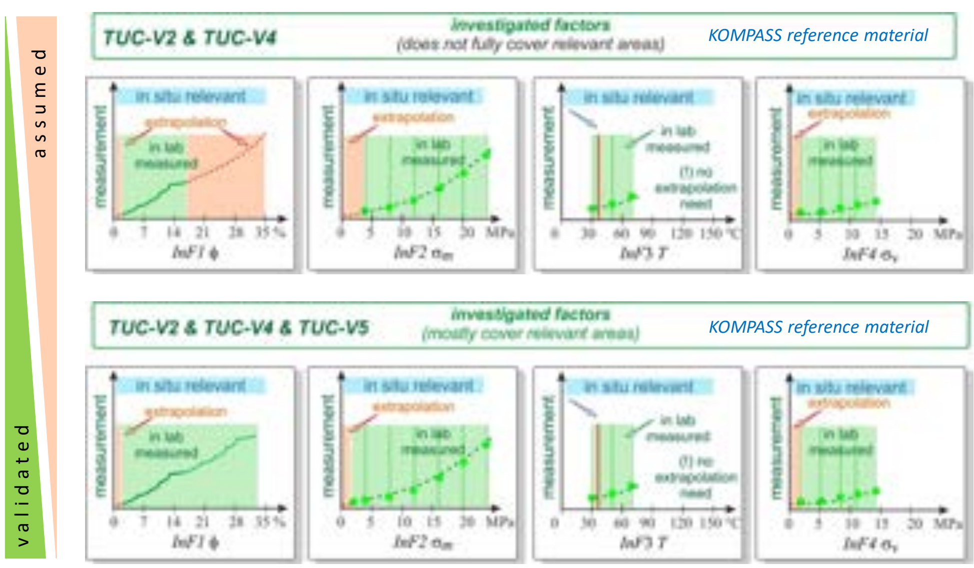


→ MEASURE

→ ...

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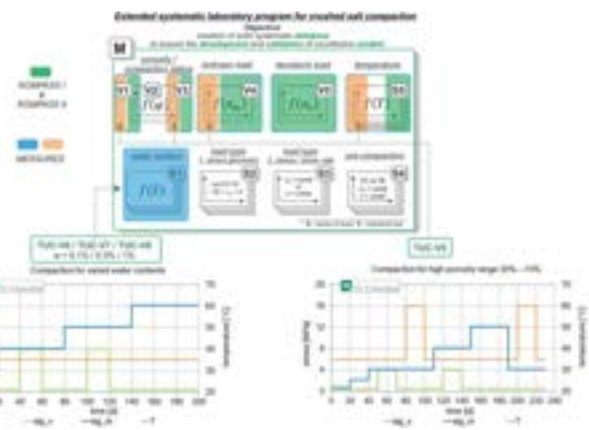
*Thank you for your attention*

*Questions ?*



KOMPASS II



## EXTRAS

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# EXTRAS

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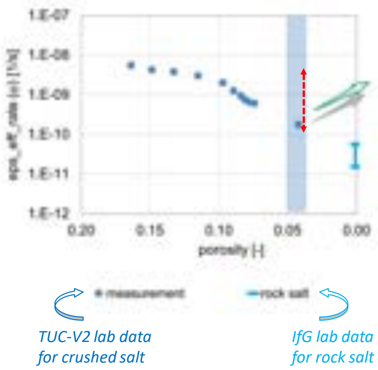
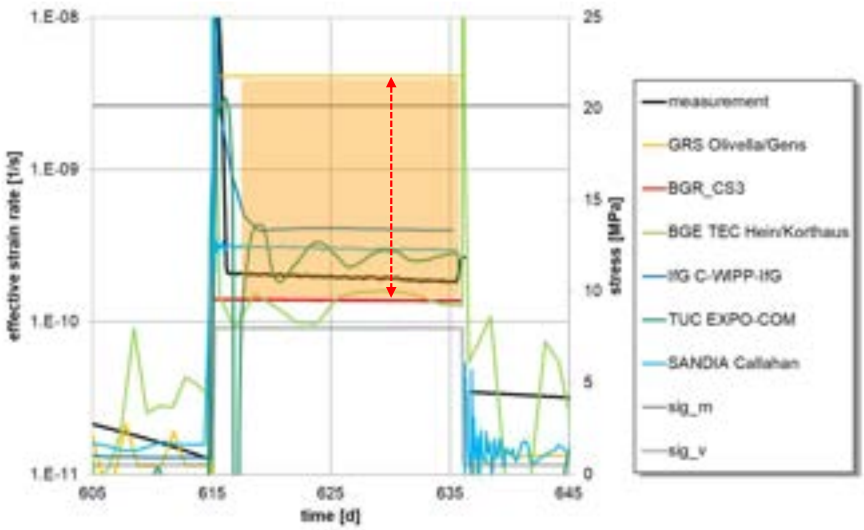
**Phase V**

Investigated effects
on volume-true creep:

- f(porosity)




effective strain rate





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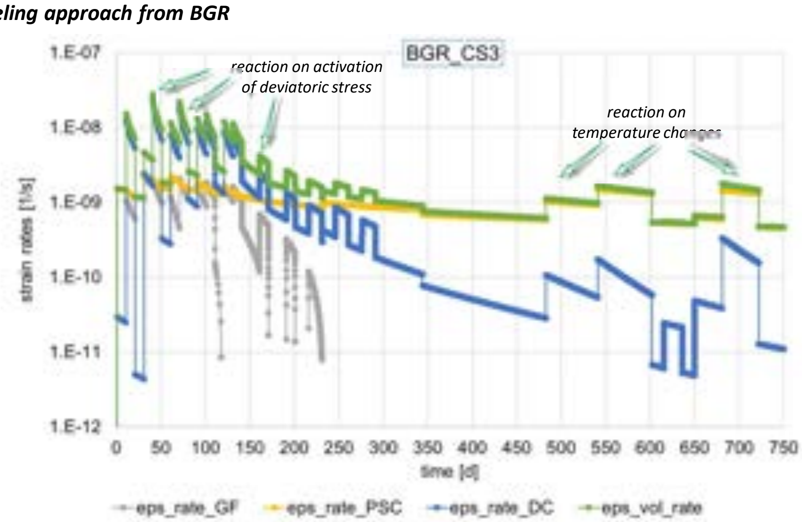
***Individual microstructural mechanisms: modeling approach from BGR***

Realized:

- Analysis of modeling assumptions
  for areas of dominance for individual
  microstructural deformation mechanisms
  → for different porosity ranges
  → for the response to the level change
  of specific influencing factors

Meaningful next steps:

- comparison with assumptions of
  other model approaches meaningful
- based on the findings on differences
  in the assumptions: planning of lab tests
  to verify these assumptions:
  planning of the tests from the point of view
  of microstructural deformation mechanisms




- GF - grain fracture
- DC - dislocation creep
- PSC - pressure solution

## EXTRAS

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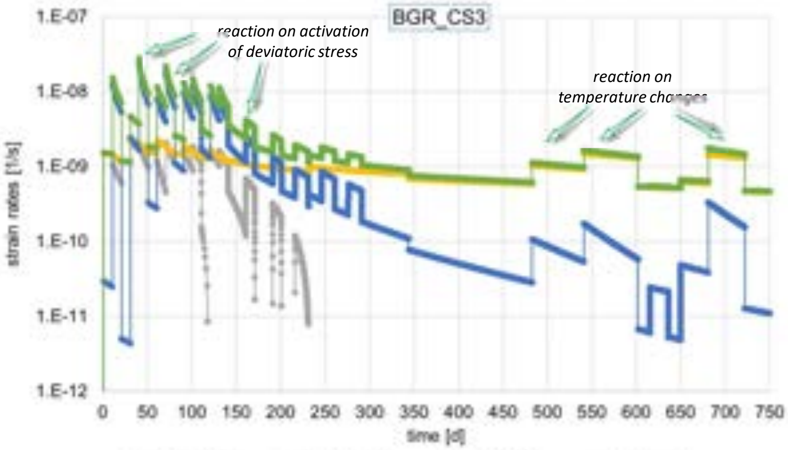
***Individual microstructural mechanisms: modeling approach from BGR***

Recognizable modeling <u>assumptions</u>:

- <u>grain fracture mechanism GF</u>
  impact is relevant
  even for the middle range of porosity (<17%)
- <u>pressure solution mechanism PSC</u>
  → dominant after 300d (porosity of ca. 7%)
  → predominates the response
  to temperature change
  in all three temperature load steps
  → does not react to the
  activation of deviatoric stress
- <u>dislocation creep mechanism DC</u>
  reacts significantly to the
  activation of deviatoric stress




- GF - grain fracture
- DC - dislocation creep
- PSC - pressure solution



## EXTRAS

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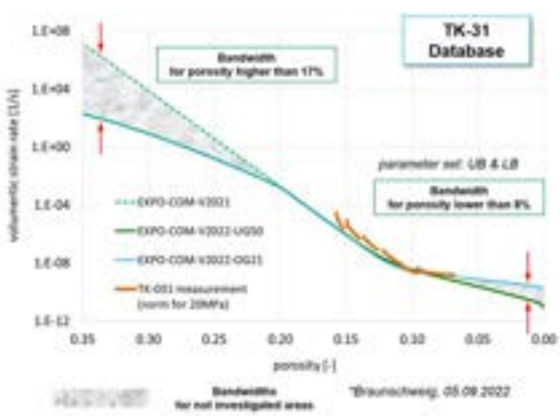


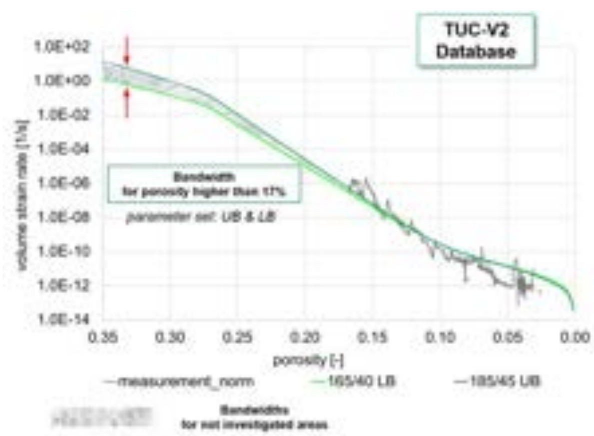

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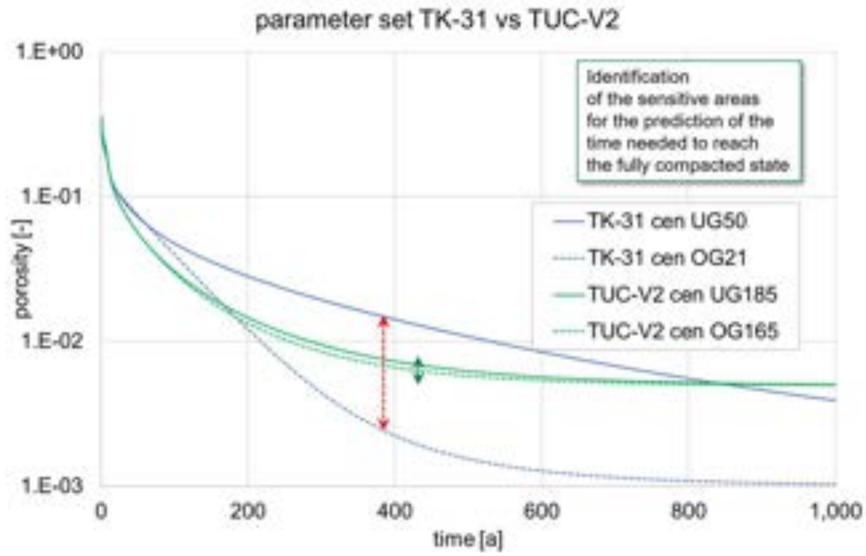




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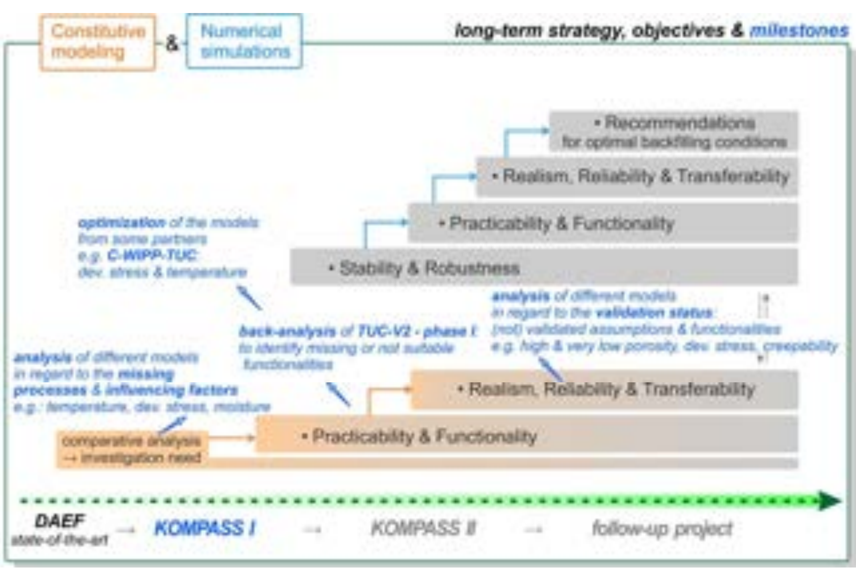

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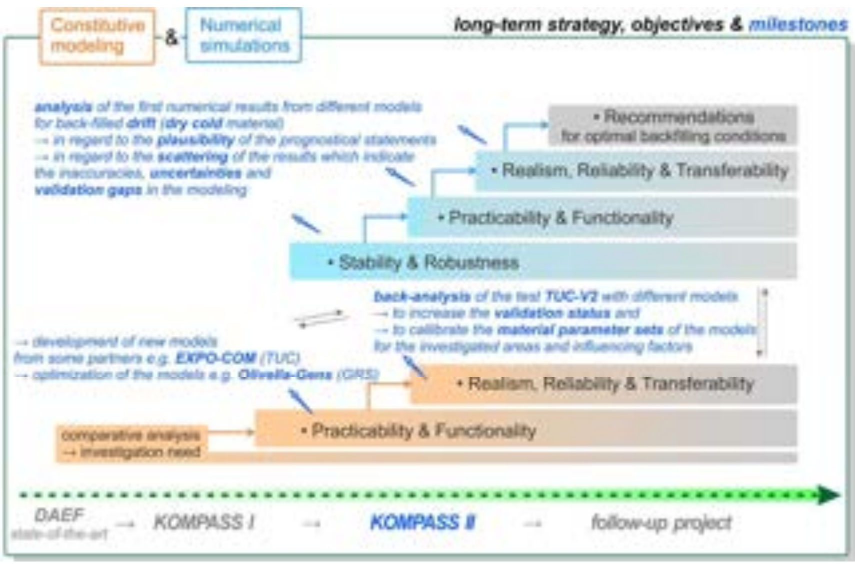






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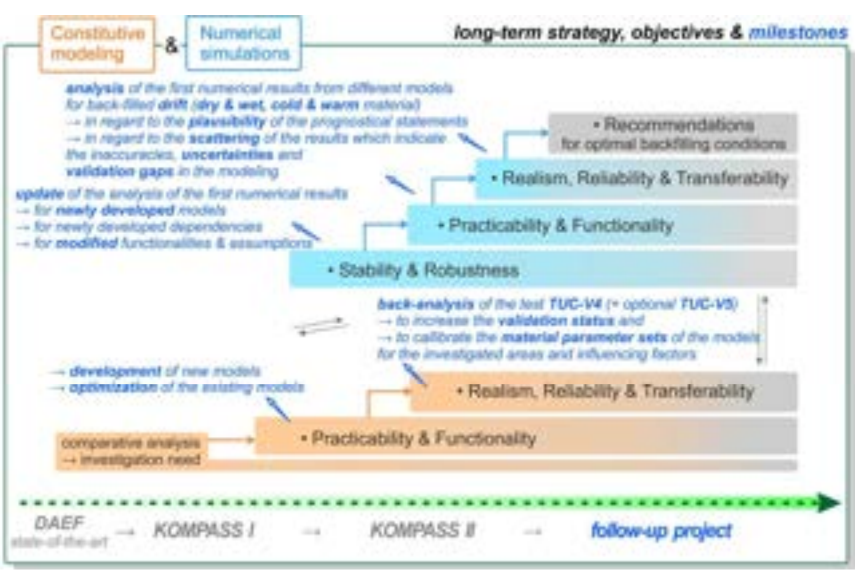

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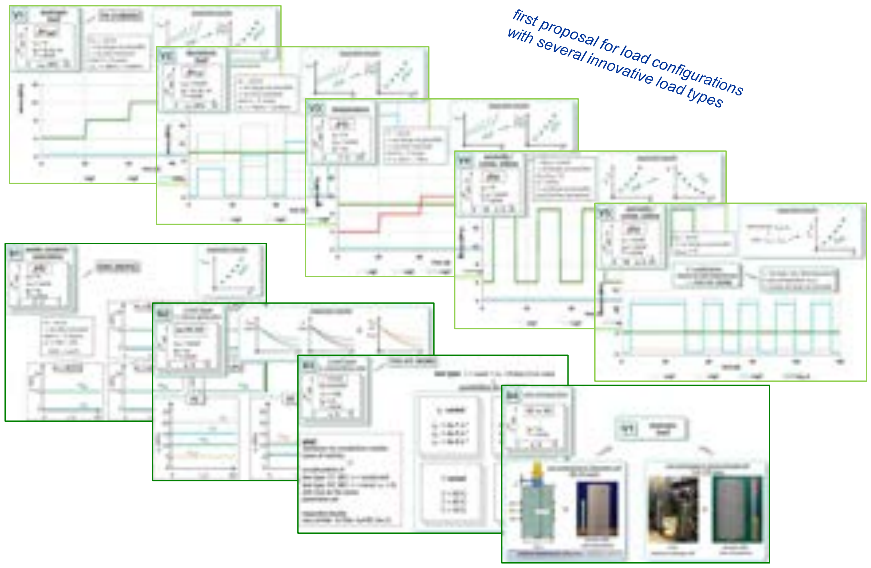




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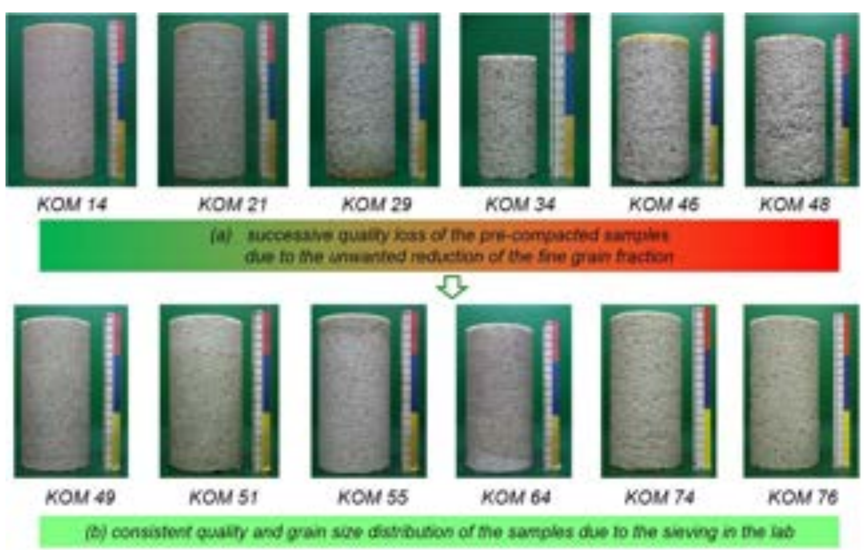
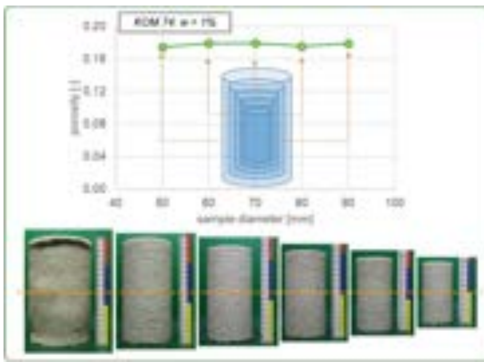
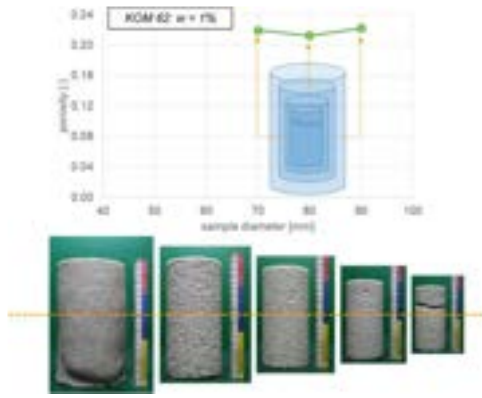
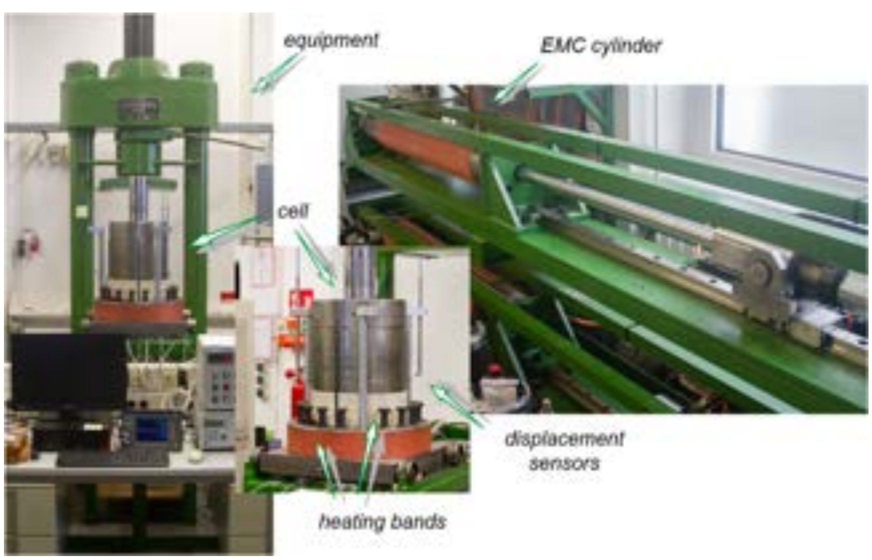




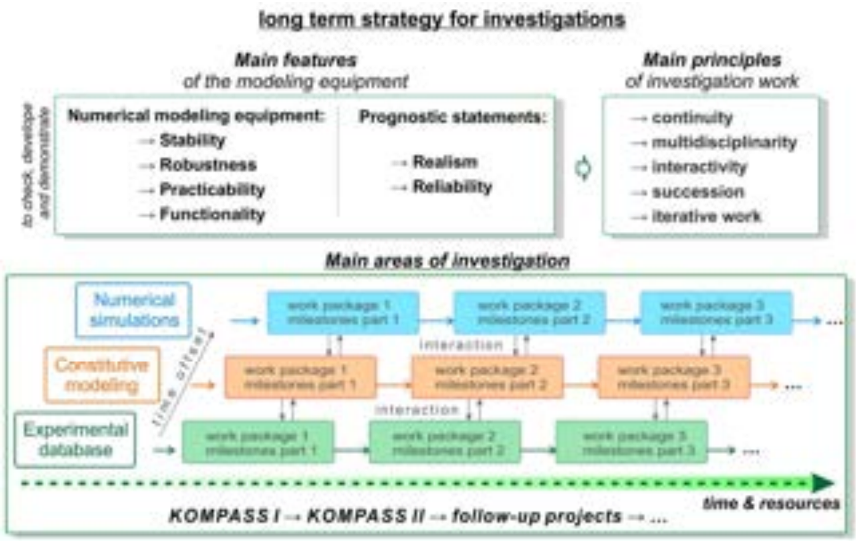






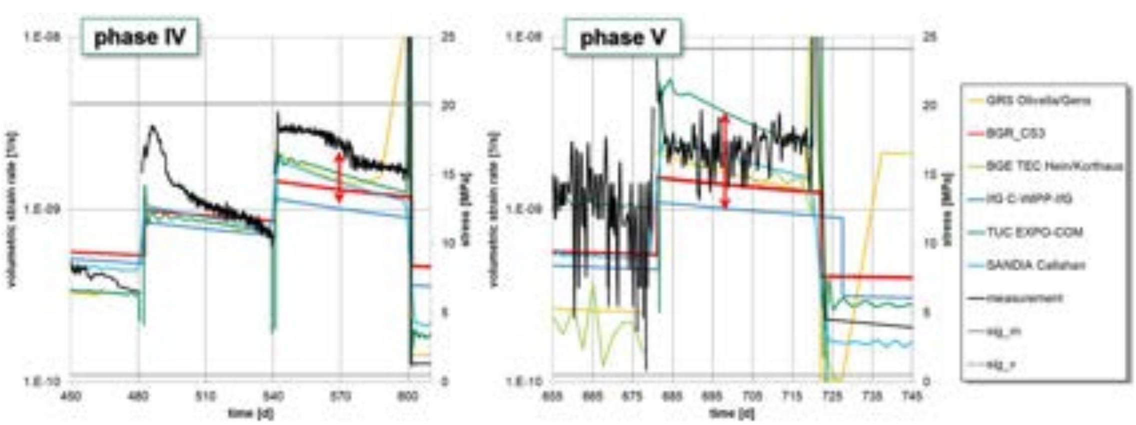

equipment
EMC cylinder
cell
displacement sensors
heating bands

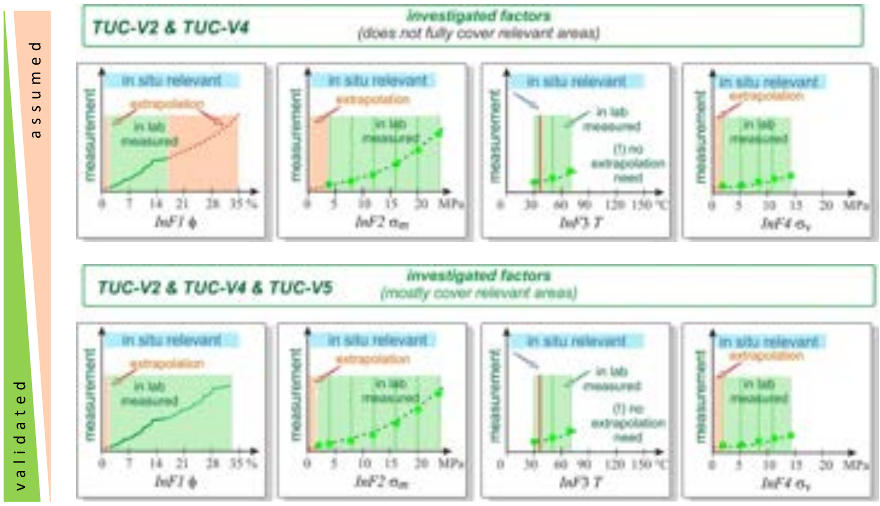
## EXTRAS






## EXTRAS



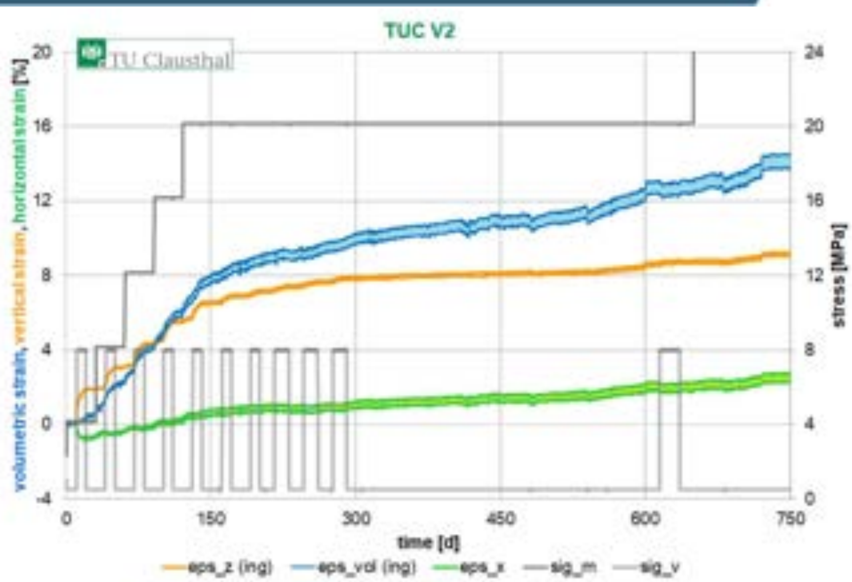



→ MEASURE

*...TUC-V6 to TUC-V8*
**(water content)**
→ ... following ...







# Ongoing Brine Availability Test in Salt (BATS) at WIPP

Richard Jayne and Kris Kuhlman
Sandia National
Laboratories


*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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. SAND2023-05159PE.*

# Agenda

## Intro: Why Salt for Radioactive Waste Disposal?

Salt Long-term Benefits at km-scale

Salt
- Low porosity ($\phi \leq\ 0.1$ vol-%) and permeability ($k \leq 10^{-22}\ \mathrm{m}^2$)
- High thermal conductivity ($\geq 5\ \mathrm{W/m \cdot K}$)
- High peak allowable temperature ($T_{\max} \approx 200$ °C)
- Openings creep closed ($> 10^0 - 10^2$ yr )
- Run-of-mine (granular) salt reverts to intact salt

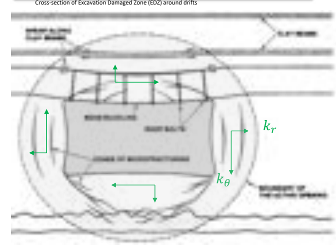
Brine
- No flowing groundwater ($\leq 5$ wt-% water)
- Chlorine ($\geq 190$ g/L) → reduces criticality concerns
- Hypersaline → reduces colloid mobility
- Low water activity ($< 0.75$) → biologically simple

Near-field, Short-term Complexities

EDZ
- Weak salt → large EDZ (~drift/borehole $r$)
- $\phi$ and $k$ higher near drift
- Damage is highly anisotropic ($k_r < k_\theta$)

Alpine miner at WIPP

Cross-section of Excavation Damaged Zone (EDZ) around drifts

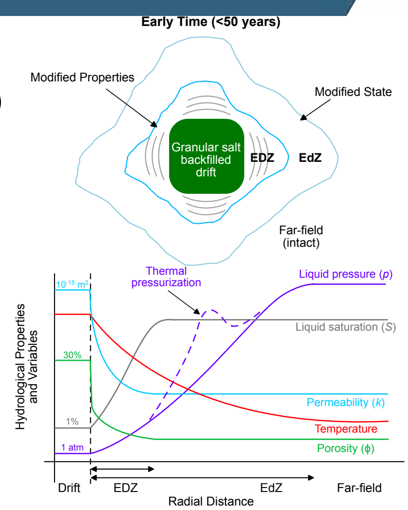


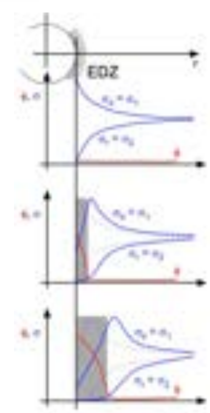

Borns & Stormont (1988)

## Intro: Near-Field EDZ Complexities

- Salt Repository Regions*
  1. Backfilled drift
  2. Excavation Damaged Zone (EDZ)
  3. Excavation disturbed Zone (EdZ)
- Early Time
  - $\Delta\sigma\ \rightarrow$ EDZ → $\Delta\phi \rightarrow \Delta k$
  - Heating → expansion → fracture closing
- Later Time (>10 – 1,000 years)
  - Backfill & EDZ → intact salt
  - EdZ shrinks significantly

*Davies & Bernier (2005)




$\sigma$ = stress, $\phi$ = porosity
$\sigma_r$ = radial stress, $\sigma_\theta$ = hoop stress
Popp (2019)

## Salt Waste Disposal Safety Assessment Strategy

**Q**: Do We *Need* Accurate EDZ Predictions?

**Option 1**: Rely entirely on geology, avoid complex processes
- Enough brine for fast corrosion
- Enough brine to dissolve radionuclides
- Microbial & corrosion gas generation (more driving force)

} Conservative Simplifications

**Option 2**: Account for complex processes
- Heat dries out waste (limits corrosion & transport)
- Thermal expansion in EDZ reduces $k$ & $\phi$
- Few halophilic microbes (less driving force)
- Timing of backfill & EDZ return to intact salt

} Understanding EDZ / Brine Processes

**Option 3**: Fall back on geology, investigate EDZ processes

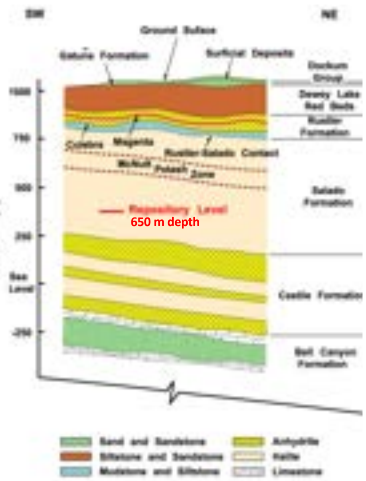
## Brine Availability Test in Salt (BATS)

- Monitoring brine from heated salt using geophysics and sampling
- What is Brine Availability?
  1. Distribution of different types of brine
  2. Evolution of pathways in EDZ

- Why do we care?
  - Brine drives metal corrosion in
    - Waste packages
    - Waste forms
  - Brine transports radionuclides
  - Brine required for gas generation
  - Brine back-pressure resists closure

Sandia National Laboratories · Los Alamos National Laboratory · Berkeley Lab · WIPP

## WIPP: Waste Isolation Pilot Plant

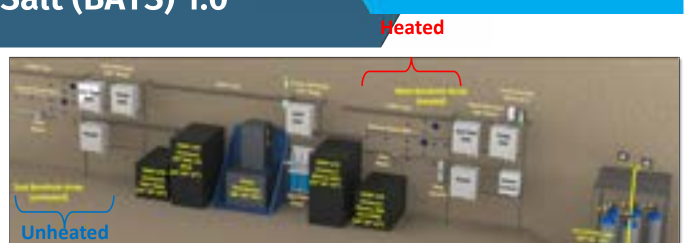



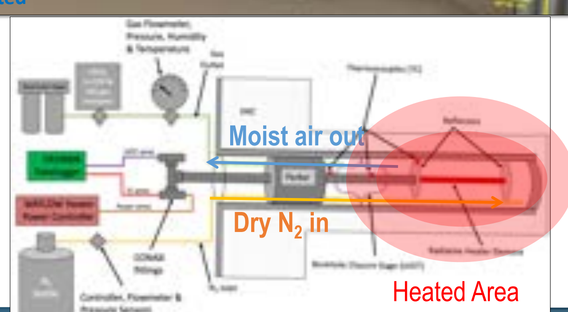

WIPP is for TRU (transuranic) waste run by DOE Office of Environmental Management (DOE-EM)

1. WIPP operating since 1999
2. Cleaning up Cold War legacy
3. WIPP allows us to use their facility

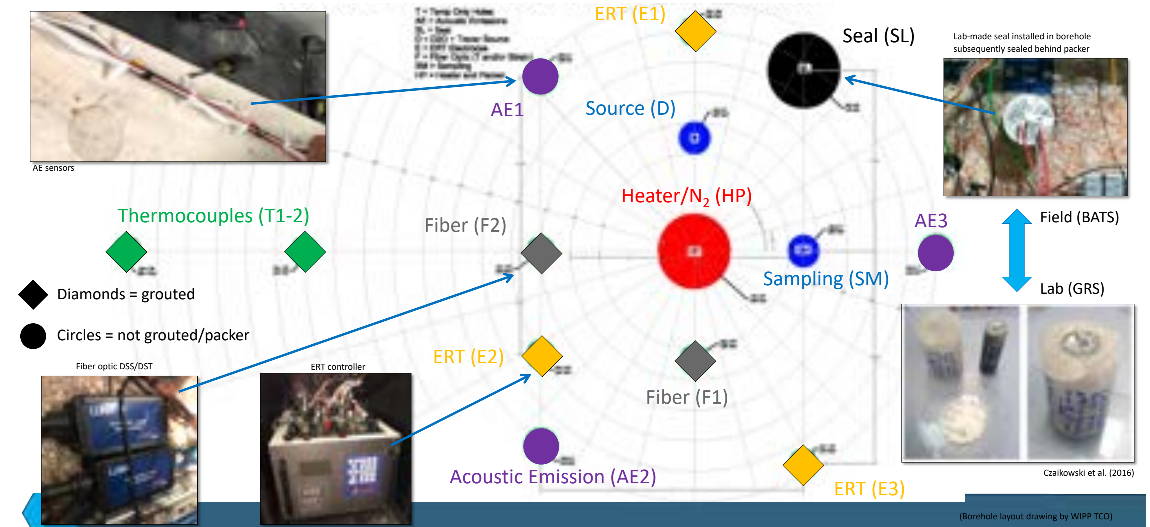
## Brine Availability in Test in Salt (BATS) 1.0

- Two Arrays: Heated / Unheated
- Behind packer
  - Circulate dry $N_2$
  - Quartz lamp heater (750 W)
  - Borehole closure gage
- Samples / Analyses
  - Gas stream (natural / applied tracers)
  - Liquid brine (natural chemistry and tracers)
  - Cores (X-ray CT at NETL)
- Cement Seals
  - Sorel cement + Salt concrete
- Geophysics
  - 3× Electrical resistivity tomography (ERT)
  - 3× Acoustic emissions (AE)
  - 2× Fiber optic distributed sensing



## BATS 1.0 Borehole Arrays

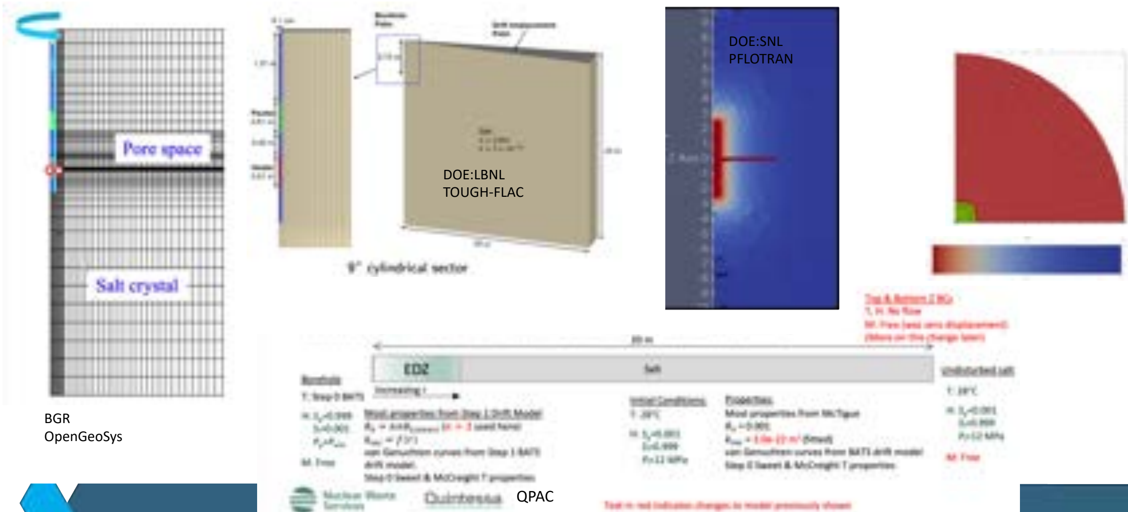



## What Have We Learned from BATS?

- Observations
  - Heating & cooling damage salt
  - Thermally induced fracture closing
  - Thermal pressurization reduces inflow
- Next generation of repository scientists
  - Last significant US testing in salt in 1980s
  - WIPP may be only active radwaste URL in US
- DOE/SNL International collaborations
  - DEvelopment of COupled models and their VALidation against Experiments (DECOVAELX)
    - Task E: BATS test
    - Task F: Granite or salt performance assessment
  - 13th US/German Workshop

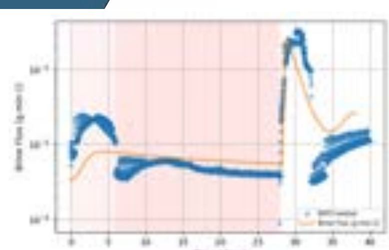

DECOVALEX 2023

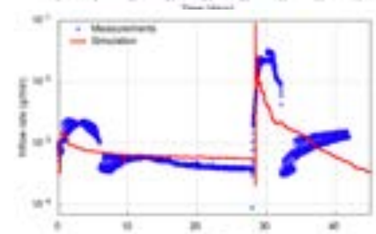
## DECOVALEX Task E: Model Domains




## DEOVALEX Lessons Learned / What Matters?

- Hydrological Initial conditions
  - Wetting up vs. drying down
  - Drying down is *simpler to implement* (but too much early brine)
- Changing permeability during cooling
  - Assigned change
  - Physics-based THM tensile damage
- Viscoplastic salt model gives better fit
  - Better predictions, even in ~short test (3 weeks)
- Additional laboratory tests in salt?
  - Some key model coefficients at meso-scale (> cm scale)
  - Biot, thermal expansion, salt viscoplastic model parameters, two-phase flow properties





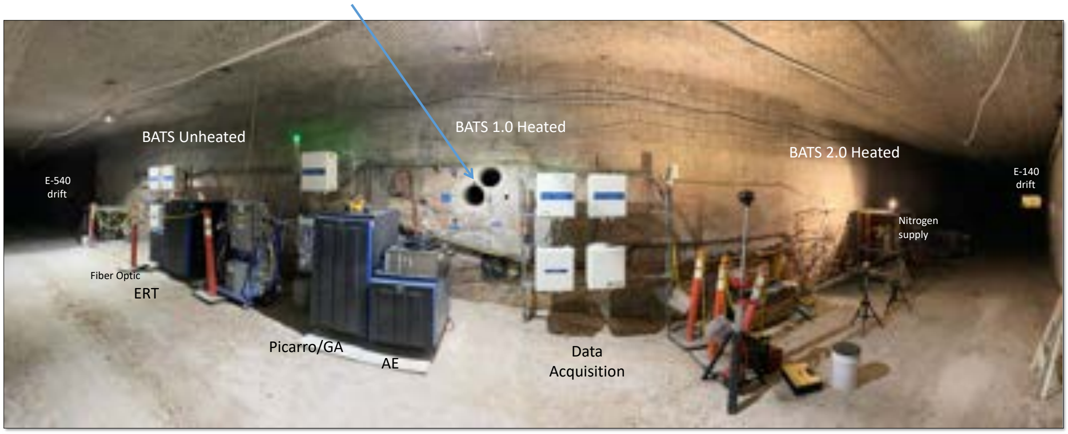
# BATS 1-2 Test Stages

- BATS 1
  - one heating/cooling phase (Jan-Mar 2020)
- **COVID-19**
- BATS 1 (cont.)
  - b/c Tracer tests (Jan-July 2021)
  - Post-test overcoring (Oct 2021)
- BATS 2
  - New heated array drilled (Jan-Feb 2022)
  - Multi-phase heating test (June 2022 - now)

Collecting BATS overcore

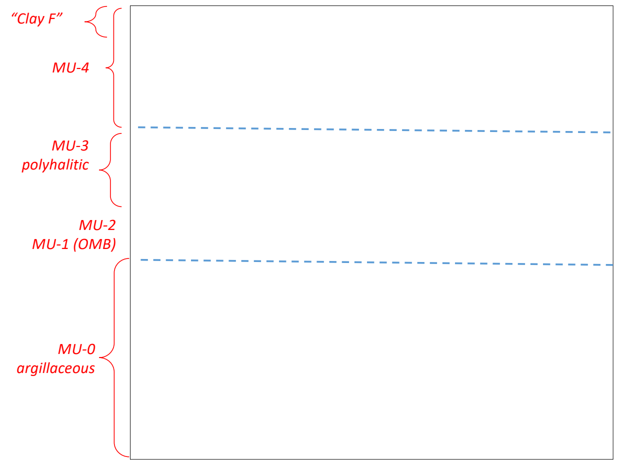
# BATS Drift at WIPP

Overcored (31 cm) BATS 1 boreholes




N-940 drift, looking south

## BATS 1 vs. BATS 2




- BATS 2
  - 3 ⇒ 4 ERT & AE boreholes
  - ERT & AE boreholes moved out
  - Moved to clay-rich horizon

**BATS 1**

Maroon/gray is clay-rich
Pink/orange is polyhalite-rich ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$)

**BATS 2**

## BATS 2.0 Tests

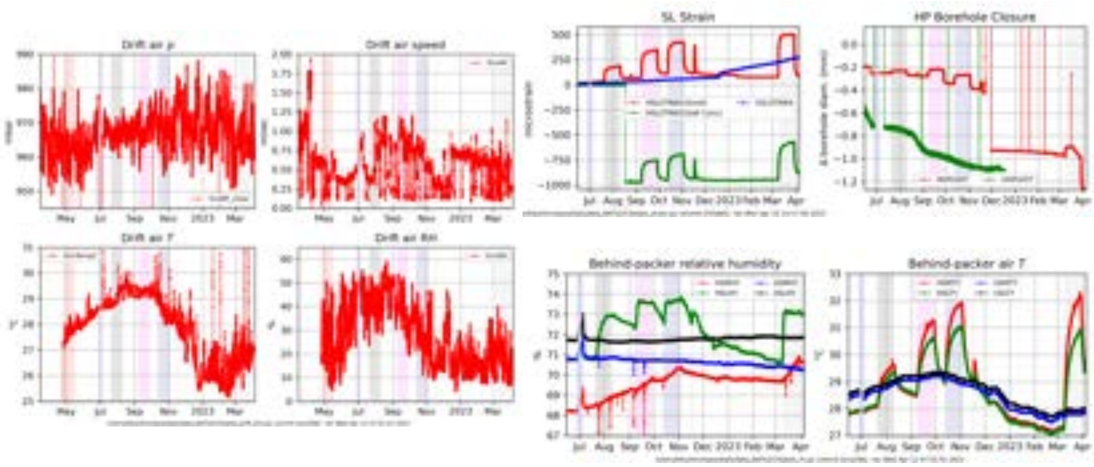
Test 1 Test 2 Test 3

Test 4

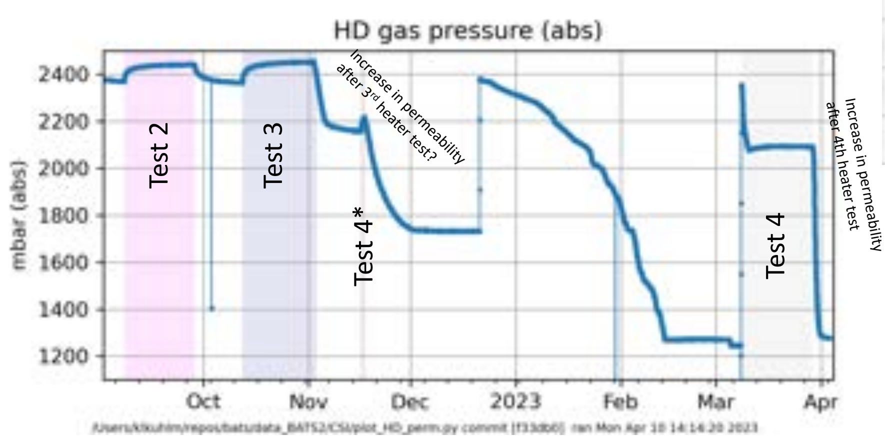
Test 4

Test 1 Test 2 Test 3

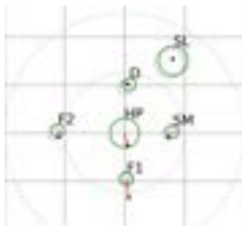
## BATS 2.0 Tests

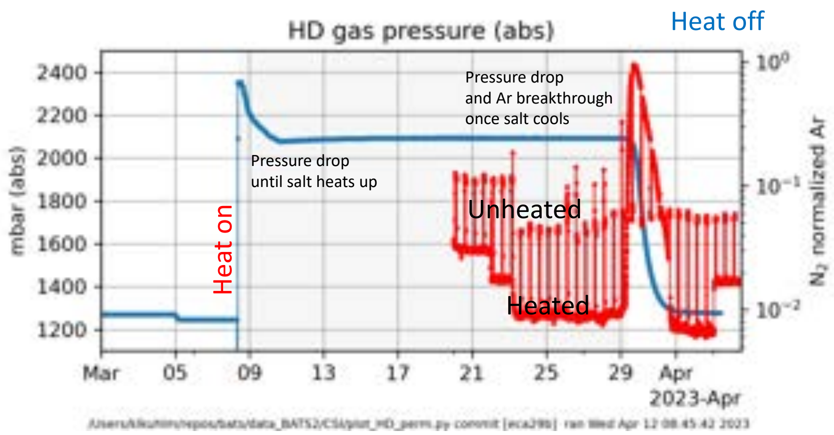



## BATS 2.0: D Packer Permeability Tests




## BATS 2.0: D Packer Ar-Permeability (Test #4)






## Conclusions

- BATS 1.0
  - What works and what doesn't
  - Lots of field data to analyze
- BATS 2.0
  - New and improved!
- Collaboration
  - DECOVALEX has been a fantastic way to analyze data in a variety of ways
  - Varying approaches leads to a better understanding of the problem at hand
  - Testing multiple assumptions

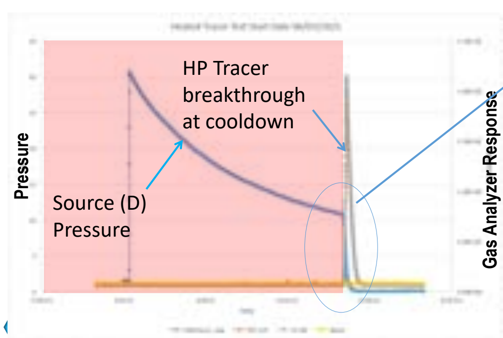
BGE TEC
BGE TECHNOLOGY GmbH
Sandia National Laboratories
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

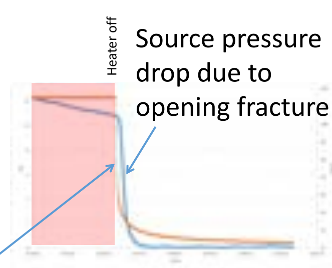
# Thank you!

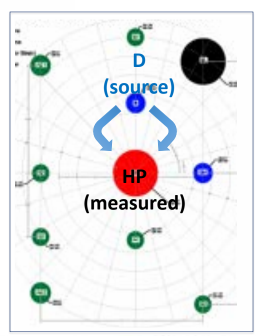

## Gas Tracer Tests

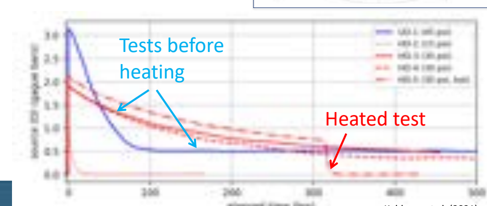
Heated Tracer Gas Tracer Tests

- No gas breakthrough until heater **off**
- Increased $T \Rightarrow$ decreased $k$
- Thermal expansion closes fractures
- <u>Heat changes permeability</u>



# Anisotropy - An Issue for Bedded Salt ?

Jürgen Hesser

BGR Federal Institute for Geosciences and Natural Resources


1

# Agenda



2

# Properties of Salt Deposits


(Flat bedded) Salt deposits are marine sediments with distinct salt layers and bedding planes

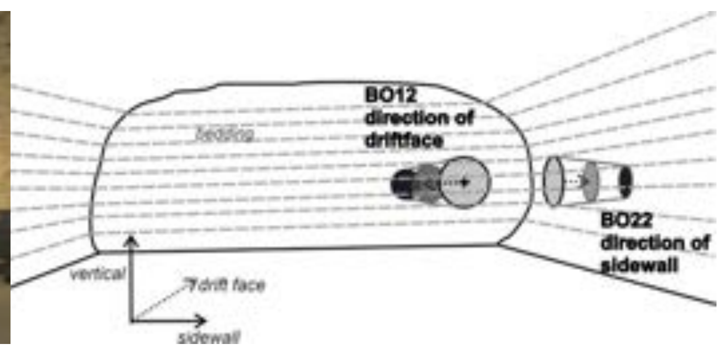
Assumption:

There could be direction-dependent differences regarding mechanical and hydraulic properties due to the bedding planes as weak interfaces:

- **Higher deformation capacity perpendicular to bedding than parallel to bedding**
- **Lower (shear) strength in the interfaces than within the salt layers**
- **Higher permeability in the interfaces than within the salt layers**



# Core Drilling and Measurements in situ




In total 6 boreholes were drilled parallel to bedding in salt rock

- 3 boreholes in the driftface
- 3 boreholes in the sidewall

In each direction (driftface and sidewall)

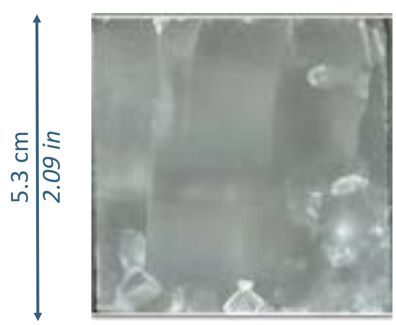
- One borehole for core drilling
- One borehole for permeability and dilatometer measurements
- One borehole for rock stress measurements

## True three-dimensional Compression Tests



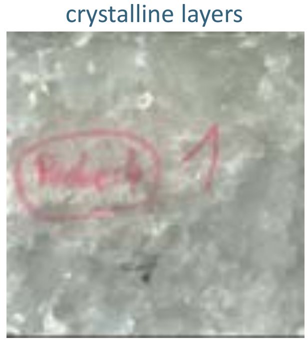
## Samples and Fabric

**Category 1:**
Monocrystalline bands




**3** Samples
- No clear bedding

**Category 2:**
Coarse to medium crystalline layers

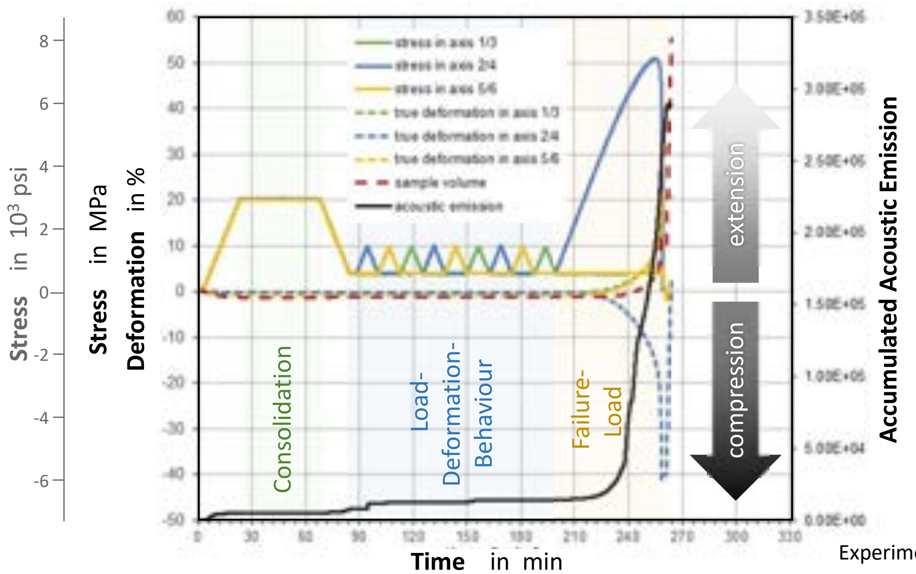


**2** Samples
- Assumed bedding

**Category 3:**
Mixed samples

**2** Samples
- Clear bedding

# True three-dimensional Compression Tests



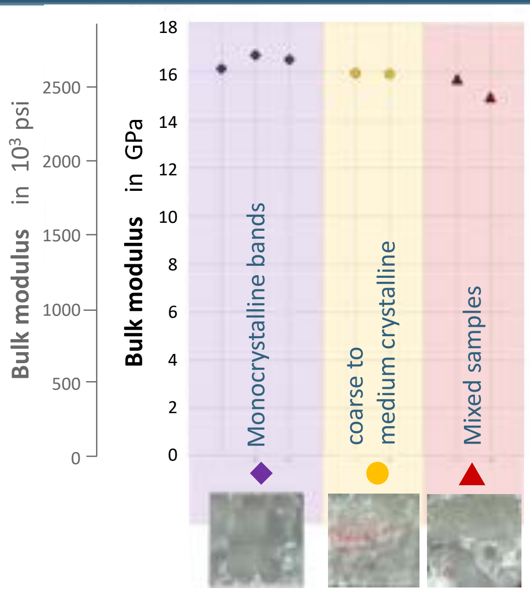

Experiment procedure

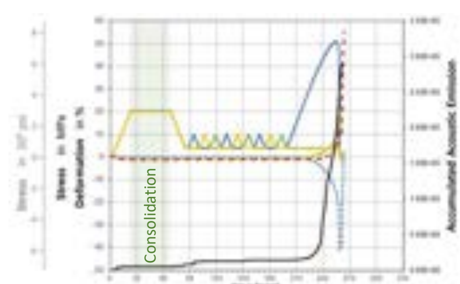
Determination of

- Bulk modulus
- Young's modulus
- Poisson's ratio
- Shear modulus
- Cubic strength
- Strain deformation
- Onset of Dilatancy
- Acoustic emission



# True three-dimensional Compression Tests



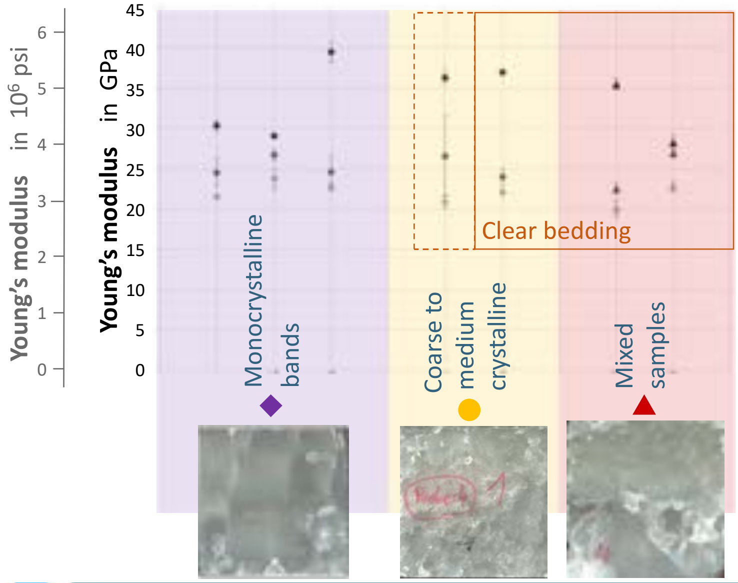

Bulk modulus $K = \frac{\Delta p}{\Delta V / V}$

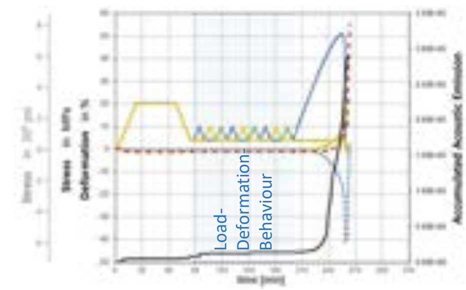
Values between 15 GPa and 17 GPa

No clear differences between

- the three structural fabric categories
- the three regional directions

# True three-dimensional Compression Tests

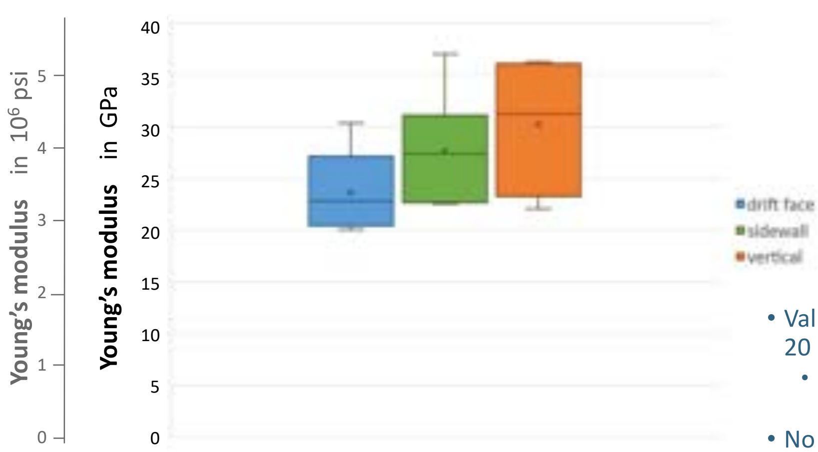


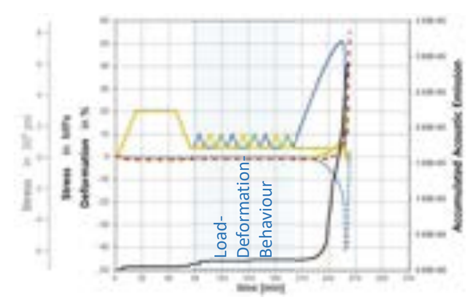




- Values for the Young's modulus range between 20 GPa and 40 GPa
  - Difference between minimal and maximal value in one sample range from 5 GPa to 22 GPa



# True three-dimensional Compression Tests



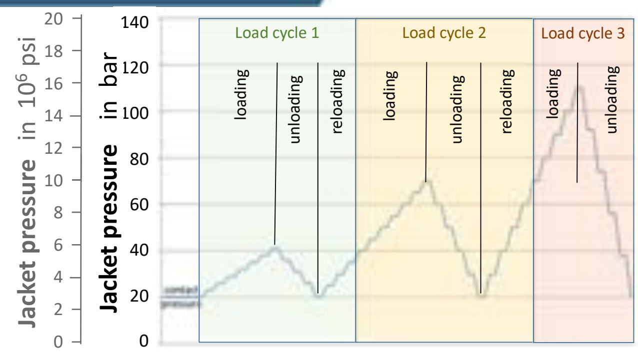


- Values for the Young's modulus range between 20 GPa and 40 GPa
  - Difference between minimal and maximal value in one sample range from 5 GPa to 22 GPa

- No significant anisotropy regarding the regional orientation

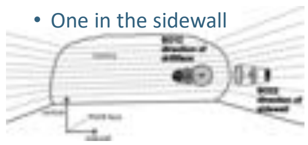
➢ Influence of individual structural fabric composition

## Dilatometer measurements in situ

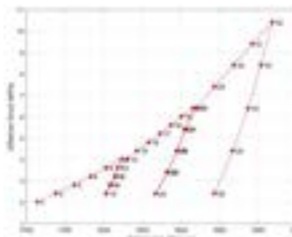



- Probe with
  - Flexible rubber jacket
  - 4 displacement transducers
- 3 loading cycles with
  - Stepwise loading
  - Stepwise unloading
  - Stepwise reloading

- Measurements in different depth of two boreholes
  - One in the driftface
  - One in the sidewall

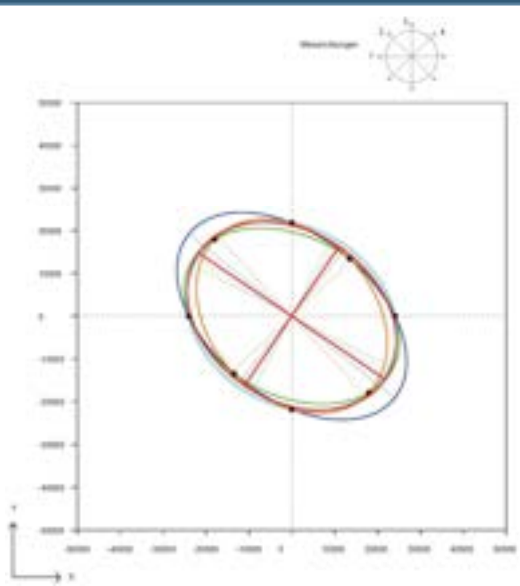


The measured load-deformation-behaviour is the basis for evaluation and determination of the Young's modulus





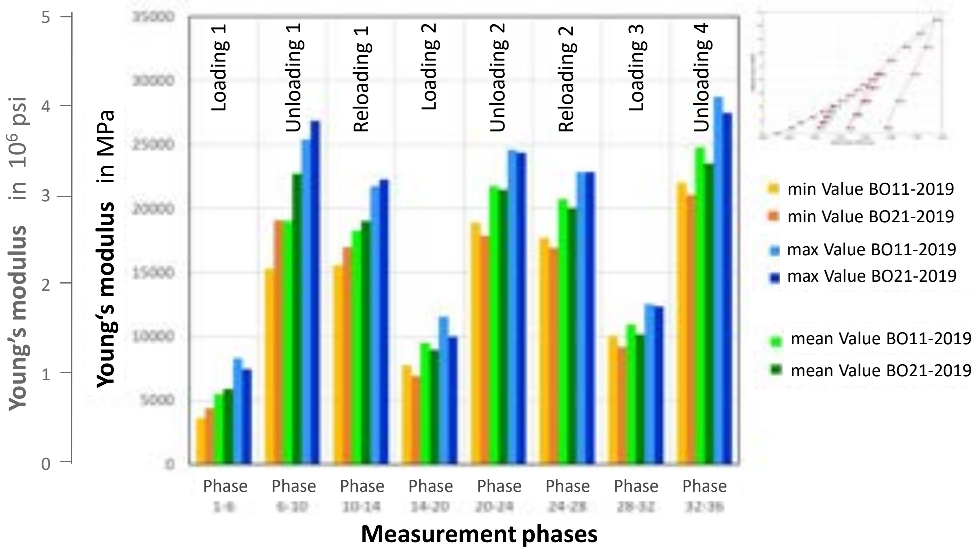
## Dilatometer measurements in situ



- Using an own software for evaluating the measurement data makes it possible to determine the Young's modulus for each measurement direction
- With 3 directions one can create an distinct distribution ellipse for the Young's modulus
- With 4 directions you get 4 different distribution ellipses
- Least square method leads to the most probable Young's modulus distribution

- Clear direction dependencies were found for the most measurements in the different depth of both boreholes
- Greater Young's modulus in the more horizontal direction than in vertical direction

## Dilatometer measurements in situ




- A greatest and a smallest Young's modulus for every measurement location
- Young's modulus in the loading phases are much lower than in unloading and reloading phases
- Unloading and reloading:
  - min Young's modulus between 15 GPa and 22 GPa
  - Max Young's modulus between 22 GPa and 28 GPa
  - Mean Young's modulus between 18 GPa and 25 GPa
- For further evaluation focus on unloading phases referring to laboratory investigations

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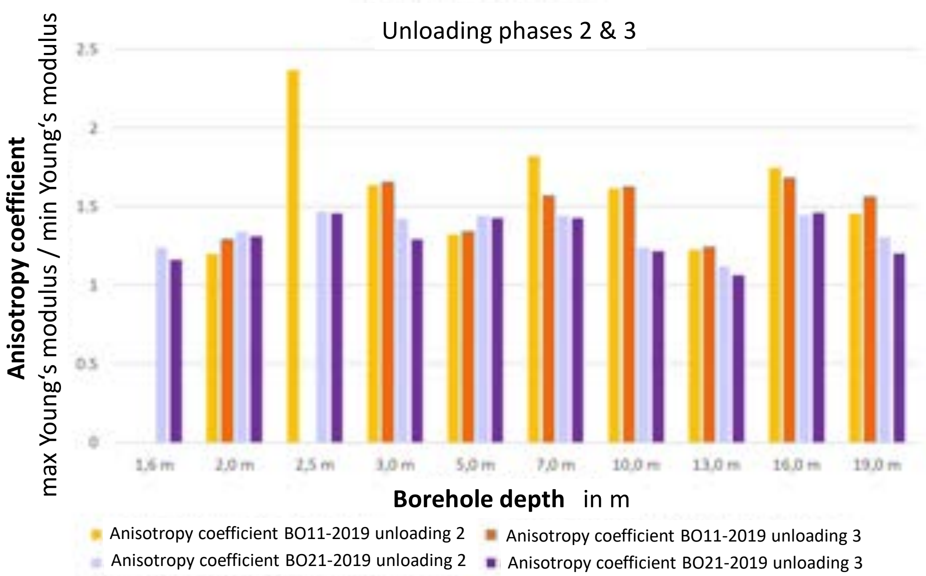
## Dilatometer measurements in situ




- Anisotropy factor as proportion of max Young's modulus and min Young's modulus
- Values between 1.1 and 2.4
- Mean value is about 1.4
- Anisotropy coefficient is by tendency higher in BO11-2019 (driftface) than in BO21-2019 (sidewall)
- At least an anisotropy of the rock mass cannot be excluded
- The reason for this anisotropy concerning the deformation is probably the bedding of the salt layers

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## Summary and conclusion

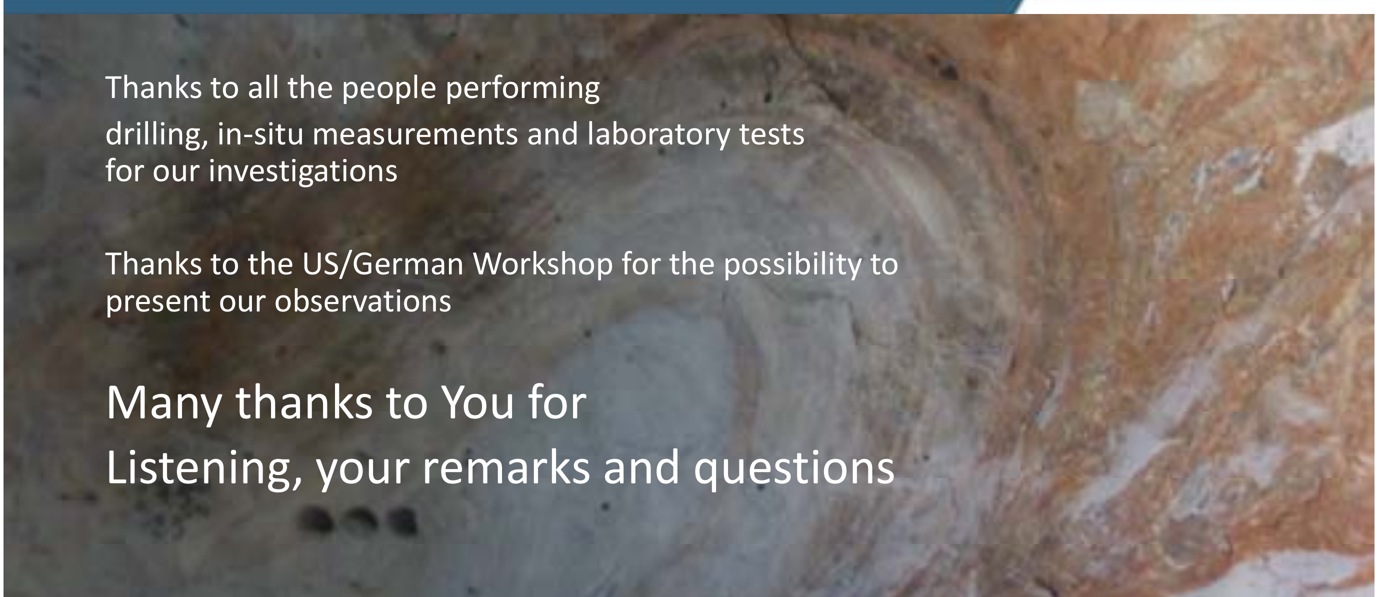
- Investigations have been done in a flat bedded salt rock deposit in a mine in Germany
  - in-situ measurements and
  - laboratory tests
- The three-dimensional tests in laboratory did not show any direction dependencies on strength or deformation behaviour
- Dilatometer measurements in situ showed a direction dependency regarding the deformation behaviour
- Greater Young’s modulus in horizontal directions
- The deformability in vertical direction is higher because of the weaker bedding planes than in horizontal direction parallel to bedding.

➔ **Anisotropy cannot be excluded for bedded salt rock deposits**

→ Considering in numerical simulations for repositories in flat bedded salt deposits

→ Further investigations necessary concerning permeability and possible flow paths





Thanks to all the people performing drilling, in-situ measurements and laboratory tests for our investigations

Thanks to the US/German Workshop for the possibility to present our observations

Many thanks to You for
Listening, your remarks and questions

# SESSION 5: EBS – Materials and Backfill

Chair: Phillip Herold (BGE TEC)

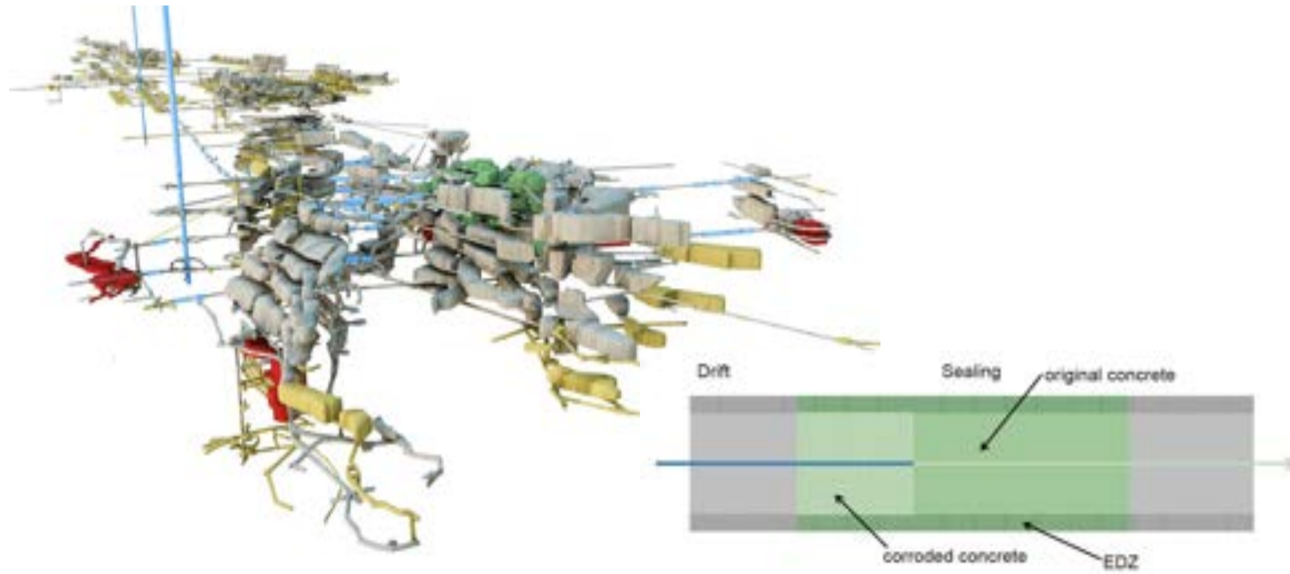
## Investigation of T-H-M-C processes on sealing systems in rock salt

**Thorsten Meyer, Kyra Jantschik, Oliver Czaikowski**
**GRS**

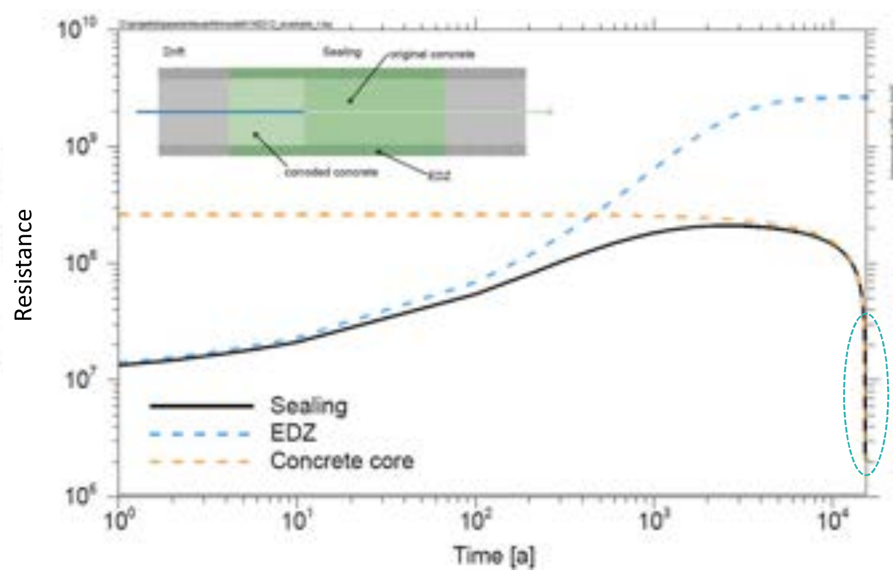

# Agenda

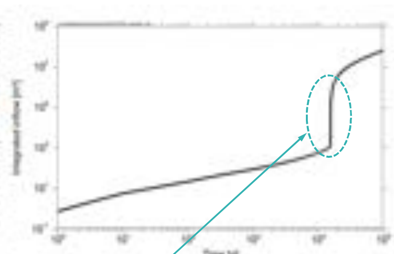
| | |
|---|---|
| Topic 1 | ERA Morsleben/PA - Overview |
| Topic 2 | T-H-M-C Processes |
| Topic 3 | Materials |
| Topic 4 | T-H-M-C Investigations |
| Topic 5 | Chemical Reactions (concrete/solution) |
| Topic 6 | Long-term experiment |
| Topic 7 | Summary |

## ERA Morsleben – Sealing locations (BfS 2015)



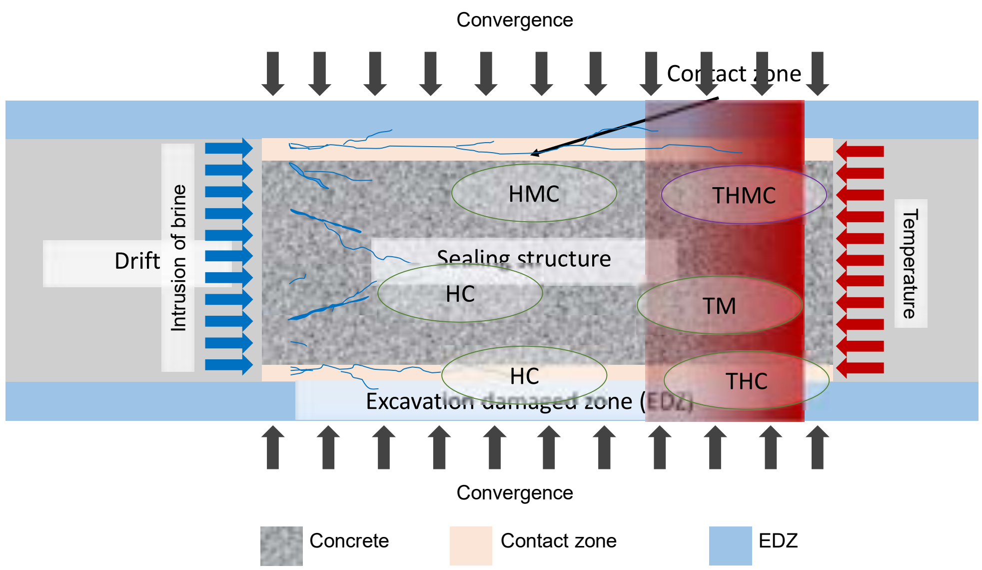

## Performance Assessment - development of the hydraulic resistivity of the sealing system



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

## T-H-M-C processes – sealing system






## Materials

| Sorel concrete A1 (318-Rezeptur) |
|---|
| 11,3 wt% MgO (reactivity 200–250 sec) |
| 63,7 wt% crushed salt (4 mm) |
| 25,0 wt% $MgCl_2$ solution (4-5 molal) |

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

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

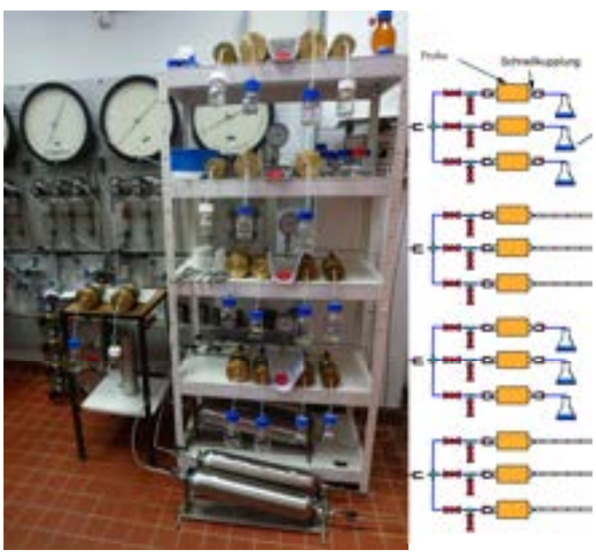
| Element | IP21 | NaCl (sat.) |
|---|---|---|
| | $mol/kg_w$ | $mol/kg_w$ |
| Ca | 0.001 | 0.000 |
| Cl | 8.873 | 6.100 |
| K | 0.547 | 0.000 |
| Mg | 4.241 | 0.000 |
| Na | 0.462 | 6.100 |
| S | 0.309 | 0.000 |
| Density [g/cm$^3$] | 1.292 | 1.200 |

## Experimental Model System

Sealing material | salt cylinder (EDZ) | sealing system



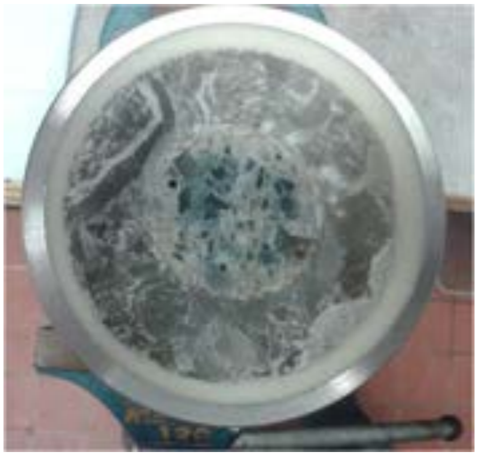
## HC – Investigations / Experimental set-up



- permeability measurement –

  no confining pressure
- advection cells
- fluids: NaCl, IP21 (Q TEC 4.0), $N_2$
- $P_{Solution}$ up to 2 MPa
- T = 25°C
- sealing material (monolithic samples)
- sealing system (combined samples)

## HC – Investigations / Experimental set-up

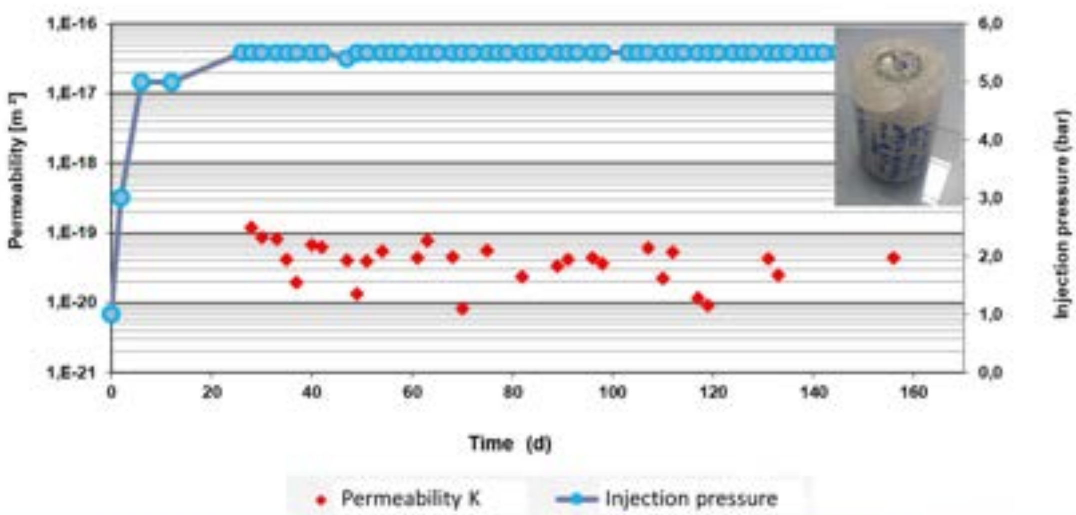


- metal jacket
- Araldit (resin)
- salt cylinder
  - Asse
  - ERAM
- concrete
  - M2 (salt concrete)
  - M4 (salt concrete)
  - A1 (Sorel concrete)
  - Asse concrete (in-situ)



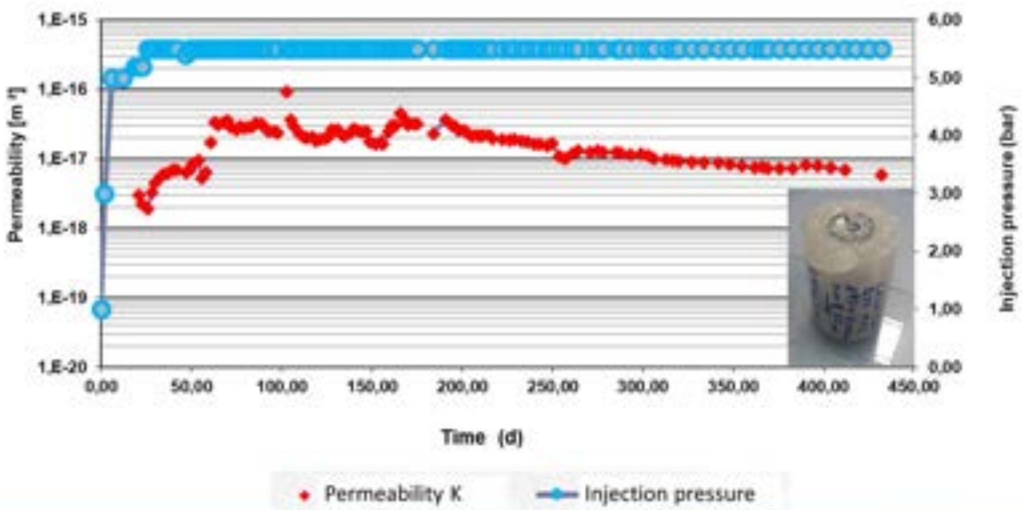
## HC – Investigations

- Salt concrete M2 / NaCl solution (sat.)



## HC – Investigations

- Salt concrete M2 / IP21 solution



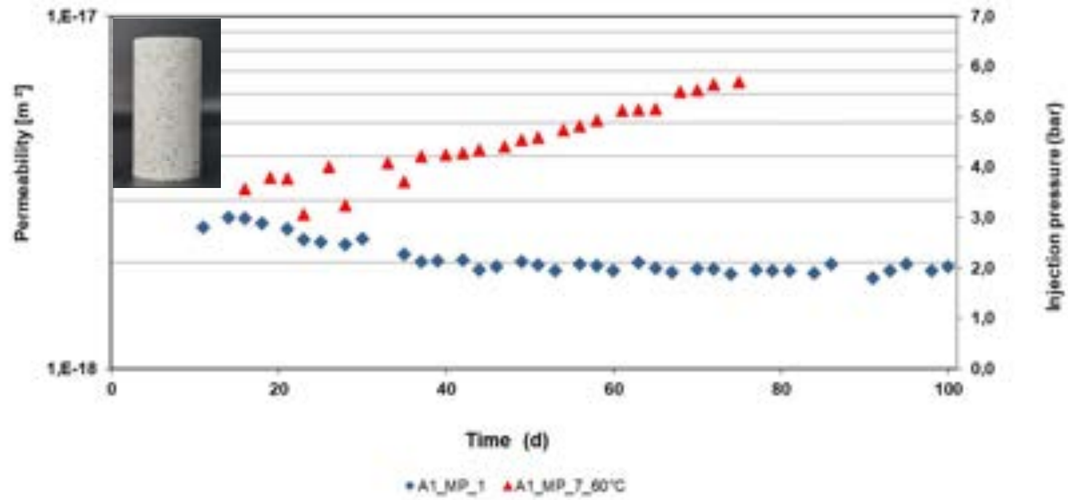



## THC – Investigations / Experimental set-up

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

## HC/THC – Comparison

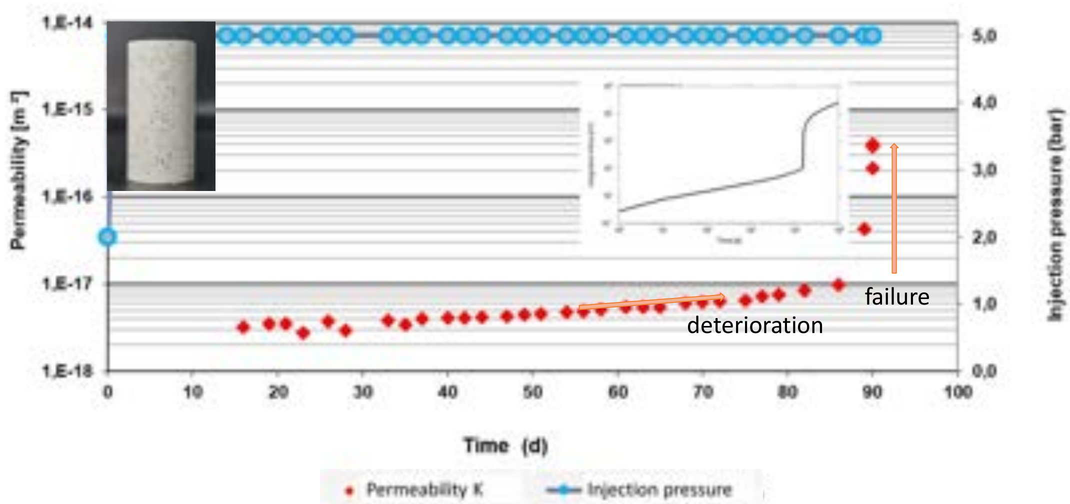
- Comparison of A1 / NaCl at 25°C (long-term) and 60°C





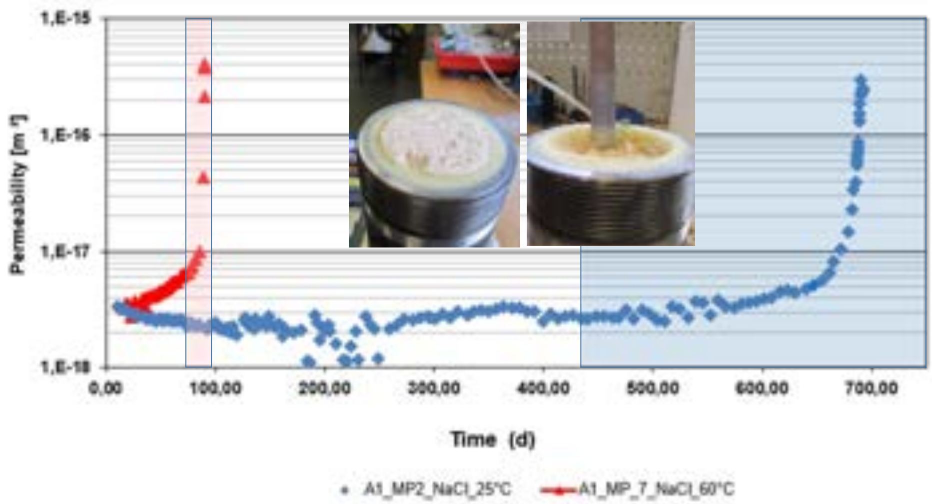

## THC – Investigations

- Sorel concrete A1 at 60°/ NaCl(sat.) solution



## HC/THC – Comparison

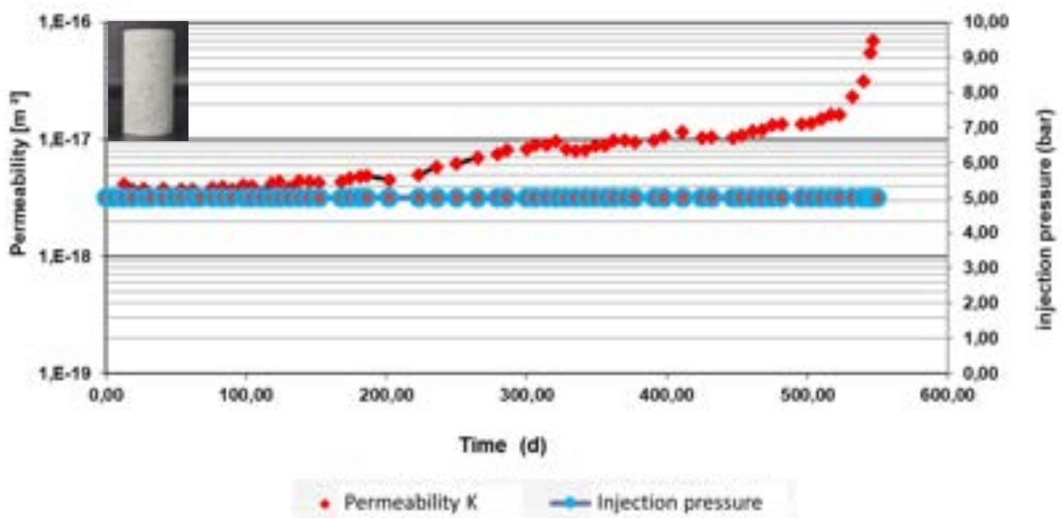
- Comparison of A1 / NaCl at 25°C (long-term) and 60°C





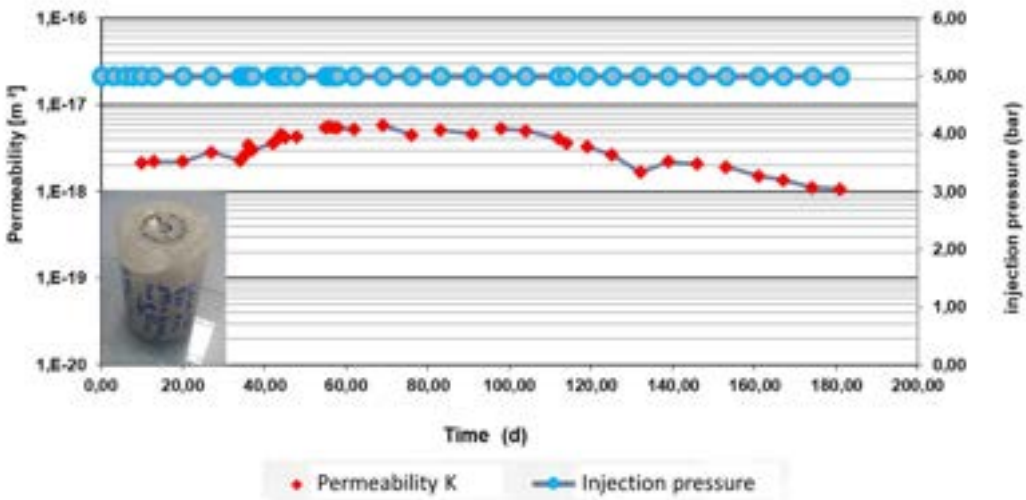

## THC – Investigations

- A1 / 0.6 M $MgCl_2$/ NaCl(sat.) at 60°C



## THC – Investigations

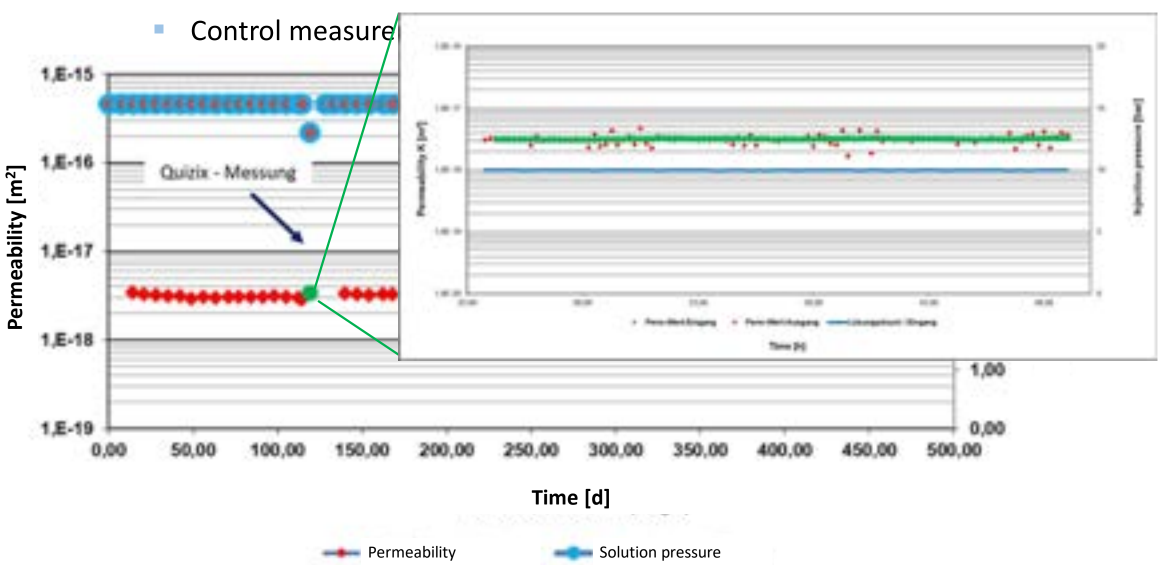
- Salt concrete M2 / IP21 at 60°C



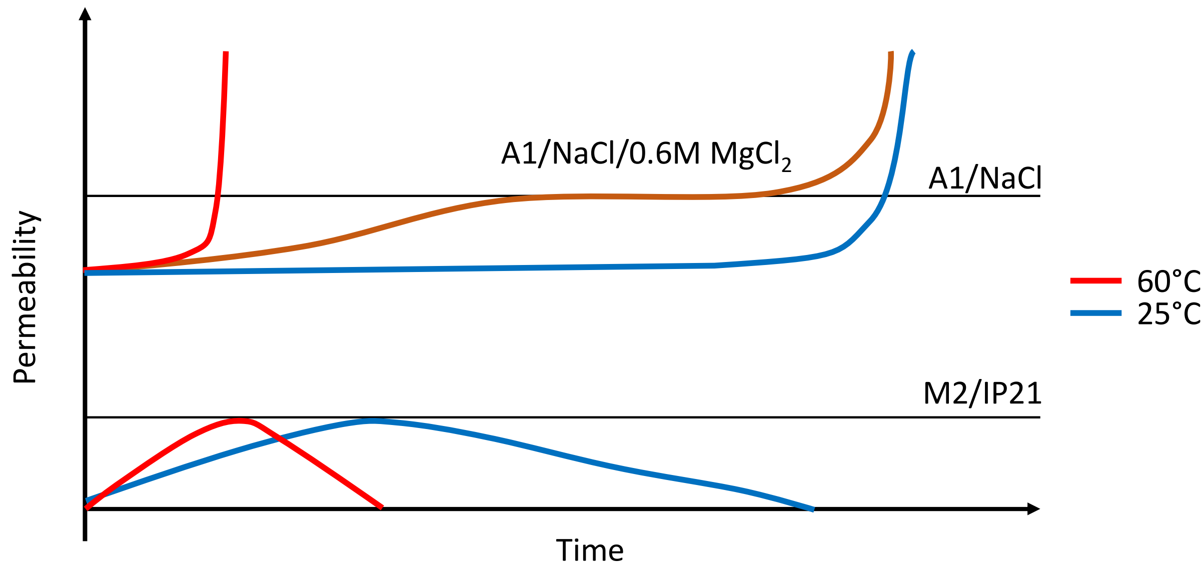



## HC – Investigations

- Control measure



## Permeability functions determined (scheme)



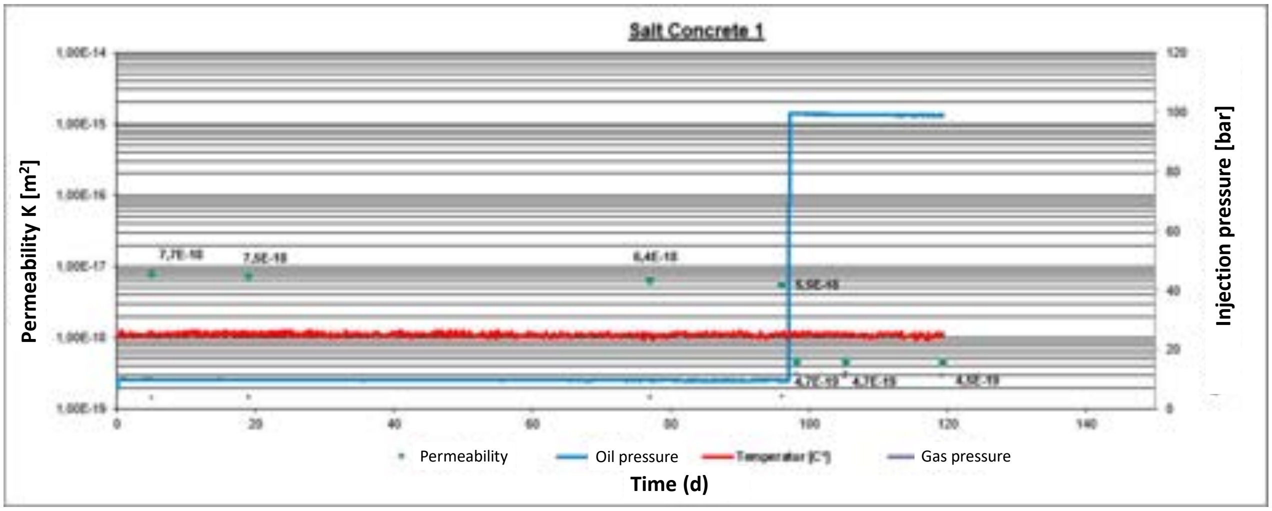



## HMC – Investigations / Experimental set-up

- Hassler cells
- permeability measurement with confining pressure
- $P_{Conf}$ up to 15 MPa
- T = 25°C
- sealing material (monolithic samples)
- sealing system (combined samples)

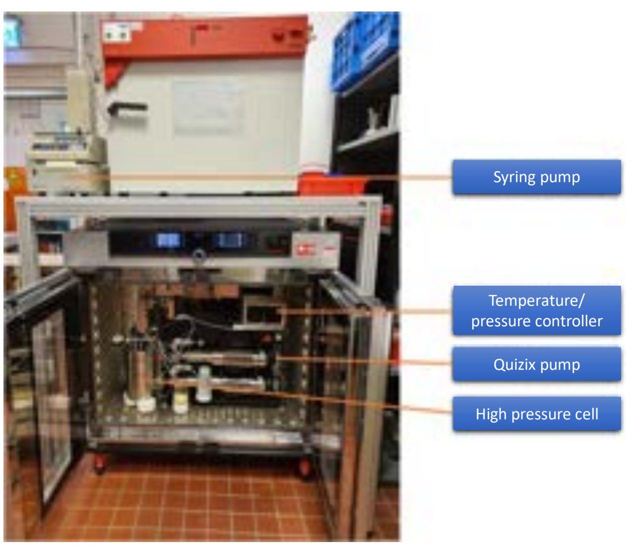
## HMC – Investigations

- US - Salt concrete / gas permeability ($N_2$)





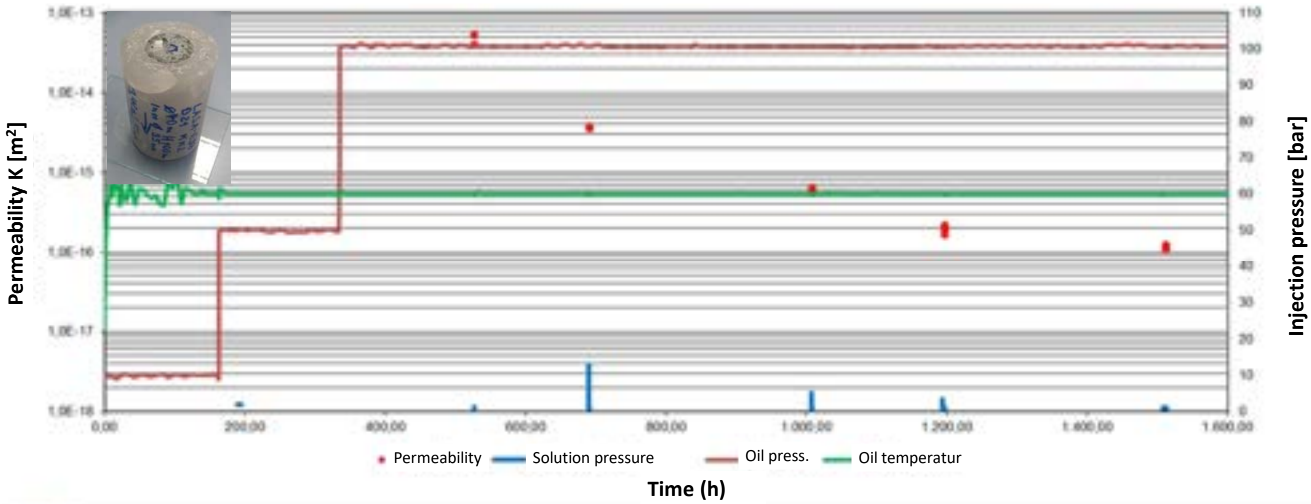

## THMC – Investigations / Experimental set-up




- permeability measurements
- high pressure cells
- confining pressure
- $P_{confining}$ up to 15 MPa
- T = 25 - 60°C
- sealing material (monolithic samples)
- sealing system (combined samples)

## HC – Investigations

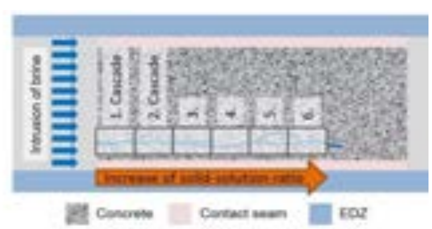
- Salt concrete M2 / IP21 at 60°C





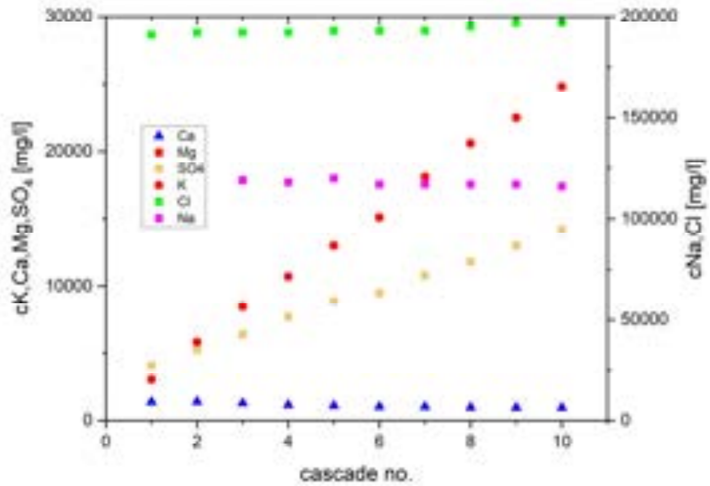

## C – Cascade Experiments

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


## C – Cascade Experiments

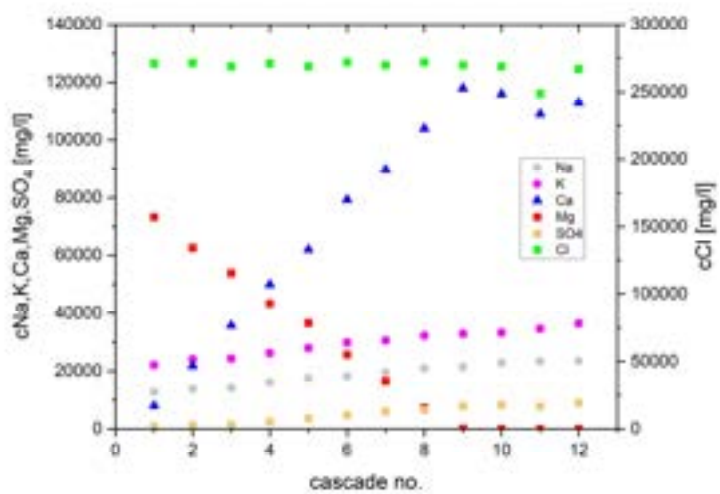
- Salt concrete M4
- NaCl(sat.)





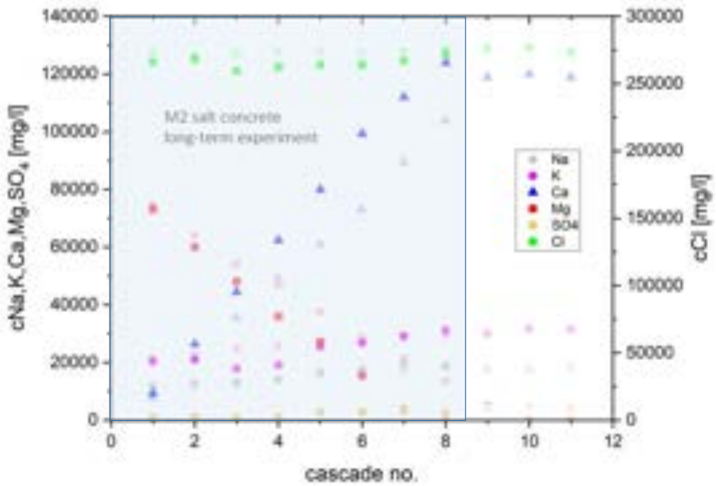

## C – Cascade Experiments

- Salt concrete M4
- Q-TEC 4.0



# C – Cascade Experiments

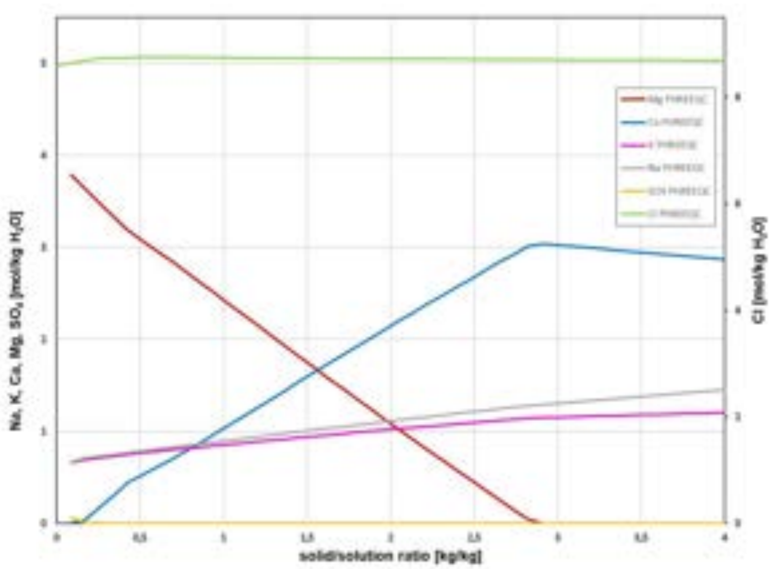
- Salt concrete M2
- Q-TEC 4.0



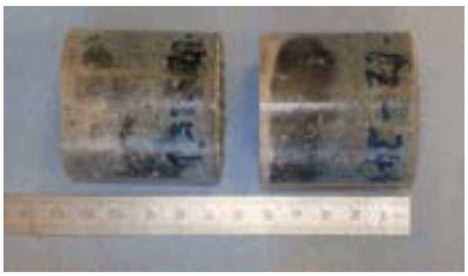



# C – Cascade Modelling (under construction)

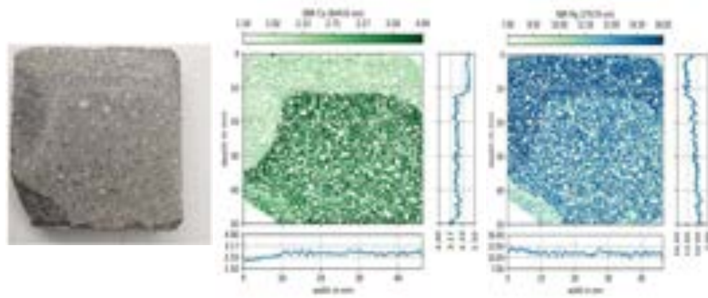
- Salt concrete M2
- Q-TEC 4.0



## Long-term corrosion experiments from 2003



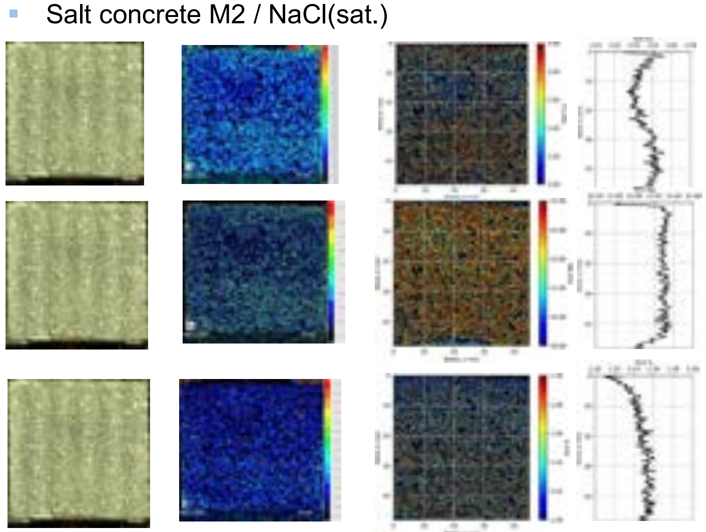
- Salt concrete M2 / NaCl(sat.) / IP21
- 5 years in contact to solution
- 15 years storage in contact to solution / undefined conditions
- LIBS / µXRF / CT





## Long-term experiments - comparison LIBS/µXRF

- Salt concrete M2 / NaCl(sat.)



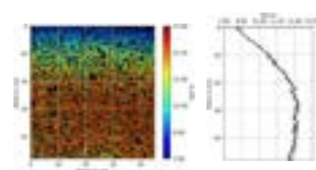
Ca

Mg

S

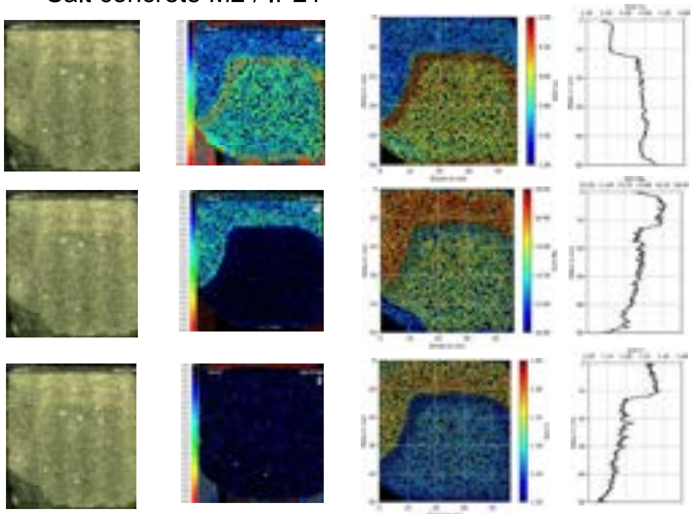
Foto µXRF LIBS

- homogeneous distribution of the elements Ca, Mg, S
- but K is depleted in the contact area to NaCl solution



## Long-term experiments - comparison LIBS/µXRF

- Salt concrete M2 / IP21



Ca

Mg

S

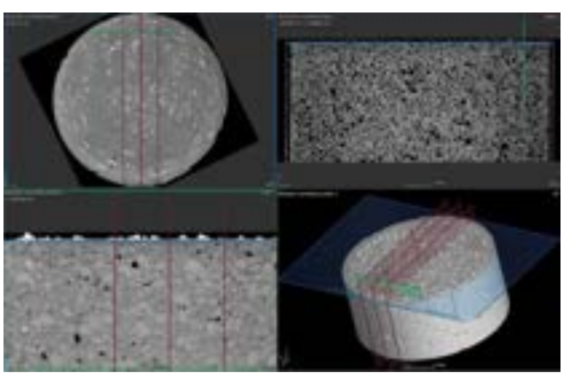
Foto µXRF LIBS

- inhomogeneous distribution of the elements Ca, Mg, S
- corrosion front of about 1,5 cm could be detected
- Ca is decreased in the corrosion zone
- Mg and S are increased, precipitation of $CaSO_4$ and MSH phases (->tbd.)

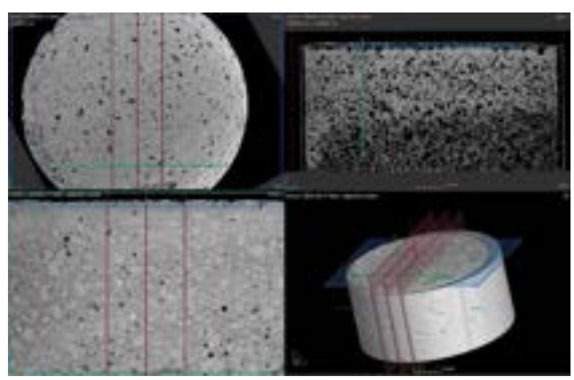


## Long-term experiments - CT

- Salt concrete M2 / NaCl (sat.)



- Salt concrete M2 / IP21



## Summary

- **Permeability measurements**
  - conducted for HC/THC/HMC/THMC; THMC set-up in operation
  - **Salt concrete M2 / IP21** -> no breakthrough at the contact zone
  - **Sorel concrete A1 / NaCl ->** failure of the material itself; Mg in solution stabilises system
- **Chemical reaction path** experimentally determined by **cascade experiment**
  - short- and long-term leaching experiments -> in short-term experiments equilibrium not achieved
  - geochemical modeling (simple model) reflects the experimental reaction path
  - advanced model with solid solutions CNASH(ss), advanced Si/Al-Pitzer parameter (THEREDA)
- **Long-term corrosion experiments** of salt concrete M2 from 2003
  - homogeneous elemental distribution in contact to NaCl(sat.)
  - inhomogeneous elemental distribution in contact to IP21 -> LIBS/µRFA
    - Ca decrease/ Mg and $SO_4$ increase in corrosion zone
    - lower porosity in corrosion zone detected -> CT, MIP to verfy results



## Acknowledgements

Thank you for your attention!

GRS

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PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie

BGE
BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

# Cement Seals in Salt


Melissa Mills, Kris Kuhlman

*Sandia National Laboratories*

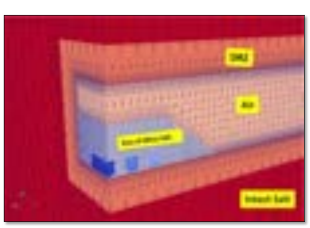
Thursday, June 22, 2023: Session 5

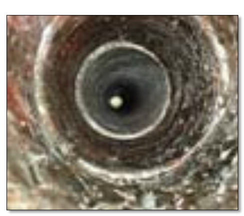
Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2023-05420PE

## Background on US Disposal Research

- US disposal programs focused on research and development activities related to storage, transportation, and disposal of spent nuclear fuel and high-level nuclear waste.

- Within disposal campaign, various host rock media are being investigated to advance the understanding and performance of long-term isolation, including salt



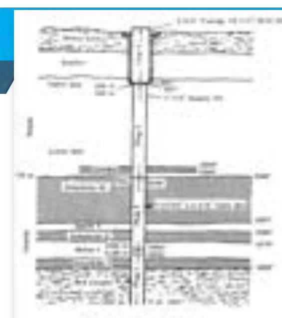


## Motivation

- Ongoing uncertainty in long-term performance of geologic repositories for nuclear waste disposal revolves around construction and temporal evolution of geotechnical barriers
  - In salt, initial barriers should have permeability and porosity approaching those of the surrounding host rock
- Residual uncertainty with respect to nuclear waste repository performance exists
  - Few large-scale, long-term in situ barrier experiments involve heat, especially including permeability and chemistry data
- Striving to add confidence in future nuclear waste repository design and performance, and revitalize barrier system research in the US

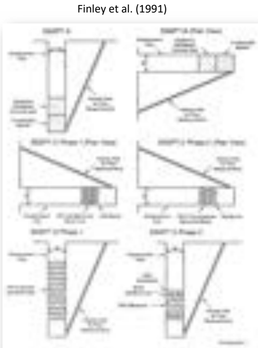
## Previous Cement Seal Experiments related to WIPP

- 1977- ERDA No. 10 Test (near WIPP)

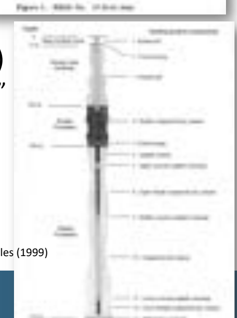


- 1979- Bell Canyon Test (near WIPP)

Finley et al. (1991)



- 1980's- Small-Scale Seal Performance Tests (at WIPP)
  - Used very specific formulation of "Expansive Salt Concrete"
  - Key ingredients potentially difficult to reproduce
- 1990's- Salado Mass Concrete
  - Design for closure



Hansen and Knowles (1999)

*None focused on effects of elevated temperature exposure*

## Current Recipes: Salt Concrete

- Recipe formulated from Germany Project LAVA2 (Müller-Hoeppe et al. 2010)
- Use of Ground Blast Furnace Slag from Diversified Minerals Inc. (Oxnard, California)
- Aggregate: Run of mine WIPP salt <4.75 mm grain size
  - Found impurities affected initial mixture
- Required to be mixed in glove box at Sandia due to silica inhalation hazards

| Modified Salt Concrete | Composition (mass-%) |
|---|---|
| Saturated NaCl | 14.7 |
| Blast Furnace Slag | 28.4 |
| Salt Aggregate | 56.9 |

## Current Recipes: Sorel Cement

- Proportions similar to Popp et al. 2018
  - Density = 2240 kg/m$^3$
  - Desired MgO reactivity from citric acid test ~200 ± 50 sec
- Desired fast curing, so chose D4 shotcrete (5-1-8 phase)
- Aggregate: Run of mine WIPP salt <4.75 mm grain size

| Sorel D4 (2019 - BATS 1) | Composition (mass-%) |
|---|---|
| 5M $MgCl_2 * 6H_2O$ | 18.3 |
| < 75 um MgO (**MagChem 10** from WIPP) | 18.3 |
| Salt Aggregate | 63.4 |

| Sorel D4 (2021 - BATS 2) | Composition (mass-%) |
|---|---|
| 5M $MgCl_2 * 6H_2O$ | 25 |
| < 75 um MgO (**MagChem 20SC**) | 25 |
| Salt Aggregate | 50 |

MgO Issues

- Two samples of MgO from WIPP (MagChem 10) had different reactivities
  - 2019 batch: citric acid test reactivity = 272 seconds
  - 2021 batch: citric acid test reactivity > 30 minutes
- 2019 sample taken from surface drum with material from a damaged sack (possible exposure to heat and moisture could have caused alterations)
- Investigated other US suppliers, yet none had reactivity in range
- Closest was MagChem 20SC from Martin Marietta Magnesia Specialties at 103 sec) and used in BATS 2.
- Thicker paste, so aggregate amounts needed to be reduced

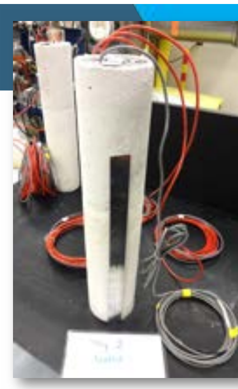
## Brine Availability Test in Salt (BATS)

- Field test monitoring brine from heated salt using geophysics and sampling methods in horizontal boreholes at WIPP
  - Parallel heated/unheated tests
  - Temperatures up to 150°C
- Only active repository research underground test in the US
- Collaboration of Sandia, Los Alamos, and Lawrence Berkeley National Labs
- Includes cement seal components
- BATS 2.0 began in 2022: newly drilled boreholes, updated equipment, and 4 heating phases



## BATS: Cement Seal Borehole

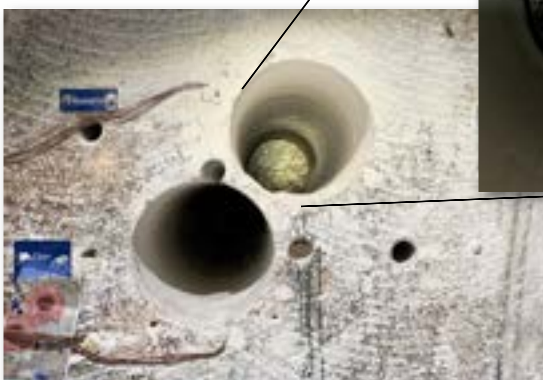
- Two types:  modified salt concrete and Sorel cement
  - Align with German programs
  - Complementary with laboratory tests
- Embedded strain gauges, and thermocouples in 2022 during fabrication
- Installed in borehole 1- 2 ft (0.3-0.6 m) from heated borehole
- Strain, temperature, moisture conditions, and brine composition monitored throughout the test
- BATS 1.0 SL borehole overcored post-test to investigate salt/cement interface
- Understand the behavior of cement/salt/brine system


2019


2021

## Overcore of BATS 1.0 Seal

View from drift: 12” (0.3m) overcore of heater and seal borehole



Overcores on pallets

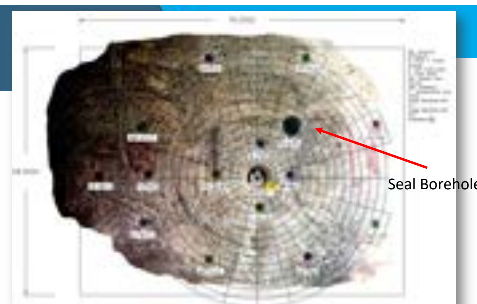
Cut strain gauge wire in salt concrete

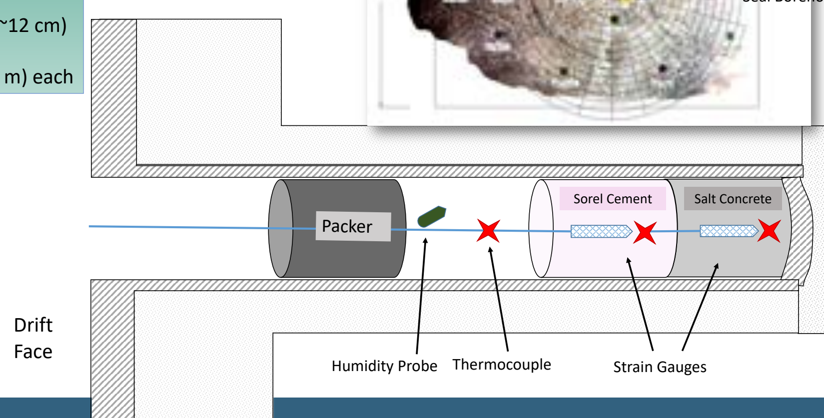
## Side Profile View of Cement Seal Borehole (BATS 2.0)

Overall Borehole length: 11.5 ft (3.5 m)

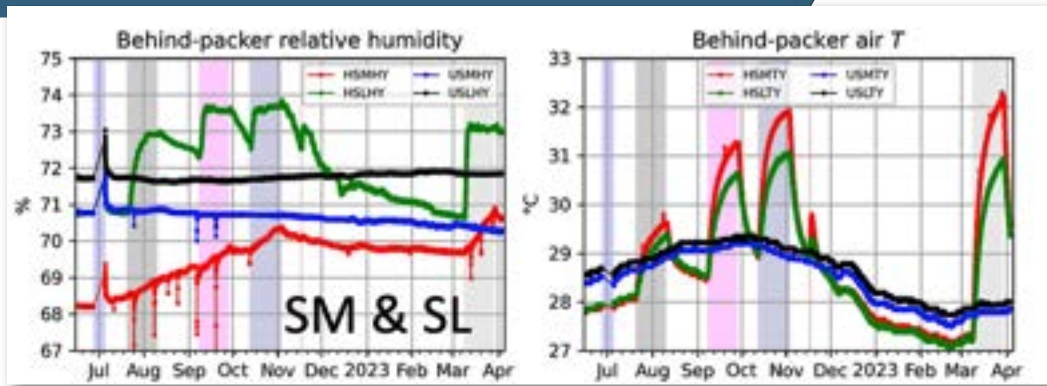
Borehole diameter: 4.8 inches (~12 cm)

Cement Plug Length: ~1 ft (~0.3 m) each



## Recent In-Situ Data: BATS 2.0




Sample borehole (right of heater):
- Red = heated array
- Blue = unheated array

Seal borehole:
- Green = heated array
- Black = unheated array

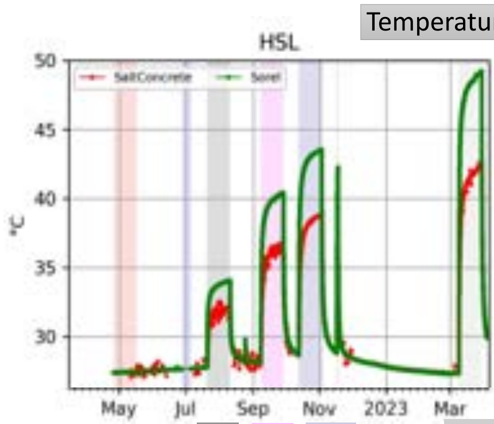
60°C 90°C 120°C 150°C

Heating events

During 4 heating events (shaded areas): Humidity rises in heated seal borehole (available brine), and temperature rises for both in heated array

## Recent In-Situ Data: BATS 2.0

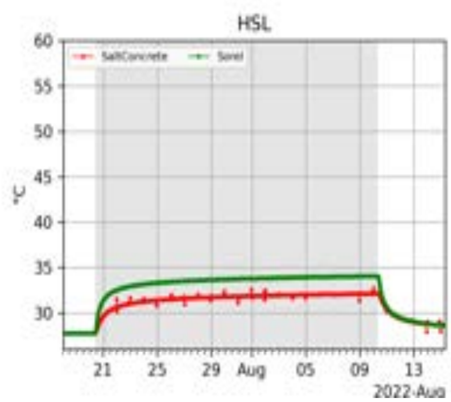
Temperature within seal plugs




60°C 90°C 120°C 150°C

Heating events

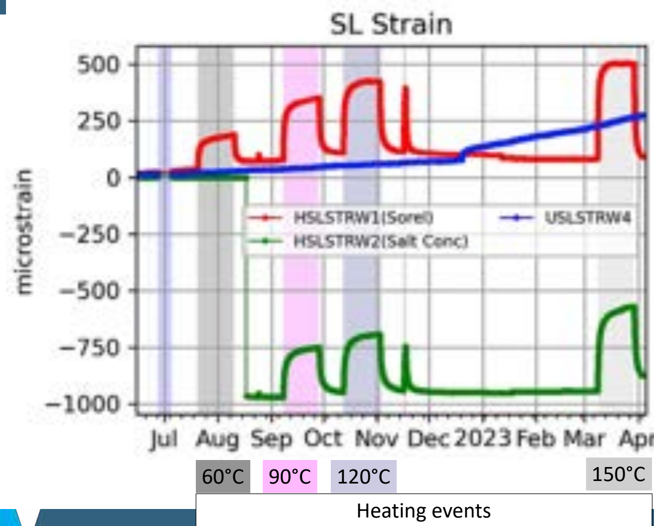
Overall




During first heating phase (60°C)

During every heating event, sorel cement experiences higher temperature change; likely due to depth alignment with heater

## Recent In-Situ Data: BATS 2.0

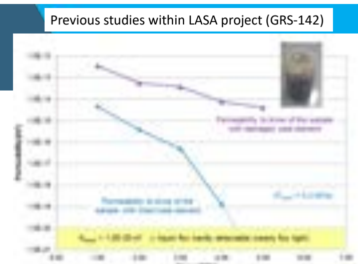



Heated array:
- Red = Sorel Cement
- Green = Salt Concrete

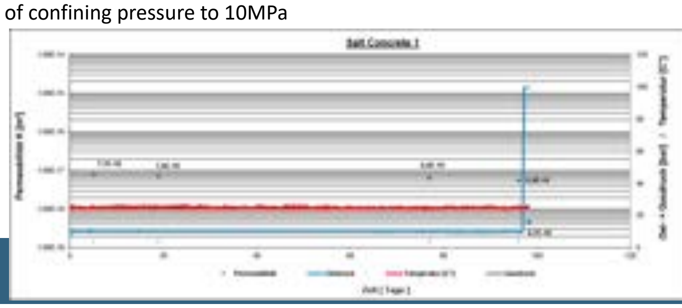
Unheated array:
- Blue = Salt Concrete

## Collaboration with GRS

Previous studies within LASA project (GRS-142)

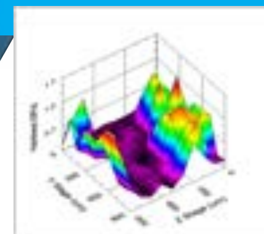


- Percolation experiments of salt concrete plug in WIPP salt
- Proposed tests
  - Hydraulic-Mechanical-Chemical at 25°C using BATS WIPP Brine
  - Thermal-Hydraulic-Mechanical at possibly 60°C
  - Hydraulic-Mechanical
- Preliminary permeability data on solid salt concrete cylinder (courtesy of T. Meyer)
  - Avg. permeability of 6.78 x$10^{-18}$ $m^2$ at 1MPa confining
  - Decreased to 4.7 x $10^{-19}$ $m^2$ with increase of confining pressure to 10MPa



## Future Goals and Endeavors

- Further investigation into other seal material recipes
- Lab-scale tests
  - Effect of brine
  - Effects of heat
  - Creep testing
  - Nano/Micro indentation
- Analysis of over-cored plug from BATS 1.0
- Additional plugs deployed in other boreholes at WIPP
  - *In situ* permeability measurements desired
  - Direct emplacement of mixture and cured in the field



# Overview of MgO Cement/Concrete Types


Iris Paschke[1], Daniela Freyer[1], Matthias Gruner[1], Till Popp[2]

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Departement of Inorganic Chemistry,
Salt and Mineral Chemistry

[2] Institute of Geomechanics GmbH Leipzig



Santa Fe, New Mexico
20-23 June 2023

# Agenda

- History & Application
- Binder phases & MgO cement/concrete
- Formulation types
- Temperature development
- Selection of R&D projects milestones
- Summary

# History & Application

## 1867

Discovery of „new cement“
by Stanislas Sorel


MÉMOIRES PRÉSENTÉS.

CHIMIE APPLIQUÉE. — *Sur un nouveau ciment magnésien.* Note de **M. Sorel**, présentée par M. Dumas.

(Renvoi à la Section de Chimie.)

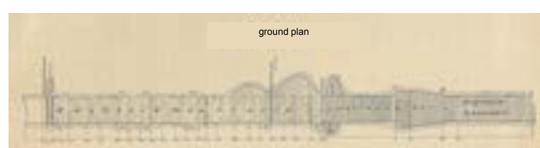
« *J'ai* l'honneur de soumettre au jugement de l'Académie un nouveau ciment qui est fondé sur le principe du ciment à l'oxychlorure de zinc que je lui ai présenté en 1855. C'est un oxychlorure de magnésium basique et hydraté.

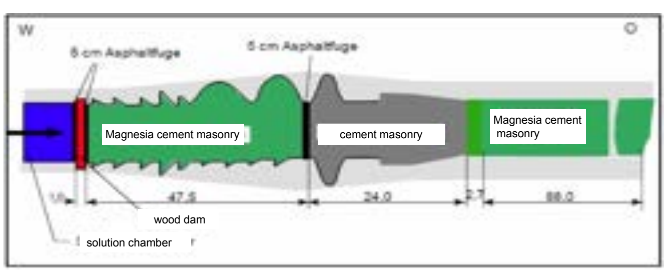


# History & Application

## 1898

1st application in salt mine Leopoldshall
→ 162m long drift seal



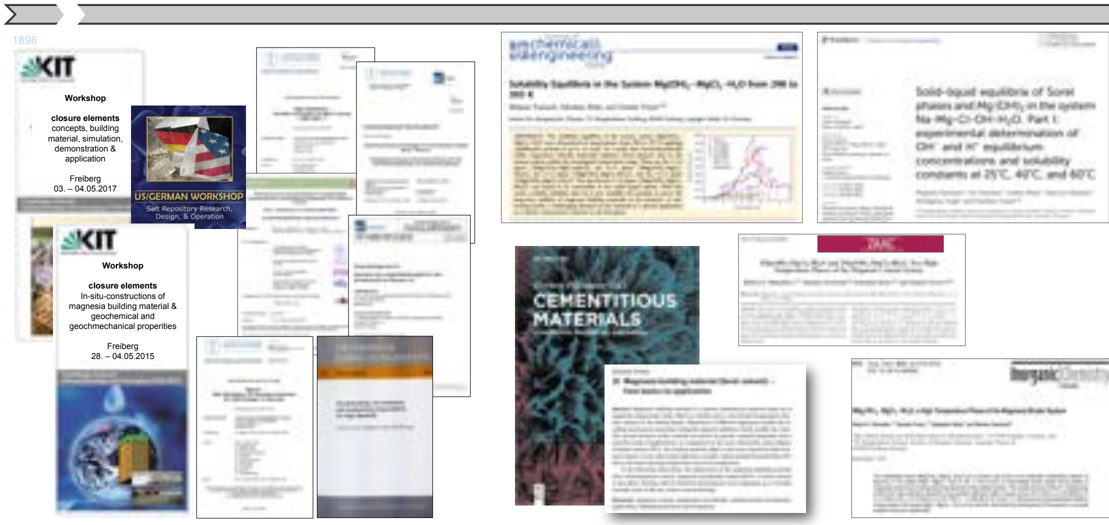




## History & Application

**1939** 1st patent: MgO concrete as building material by Karl Kammüller & Norbert Scheibe




## Progress of knowledge in the last decade



## Binder phases

**MgO**

**$MgCl_2$-containing salt solution**

**Binder phase(s):**
Basic Mg-Chlorid-Hydrates
**x** $Mg(OH)_2$ · **y** $MgCl_2$ · **z** $H_2O$:
**x-y-z** phase (Sorel phases)

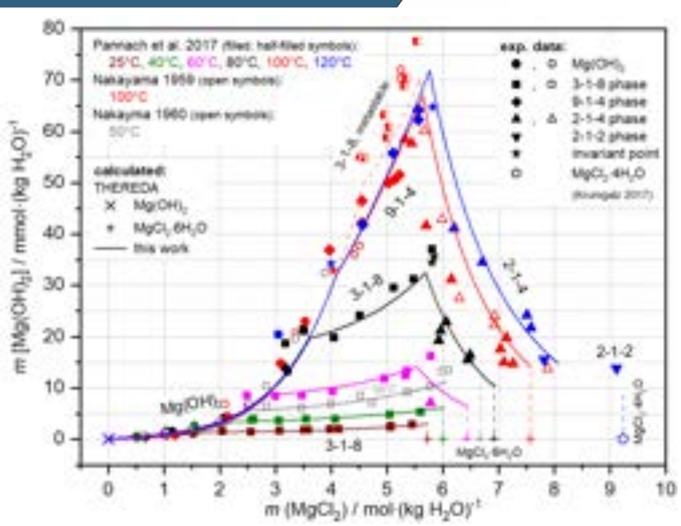
Long term stability at/after brine access?
⇨ Solubility equilibria in the system
$Mg^{2+}$, $Cl^-$, $OH^-$ - $H_2O$, 25°C-120°C



## Binder phases

Solubility equilibria in the system
$Mg^{2+}$, $Cl^-$, $OH^-$ - $H_2O$, 25°C-120°C

- 3-1-8 phase = thermodynamically stable up to 80°C, at higher temperatures: 9-1-4 phase
- no existing field for the 5-1-8 phase (metastable)

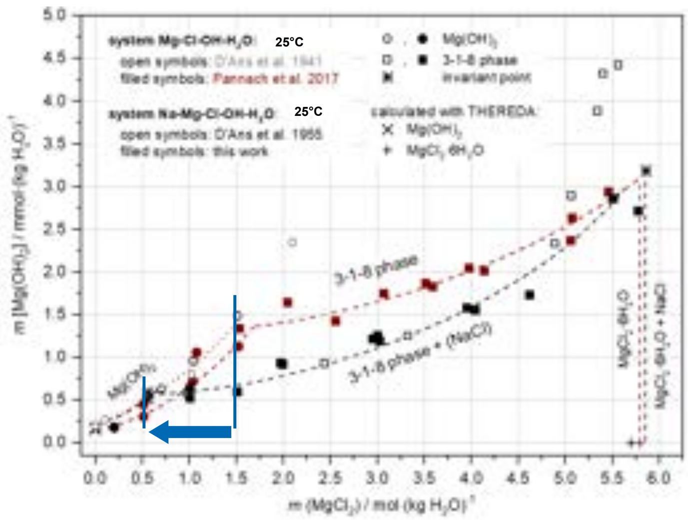



Freyer D. et al, Solid-liquid equilibria of Sorel phases and $Mg(OH)_2$ in the system Na-Mg-Cl-OH-$H_2O$, Part II: Pitzer Modeling, *Front. Nucl. Eng.* (2023) – submitted.
Pannach, M. et al, Solubility Equilibria in the System $Mg(OH)_2$–$MgCl_2$–$H_2O$ from 298 to 393 K, *J. Chem. Eng. Data* (2017) 62 (4), 1384-1396.

# Binder phases

Solubility equilibria in the system
$Mg^{2+}$, $Cl^-$, $OH^-$ - $H_2O$, 25°C-120°C

- 3-1-8 phase = thermodynamically stable up to 80°C, at higher temperatures: 9-1-4 phase
- no existing field for the 5-1-8 phase (metastable)
- at NaCl saturation (rock salt "conditions") the stability field of the 3-1-8 is extended to 0.5 mol $Mg^{2+}$ / kg $H_2O$





# Binder phases

Solubility equilibria in the system
$Mg^{2+}$, $Cl^-$, $OH^-$ - $H_2O$, 25°C

- 3-1-8 phase = thermodynamically stable up to 80°C, at higher temperatures: 9-1-4 phase
- no existing field for the 5-1-8 phase (metastable)
- at NaCl saturation (rock salt "conditions") the stability field of the 3-1-8 is extended to
Mg²⁺ / kg H₂O

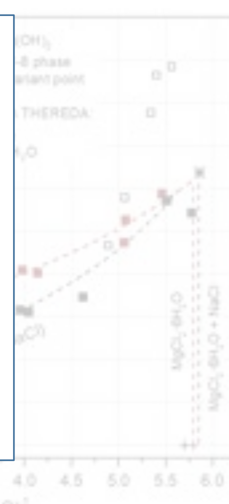
**Thermodynamic modeling** *(behavior of MgO building material in contact with brine)* **is possible!**

Presentation was held at

**ABC -Salt (VII) Workshop, 15-16 June 2023, Santa Fe, NM-USA**

**"Magnesia building material – Solubility data of Sorel phases and modeling in the oceanic salt system"**

Melanie Pannach, Iris Paschke, Daniela Freyer & Wolfgang Voigt

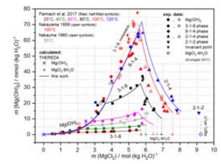


## MgO cement / concrete

**MgO**

**$MgCl_2$-containing salt solution**

**Binder phase(s):**
Basic Mg-Chlorid-Hydrates
**x** $Mg(OH)_2 \cdot$ **y** $MgCl_2 \cdot$ **z** $H_2O$:
**x-y-z** phase (Sorel phases)



**Aggregates / Additives**

crushed salt | Anhydrite-powder | Quartz-powder | sand / gravel

cement …. … concrete



## MgO cement / concrete

**MgO**

**$MgCl_2$-containing salt solution**

**mol ratio**
**$MgO : MgCl_2 : H_2O$**

**3…3,5 : 1 : ~ 11** | **5…10 : 1 : ~ 11**

⇨ expected **binder phases** after setting reaction:

**3-1-8,** 5-1-8 | **5-1-8,** MgO

## MgO cement / concrete

**MgO**

**$MgCl_2$-containing salt solution**

**mol ratio**
**$MgO : MgCl_2 : H_2O$**

| | **3…3,5 : 1 : ~ 11** | **5…10 : 1 : ~ 11** |
|---|---|---|
| ➪ expected **binder phases** after setting reaction: | **3-1-8,** 5-1-8 | **5-1-8,** MgO |
| ***formulation type:*** | ***„3-1-8“*** | ***„5-1-8“*** |



## Formulation types

**Currently used formulations for sealing measures in german salt mines**

**A1**
Asse mine

**DBM2 / B2**

**C3**

**MB10 / D4**

10.8-11.8 ma% MgO
24-26 ma% $MgCl_2$-solution
62-65 ma% crushed salt

R&D-Projects
- ESA
- STROEFUN III (A1-variante)

# Formulation types

**Currently used formulations for sealing measures in german salt mines**

R&D-Projects

**A1**
Asse mine

10.8-11.8 ma% MgO
24-26 ma% $MgCl_2$-solution
62-65 ma% crushed salt

- ESA
- STROEFUN III (A1-variante)


**DBM2 / B2**
Bleicherode mine

10.5 ma% MgO
20.8 ma% $MgCl_2$-solution
34.3 ma% sand
29.5 ma% anhydrite
4.5 ma% microsilica
(amorphous $SiO_2$)

- for ERAM


**C3**

**MB10 / D4**



# Formulation types

**Currently used formulations for sealing measures in german salt mines**

***formulation type „3-1-8“***

R&D-Projects

**A1**
Asse mine

10.8-11.8 ma% MgO
24-26 ma% $MgCl_2$-solution
62-65 ma% crushed salt

- ESA
- STROEFUN III (A1-variante)


**DBM2 / B2**
Bleicherode mine

10.5 ma% MgO
20.8 ma% $MgCl_2$-solution
34.3 ma% sand
29.5 ma% anhydrite
4.5 ma% microsilica
(amorphous $SiO_2$)

- for ERAM


**C3**
Sondershausen mine
Teutschenthal mine

7 ma% MgO
16 ma% $MgCl_2$-solution
65 ma% sand/gravel, 0-8 mm
21 ma% quarz powder
($SiO_2$, crystalline)

- MgO-Project
- ELSA II
- MgO-C3


**MB10 / D4**

# Formulation types

**Currently used formulations for sealing measures in german salt mines**

## *formulation type „3-1-8“*

### A1
Asse mine

10.8-11.8 ma% MgO
24-26 ma% $MgCl_2$-solution
62-65 ma% crushed salt

R&D-Projects:
- ESA
- STROEFUN III (A1-variante)

### DBM2 / B2
Bleicherode mine

10.5 ma% MgO
20.8 ma% $MgCl_2$-solution
34.3 ma% sand
29.5 ma% anhydrite
4.5 ma% microsilica
(amorphous $SiO_2$)

- for ERAM

### C3
Sondershausen mine
Teutschenthal mine

7 ma% MgO
16 ma% $MgCl_2$-solution
65 ma% sand/gravel, 0-8 mm
21 ma% quarz powder
($SiO_2$, crystalline)

- MgO-Project
- ELSA II
- MgO-C3

## *formulation type „5-1-8“*

### MB10 / D4
Teutschenthal mine

| *site concrete* | *shotcrete* | |
|---|---|---|
| 18.2 ma% | 15.6 ma% | MgO |
| 18.2 ma% | 11.5 ma% | $MgCl_2$-sol. |
| 63.6 ma% | 72.9 ma% | sand/gravel 0-8 mm |

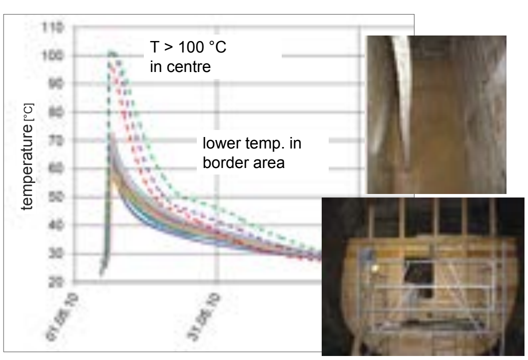
- CARLA / MgO-SEAL
- MgO-S[3]
- MgO-Project



# Temperature development

MgO + $MgCl_2$-Lösung ⟹ Binder phases (3-1-8 / 5-1-8 phase)

**site concrete**

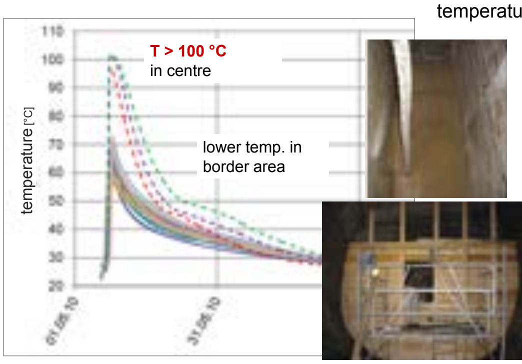


# Temperature development

MgO + $MgCl_2$-Lösung ⟹ Binder phases (3-1-8 / 5-1-8 phase)

Setting reaction via high temperature phases

**site concrete**



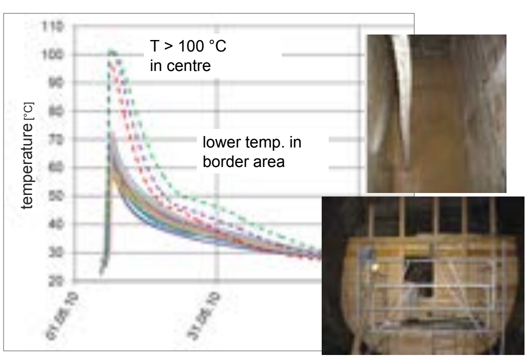


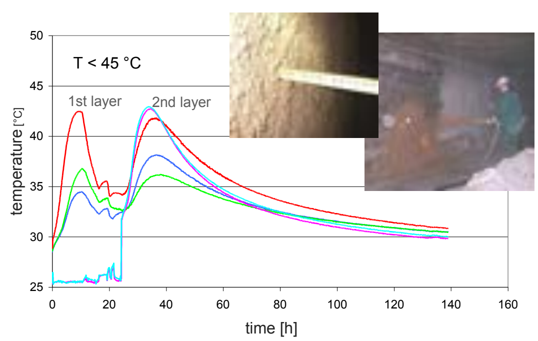

# Temperature development

MgO + $MgCl_2$-Lösung ⟹ Binder phases (3-1-8 / 5-1-8 phase)

**site concrete**

**shotcrete**



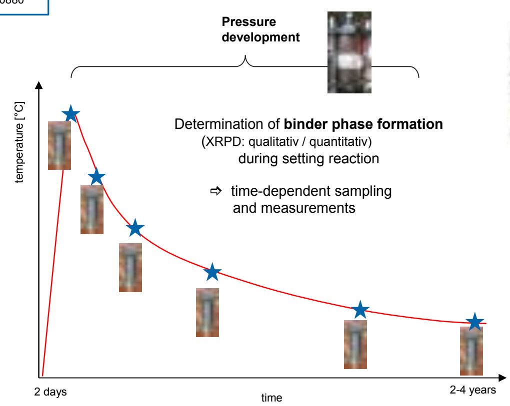



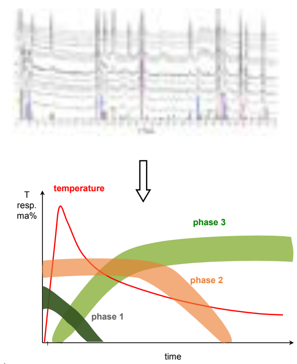
# R&D projects milestones

1898 1st applicati | 11/2004 – 06/2010 CARLA | **12/2010 – 09/2014 MgO-Project** BMWi funding code 02E10880 | 06/2017 A | 05/2013 – 08/2020 ELSA II | 10/2015 – 03/2019 MgO-SEAL | 05/2019 – 03/2022 MgO-S³ | 01/2019 – STROE | 10/2022 De | 12/2022 – 11/2025 MgO-C3

**Development of a fundamental understanding of the setting reaction of magnesia building material**

- Formulation typs 3-1-8 resp. 5-1-8



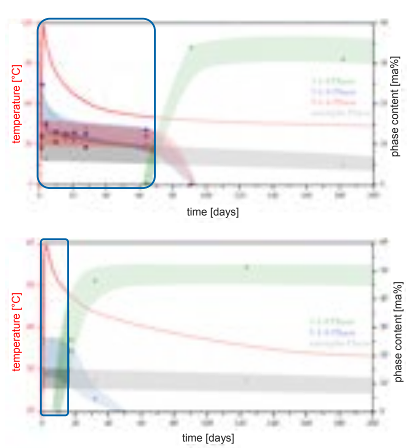






# Formulation type „3-1-8“ (A1, B2, C3)

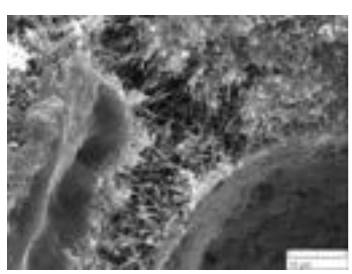
Mol ratio : MgO : $MgCl_2$ : $H_2O$
**~ 3 : 1 : 11**

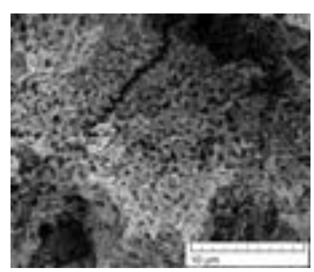
## binder phase formation development




### Setting reaction in two steps

primary: 5-1-8 resp. 9-1-4 phase, amorphous phase + pore solution

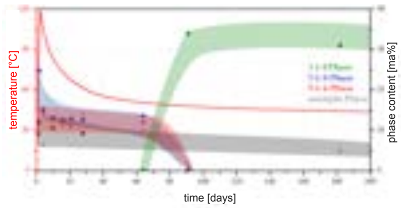


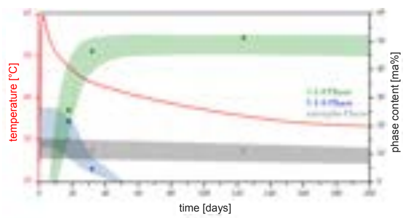


# Formulation type „3-1-8“ (A1, B2, C3)

Mol ratio : $MgO : MgCl_2 : H_2O$
~ 3 : 1 : 11

## binder phase formation development



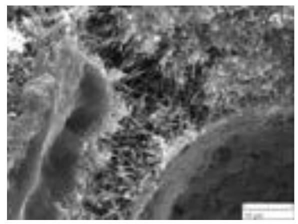




**Setting reaction in two steps**

primary: 5-1-8 resp. 9-1-4 phase, amorphous phase + pore solution

⇓

secondary: 3-1-8 phase

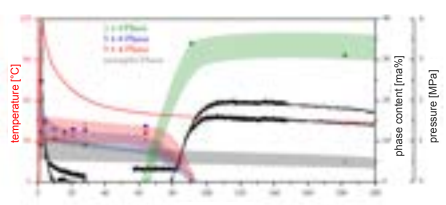


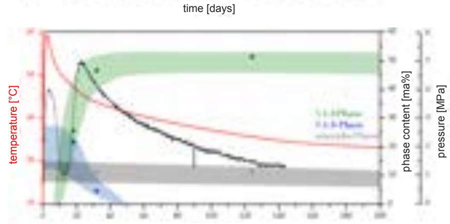


# Formulation type „3-1-8“ (A1, B2, C3)

Mol ratio : $MgO : MgCl_2 : H_2O$
~ 3 : 1 : 11

## pressure development



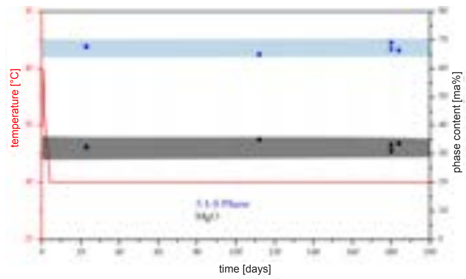




- pressure increase correlates with secondary crystallization of the 3-1-8 phase
- pressure built up declines with time

# Formulation type „5-1-8“ (D4)

Mol ratio : $MgO : MgCl_2 : H_2O$
**~ 10 : 1 : 11**

## binder phase formation development




**primary and non-changing phase formation:**

5-1-8 phase + unreacted MgO

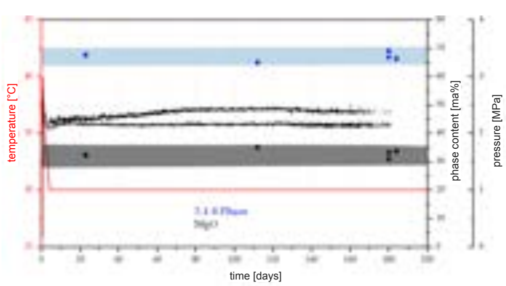
mixing liquid completely consumed for 5-1-8-phase formation



# Formulation type „5-1-8“ (D4)

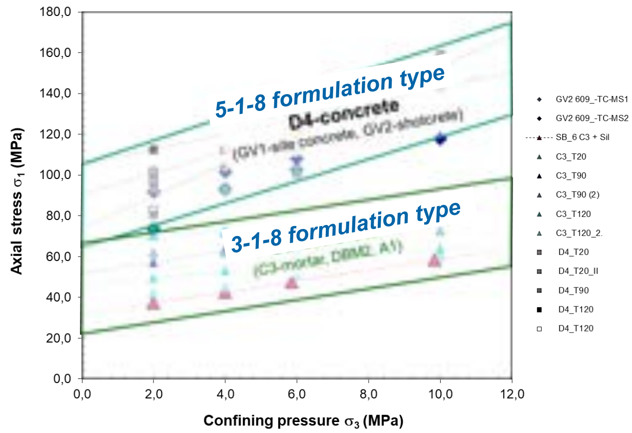
Mol ratio : $MgO : MgCl_2 : H_2O$
**~ 10 : 1 : 11**

## pressure development




- no pressure changes

# Strength properties




- Ultra-High strength values
- transition from 5-1-8 to 3-1-8 formulations ⇨ moderate decrease

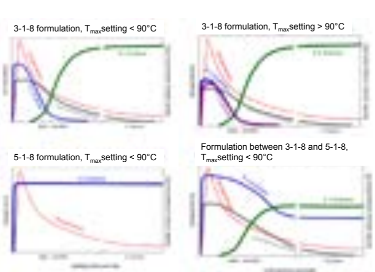


# R&D projects milestones

1898 1st applicati… | 11/2004 – 06/2010 CARLA | **12/2010 – 09/2014 MgO-Project** BMWi funding code 02E10880 | …06/2017 …A | 05/2013 – 08/2020 ELSA II | 10/2015 – 03/2019 MgO-SEAL

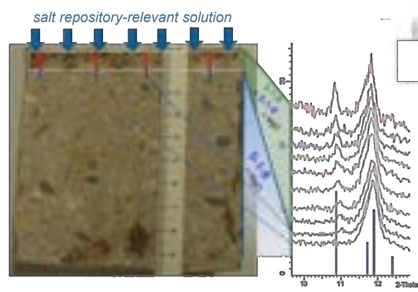
**Development of a fundamental understanding of the setting reaction of magnesia building material**

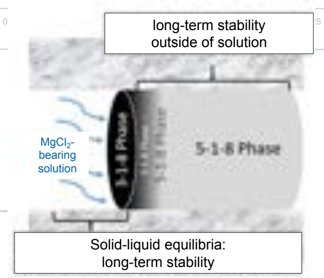
- Formulation types 3-1-8 resp. 5-1-8

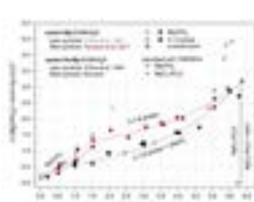



**Proof of integrity formulation type 5-1-8**

- Behavior of the building material after exposure to salt repository-relevant solution



Zusammenhang von Chemismus und mechanischen Eigenschaften des MgO-Baustoffs (Relationship between geochemical and geochemical properties of magnesia building material), BMWi funding code 02E10880

# R&D projects milestones

1898 1st applicati…

11/2004 – 06/2010 CARLA

12/2010 – 09/2014 MgO-project

**06/2011 – 06/2017**
**ESA**
funding by BGE (prev. BfS)

05/2013 – 08/2020 ELSA II

10/2015 – 03/2019 MgO-SEAL

05/2019 – 03/2022 MgO-S³

01/2019 – STROE…

10/2022 De…

12/2022 – 11/2025 MgO-C3

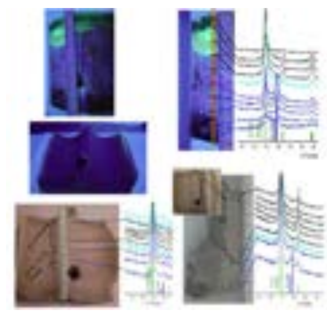
***3-1-8 type***

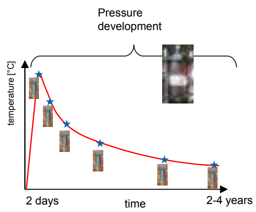
**Demonstration of A1 – long term stability**

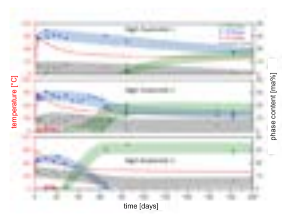
- Binder phase / pressure development analogue MgO-Project
- Investigation different MgO reactivities
- Behavior of the building material after exposure to salt repository-relevant solution

**A1:**
10.8-11.8 ma% MgO
24-26 ma% $MgCl_2$-solution
62-65 ma% crushed salt

→ after setting reaction:
3-1-8 phase,
proportionally 5-1-8








# R&D projects milestones

1898 1st applicati…

11/2004 – 06/2010 CARLA

12/2010 – 09/2014 MgO-project

06/2011 – 06/2017 ESA

05/2013 – 08/2020 ELSA II

10/2015 – 03/2019 MgO-SEAL

05/2019 – MgO…

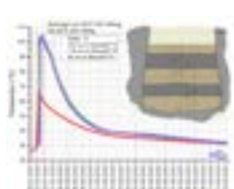
**01/2019 – 07/2022**
**STROEFUN III**
BMWi funding code 02E11748A

…11/2025 …-C3

***3-1-8 type***

**Fluidic functional verification for closing structures and fluid supported sealing of the contact zone**

- Construction of a half dam in Teutschenthal mine using formulation A1 variante
  11.8 ma% MgO
  23.7 ma% $MgCl_2$-solution
  3.9 ma% Anhydrite
  60.6 ma% crushed salt



# R&D projects milestones

1898 1st applicati…

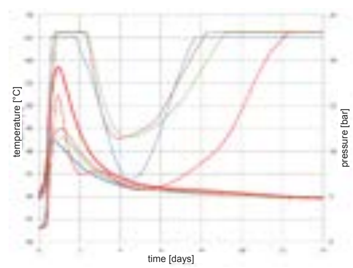
11/2004 – 06/2010 CARLA | 12/2010 – 09/2014 MgO-project | 06/2011 – 06/2017 ESA | **05/2013 – 08/2020 ELSA II** BMWi funding code 02E11193A/B | 05/2019 – 03/2022 MgO-S³ | 01/2019 – STROE… | 10/2022 De… | 12/2022 – 11/2025 MgO-C3

***3-1-8 type***

**C3**
7 ma% MgO
16 ma% $MgCl_2$-solution
65 ma% sand/gravel,
21 ma% quarz powder

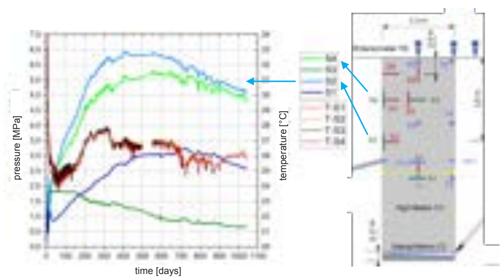
**large scale test 1** (Sondershausen mine)

- technical realization and first data for heat and pressure development




**large scale test 2** (Teutschenthal mine)

- more instrumented than test 1
- measurement data on heat development
- radial and axial pressure development







# R&D projects milestones


1898 1st applicati…

11/2004 – 06/2010 CARLA | 12/2010 – 09/2014 MgO-project | 06/2011 – 06/2017 ESA | 05/2013 – 08/2020 ELSA II | 10/2015 – 03/2019 MgO-SEAL | 05/2019 – 03/2022 MgO-S³ | **12/2022 – 11/2025 MgO-C3** BMUV funding code 02E12072A/B

***3-1-8 type***

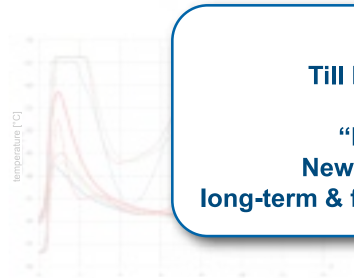
**C3**
7 ma% MgO
16 ma% $MgCl_2$-solution
65 ma% sand/gravel,
21 ma% quarz powder

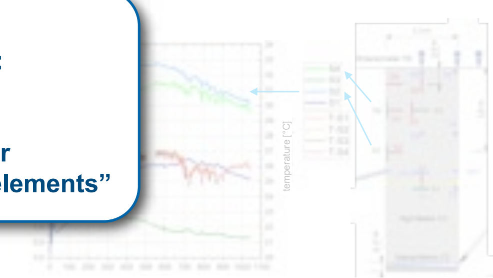
**large scale test 1** (Sondershausen mine)

- technical realization and first data for heat and pressure development

**large scale test 2** (Teutschenthal mine)

- more instrumented than test 1
- measurement data on heat development
- radial and axial pressure development





**Presentation**
**Till Popp today at 11:30:**

**"MgO concrete C3:**
**New building material for**
**long-term & fast-acting closure elements"**

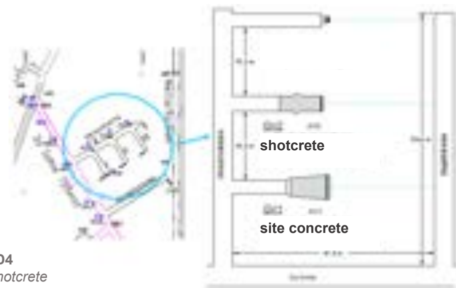
# R&D projects milestones

1898 1st app | **11/2004 – 06/2010 CARLA** BMBF funding code 02C1204 | …/2014 …ject | 06/2011 – 06/2017 ESA | 05/2013 – 08/2020 ELSA II | 10/2015 – 03/2019 MgO-SEAL | 05/2019 – 03/2022 MgO-S³ | 01/2019 – STROE | 10/2022 DeS | 12/2022 – 11/2025 MgO-C3

***5-1-8 type***

**construction of 2 dams** (feasibility test)

Teutschenthal mine




| MB10 / D4 | | |
|---|---|---|
| *site concrete* | *shotcrete* | |
| 18.2 ma% | 15.6 ma% | MgO |
| 18.2 ma% | 11.5 ma% | $MgCl_2$-sol. |
| 63.6 ma% | 72.9 ma% | sand/gravel |



# R&D projects milestones

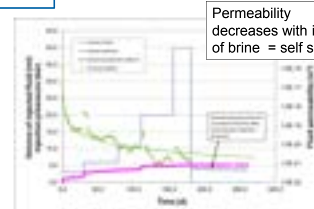
1898 1st applicati… | **11/2004 – 06/2010 CARLA** | **12/2010 – 09/2014 MgO-project** | 06/2011 – 06/2017 ESA | 05/2013 – 08… ELSA | **10/2015 – 03/2019 MgO-SEAL** BMWi funding code 02E11435 | 05/2019 – 03/2022 MgO-S³ | 01/2019 – STROE | 10/2022 DeS | 12/2022 – 11/2025 MgO-C3

***5-1-8 type***

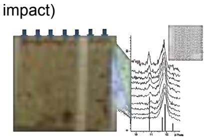
**Characterization of the geochemical and hydro-mechanical state of the MgO-shotcrete dam after 7 years of service life**

**Demonstrating the integrity of the MgO-concrete D4 for future HAW repositories in salt**

- Proof of long-term safety of geotechnical barriers made of MgO concrete with the 5-1-8 binder phase,
- Behavior of the building material after exposure to the typical (German) salt repository-relevant solution:
  - 2 molal $MgCl_2$ NaCl-saturated brine
  - saturated NaCl-brine ($Mg^{2+}$ - free)
  - (=solution with the strongest impact)




Permeability decreases with inflow of brine = self sealing !



# R&D projects milestones

1898 1st applicati… | 11/2004 – 06/2010 **CARLA** | 12/2010 – 09/2014 MgO-project | 06/2011 – 06/2017 ESA | 05/2013 – 08/2020 ELSA II | 10/2015 – 03/2019 **MgO-SEAL** | 05/2019 – 03/2022 **MgO-S³** BMUV funding code 02E11769A | 12/2022 – 11/2025 MgO-C3

***5-1-8 type***

**selective deconstruction of GV2**
**-** survey the distribution of the injectives

**Testing & investigate various shotcrete formulations**
- layer thickness
- permeability, porosity, density,..
- ….



# R&D projects milestones

1898 1st applicati… | 11/2004 – 06/2010 CARLA | 12/2010 – 09/2014 MgO-project | 06/2011 – 06/2017 ESA | 05/2013 – 08/2020 ELSA II | 10/2015 – 03/2019 MgO-SEAL | 05/2019 – 03/2022 MgO-S³ | 01/20… STR… | 10/2022 – 09/2025 **DeSpriBi** funding by BGE

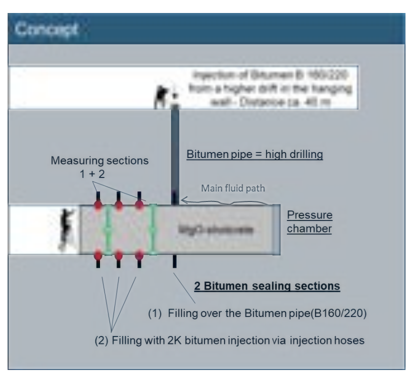
***5-1-8 type***

**Demonstration building for a drift sealing in anhydrite made of magnesia construction material as shotcrete and bitumen/asphalt**

Actual state at the test site


Width: ca. 3,8 m / height: 3,5 m/ length: ca. 12 m

Bernburg mine



# Tool box of formulations

## … two formulation types with different properties

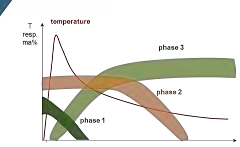
| Formulation typ | „3-1-8" | | „5-1-8" | |
|---|---|---|---|---|
| **Name** | C3 DBM2 A1 | | | D4 (MB10) |
| **Mol Ratio** MgO : $MgCl_2$ : $H_2O$ | 3 : 1 : 11 | (3 - 5) : 1 : (11 - 13) | 5 : 1 : 13 | (>5) : 1 : 13 |
| **Geomechanical Properties in relative comparison** | **Creep and relaxation behaviour** | | **Strength** | |
| **Brine permeability** **(repository solution)** | k ~ 10[illegible] … 10[illegible] m² | < 10[illegible] m² | … < 10[illegible] m² | tight |
| **Role of aggregates or additives** | Aggregates of various types and grains influence the geomechanical properties to some extent, but do not cause any fundamental changes in the typical hydraulic-mechanical properties of the binder phases. The aggregates should be inert to the ongoing geochemical processes for preserving / demonstrating long-term stability (i.e. no reactions with the $MgCl_2$-solutions); that means "inert" materials such as rock salt (NaCl), sand / gravel, crystalline silica flour ($SiO_2$), anhydrite, magnesite). | | | |

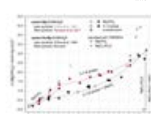
Freyer, D.; Gruner, M. & Popp, T., Zusammenhang von Chemismus und mechanischen Eigenschaften des MgO-Betons, Freiberger Forschungshefte E15 – Naturwissenschaften (2015).



# Summary

- Depending on binder phases (3-1-8, 5-1-8 phase) two formulation types are usable
- Fundamental understanding on binder phase formation in relation to composition of the formulation and setting temperature development
- 3-1-8 type: long-term stability → thermodynamic solid solution equilibria with salt solution of the host rock salt
- 5-1-8 type: proof of integrity → indirect long-term stability in case of 5-1-8 binder phase
- Comprehensive data base of hydro-mechanical properties
- Demonstration of feasibility for drift and shaft seals by large scale tests



# Contributing Institutions, Funding & Support

1898 — 1st application — today

| 11/2004 – 06/2010 | 12/2010 – 09/2014 | 06/2011 – 06/2017 | 05/2013 – 08/2020 | 10/2015 – 03/2019 | 05/2019 – 03/2022 | 01/2019 – 07/2022 | 12/2022 – 11/2025 | 10/2022 – 09/2025 |
|---|---|---|---|---|---|---|---|---|
| **CARLA** | **MgO-project** | **ESA** | **ELSA II** | **MgO-SEAL** | **MgO-S³** | **STROEFUN III** | **MgO-C3** | **DeSpriBi** |
| BMBF funding code 02C1204 | BMWi funding code 02E10880 | funding by BGE (prev. BfS) | BMWi funding code 02E11193A/B | BMWi funding code 02E11435 | BMUV funding code 02E11769A | BMWi funding code 02E11748A | BMUV funding code 02E12072A/B | funding by BGE |

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Institute of Mining and Special Civil Engineering

Institut für Gebirgsmechanik GmbH

BGE TEC
BGE TECHNOLOGY GmbH

IBeWa – Ingenieurpartnerschaft für Bergbau, Wasser und Deponietechnik

GSES

Grube Teutschenthal

K+S

MFPA Materialforschungs- und -prüfanstalt Weimar

SCHACHTBAU NORDHAUSEN

TS BAU

BAM

TU Clausthal

ERCOSPLAN

K-UTEC

# KOMPASS & MEASURES

## A young story on crushed salt investigations

Larissa Friedenberg
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH


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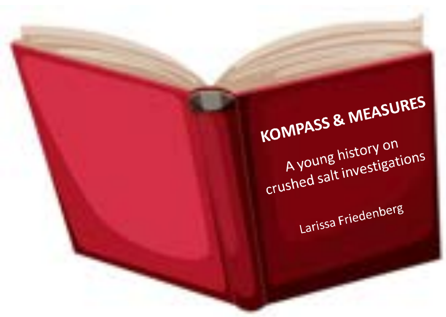
# Agenda



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# 1. The origin

- Investigations on crushed salt have been performed during the last decades
  - Focus on the mechanical evolution
  - Crushed salt as stabilization for the host rock
- Important paradigm shift in German repository design with the Site Selection Act (2017)
  - Shift from limited release to safe containment
  - Crushed salt as **geotechnical barrier**
  - Focus on the evolution of hydraulic properties


*Ref: Korthaus, Callahan, Hansen, Hunsche, Spiers, Stührenberg, WIPP Site, Asse mine, Gorleben mine…*

DAEF State-of-the-art report (2017)

→ Need for future R&D work



# 2. The synthesis

KOMPASS-I (09/2018 – 08/2020) → KOMPASS-II (07/2021 – 06/2023) → MEASURES (xx/2024)

- Improve scientific database behind using crushed salt for long-term isolation of high-level nuclear waste
- Improve prediction of crushed salt compaction process
- Work with relevance for long-term safety of HLW a repository in rock salt

KOMPASS Family:

GRS: L. Friedenberg, O. Czaikowski, K. Jantschik

BGE TEC: Ch. Lerch, M. Rahmig

BGR: S. Beese, R. Eickemeier, A.-K. Gartzke, B. Laurich, W. Liu, K. Svensson, J. Thiedau, K. Zemke

TU Clausthal: U. Düsterloh, S. Lerche, N. Saruulbayar

Sandia National Laboratories: J. Bean, J. Coulibaly, M. Mills, B. Reedlunn

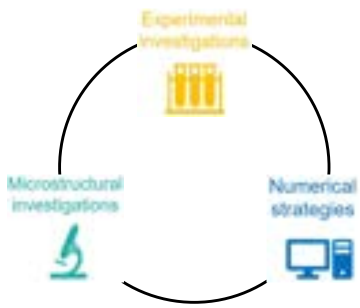
COVRA: J. Bartol

Institut für Gebirgsmechanik GmbH: Ch. Lüdeling, D. Naumann, T. Popp, O. Rabbel, Ch. Rölke

Utrecht University: H. De Bresser, S. Hangx, Ch. Spiers, B. Van Oosterhout

## 2. The synthesis

- KOMPASS:
  Kompaktion von Salzgrus für sicheren Einschluss (Compaction of crushed salt for safe containment)
- MEASURES:
  Multi-scale experimental and numerical analysis of salt material used as engineered backfill for a nuclear waste repository in rock salt







## 3. The creation of a solid basis

Basis for generic investigations: **KOMPASS reference material**

- Well-defined crushed salt material
- Sondershausen mine, Germany
- Staßfurt sequence in a bedded Zechstein formation
- Optimized grain size distribution (Fuller curve)

[IfG, 2022]

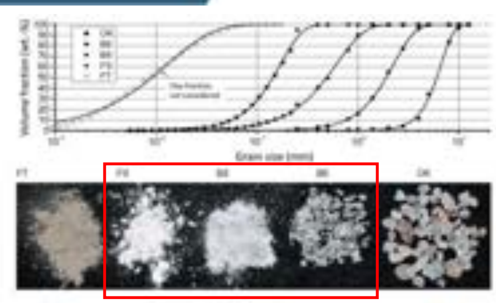


Fig. 4.2 Salt grain fractions and grain size distributions

Tab. 4.1 Grain size fractions in the raw salt material and the optimized mixture

| Material-fraction | Grain size distribution $d_1$-$d_u$ [mm] | $d_{50}$ [mm] | m [-] | Optimized mixture [wt.-%] |
|---|---|---|---|---|
| Überkorn (OK) – oversized grains | 3 - 10 | 6.03 | 3.44 | - |
| Band 6 (B6) – production line 6 | 0.4 - 4 | 1.90 | 2.08 | 65.6 |
| Band 8 (B8) – production line 8 | 0.1 - 1 | 0.49 | 1.58 | 20.2 |
| Feinsalz (FS) – fine salt | 0.03 - 0.3 | 0.14 | 2.01 | 14.2 |
| | | | sum | 100.0 |
| Materials from other investigations or sources | | | | |
| REPOPERM | 0.1 - 30 | 2.35 | 0.81 | |
| ESCO - salt | 0.1 - 8 | 1.48 | 1.02 | |

[KOMPASS-I, 2020]

## 4. The love of detail

**Compaction of crushed salt is facilitated by several microstructural deformation mechanism**

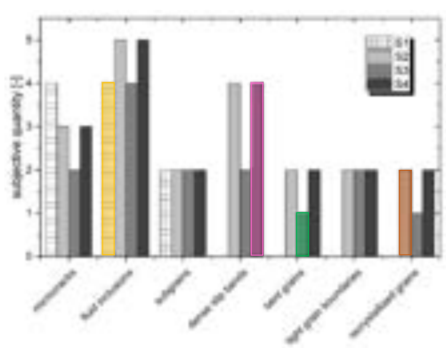
Topic: Large uncertainties regarding actual contribution of each mechanism to the overall compaction depending on porosity, water content, grain size and usual environmental influencing factors still remain

Storyline:
- ➢ Establishment and improvement of microstructural investigation methods
- ➢ Relating the abundancy of indicators for microscale deformation mechanism to compaction conditions
- ➢ Focussing on comparison of different pre-compaction methods



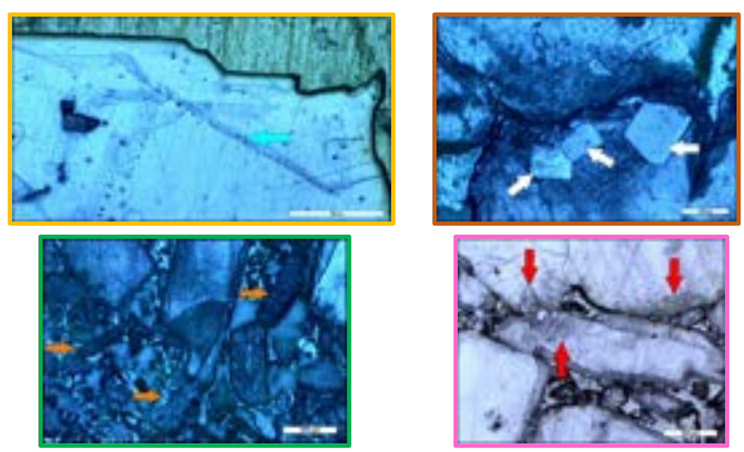
## 4. The love of detail

Storyline:
- ➢ Establishment and improvement of microstructural investigation methods
- ➢ Relating the abundancy of indicators for microscale deformation mechanism to compaction conditions
- ➢ **Focussing on comparison of different pre-compaction methods**




S1 loose crushed salt
S2 BGR pre-comp.
S3 TUC pre-comp.
S4 IfG pre-comp.

[KOMPASS-II, 2023]



# 5. The impact of stress

**A comprehensive database is needed for the THM-coupled compaction behavior of crushed salt**

Topic: The compaction behavior is influenced by different factors whose impact must be investigated. The investigation is not completed, there are still some knowledge gaps in process understanding.

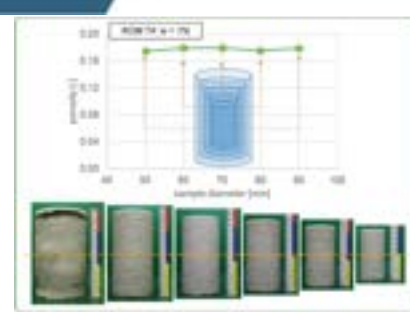
Storyline:
- ➢ Development of pre-compaction methods
- ➢ Establishment of an extended systematic laboratory program addressing the known relevant influencing factors
- ➢ Execution of long-term compaction experiments
- ➢ Collaboration with SAVER project: in-situ KOMPASS backfill body



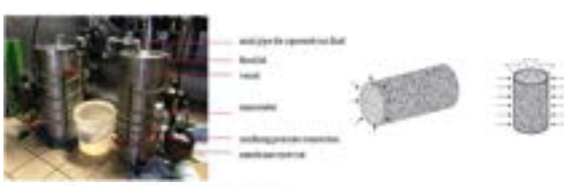
# 5. The impact of stress

**Pre-compaction methods**

- Aim: produce samples for long-term compaction tests
  - Relatively low porosity (15 – 20 %)
  - Natural grain structure
  - Short-term, but with in-situ relevant stresses

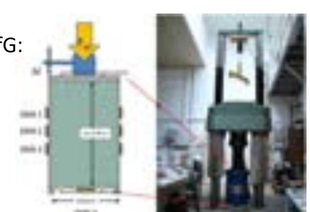


TUC:

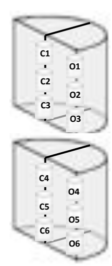


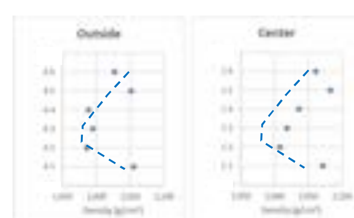
BGR:

IfG:



[KOMPASS-I, 2020]



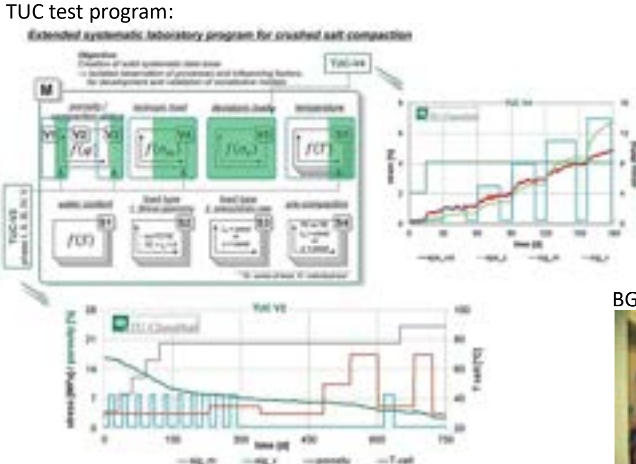
Friction effect on compaction:
- End effects bottom /top: higher
- Center of the cylinder is higher consolidated than the outsides

[IfG, 2022]

# 5. The impact of stress

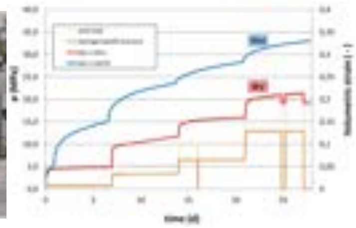
**Long-term compaction experiments**: comprehensive database for the THM-coupled compaction behavior

TUC test program:



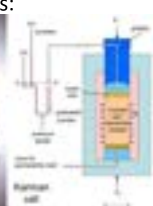
[MEASURES, 2023]

IfG creep tests:



[IfG, 2022]

BGR triaxial tests:



[KOMPASS-I, 2020]

| sample name | Water content [wt.%] | T [°C] | run-time [d] | load [MPa] | porosity [%] start | porosity [%] end |
|---|---|---|---|---|---|---|
| TK-038 | 0.1 | 50 | 34 | 5,10 | 16.7 | 15.0 |
| TK-041 | 0.35 | 50 | 145 | 5,10,15,20 | 17.4 | 4.8 |
| TK-042 | 0.35 | 50 | 72 | 10,15 | 17.4 | 10.2 |
| TK-044 | 0.5 | 30 | 144 | 4,8,12, 16,20 | 17.7 | 4.6 |
| TK-045 | 0.5 | 50 | 220 | 4,8,20 | 13.2 | 5.4 |

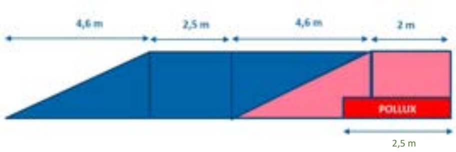
[Friedenberg et al., 2023]

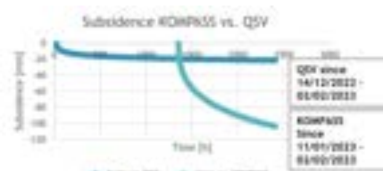


# 5. The impact of stress

**In-situ conditions**: KOMPASS backfill body in the Sondershausen mine

➜ Collaboration with the SAVER project (TU BAF)　　➜ Presentation by L. Schaarschmidt



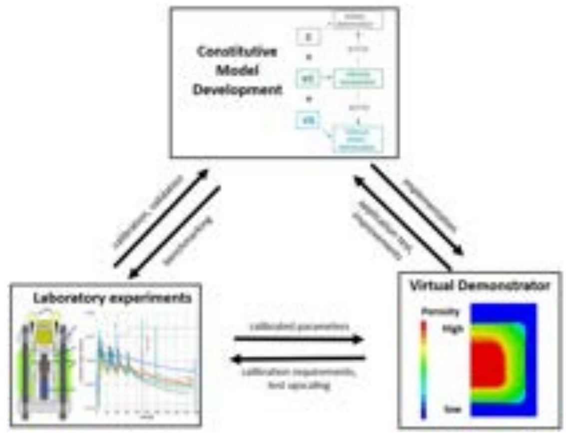
[Schaarschmidt, 2023]

## 6. The prediction of the future

**A reliable prediction of crushed salt compaction behavior is needed for long-term safety assessment purposes**

Topic: Suitable constitutive models are needed which are able to describe the mechanical/hydraulic property changes over a wide range of influencing parameters.

Storyline:
- Application of various constitutive models
- Benchmark calculations against laboratory experiments
  - ➡ Presentation by S. Lerche (yesterday)
- Application of a virtual demonstrator
- Development/optimization of constitutive models




[KOMPASS-II, 2023]



## 7. The end and epilogue

The KOMPASS projects contribute to the improvement of the scientific knowledge for using crushed salt as backfill for HLW containment.

*The End*

BUT... The KOMPASS projects also identified some important shortcomings!

- Laboratory program is not completed
- Effects of laboratory shortcomings has to be addressed
- Hydraulic properties of crushed salt need to be considered
- Need for optical experiments on the activation and quantification of micro deformation mechanism
- Update the permeability reduction with time for the long-term safety analisys

*To be continued...* MEASURES (coming 2024)

## Acknowledgements


THANKS TO THE KOMPASS FAMILY!

FKZ: 02 E 11951A


THANKS FOR YOUR ATTENTION!



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# Big Scale In-Situ Application of Matrix-stabilized vs. Conventional Backfill With Improved Backfilling Method

Louis Schaarschmidt, Dr. Iris Paschke, Dr. Daniela Freyer, Prof. Dr.-Ing. Helmut Mischo

**Technical University Bergakademie Freiberg**

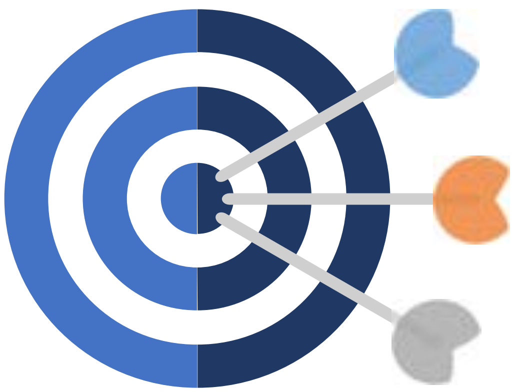

1

# Agenda

- What is the SAVER Project about?
- Material Compositions
- Project Time Line
- Test Site Setup
- Backfill Body Building Process
- Retrieved Data
- Achievements
- Ongoing Work
- Future Prospects

2

## What is the SAVER Project about?



**Comparison GESAV vs. KOMPASS materials**
Comparison of conventional moist salt grit (KOMPASS) vs. internally-stabilized salt grit material (GESAV)

**Optimize and Improve**
Researching potential optimization of backfill method used for GESAV material

**Practical Relevance**
Development of POLLUX-Dummy and building of unique



## Material Compositions

### GESAV Material

Crushed rock salt – NaCL: 85%

Salt binder components: 15%

- $CaSO_4 \cdot 0{,}5\ H_2O$ (Hemihydrate)
- $MgSO_4 \cdot H_2O$ (Kieserite)
- $K_2SO_4$ (Arcanite)
- $MgCl_2$-brine (5 molal)
- Moisture content 3,75 %

### KOMPASS Material

Crushed rock salt – NaCL: 100%

- Moisture content 1%

**<u>Main difference:</u>**
**Polyhalite development within GESAV material rapidly forming a skelletial structure within the backfill body resulting in early stabilization and low settlement**

# Project Time Line

**Summer 2021**

- Kick-Off SaVer – Phase I
- Start of conceptual design
- Conducting approval procedures with mining authority
- Supply chain issues due to Ukraine war
- Blasting issues while drift extension
- Evaluation of previous GESAV II project

**Summer 2022**

- Finalization of layout plan and design of in-situ underground test sites
- Receiving all materials and approvals
- Setup of measurement devices and POLLUX-Dummy

**December 2022 - February 2023**

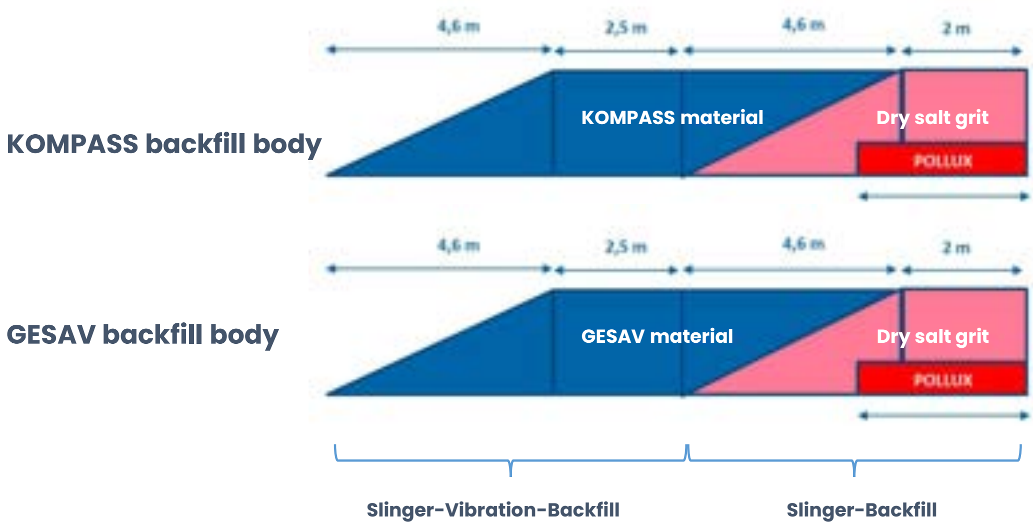
- Finalization of both underground back fill bodies in rock salt Sondershausen
- Start of data logging

**Spring –Summer 2023**

- Beginning of analysis of logged data



# Test Site Setup



## Test Site Setup

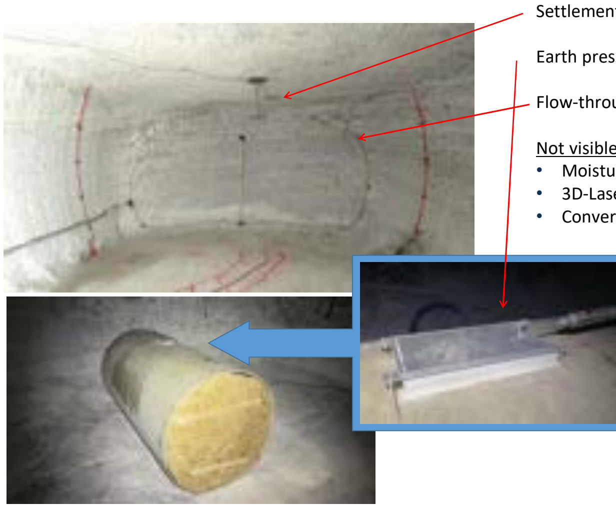
### IN-SITU-MONITORING

Settlement sensor

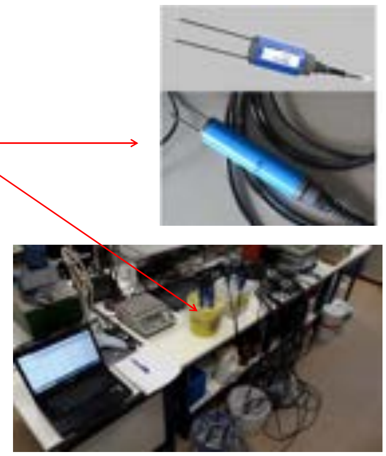
Earth pressure sensor

Flow-through installation

Not visible:
- Moisture & temperature sensors
- 3D-Laserscans
- Convergence measurements

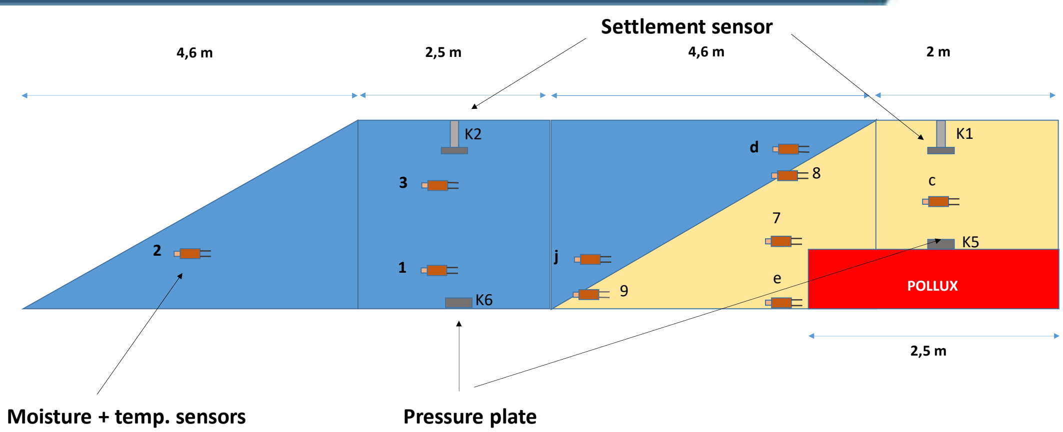


Picture from supplier „IMKO“

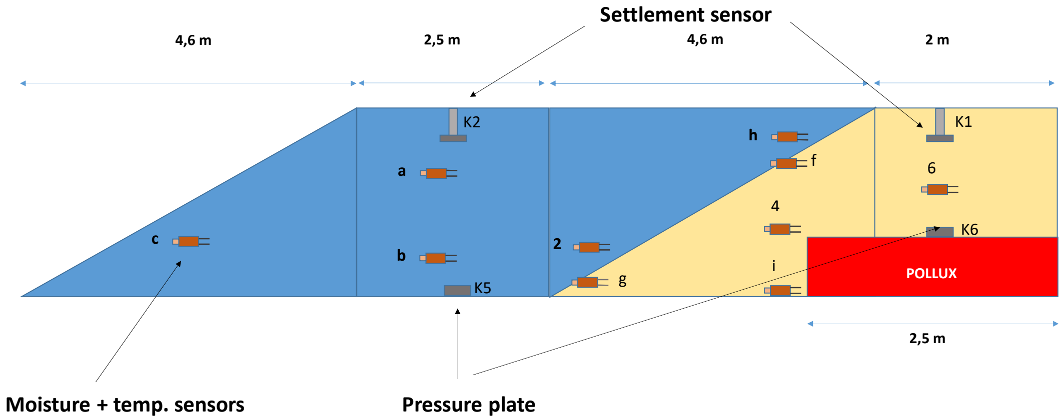




## Test Site Setup – Devices GESAV

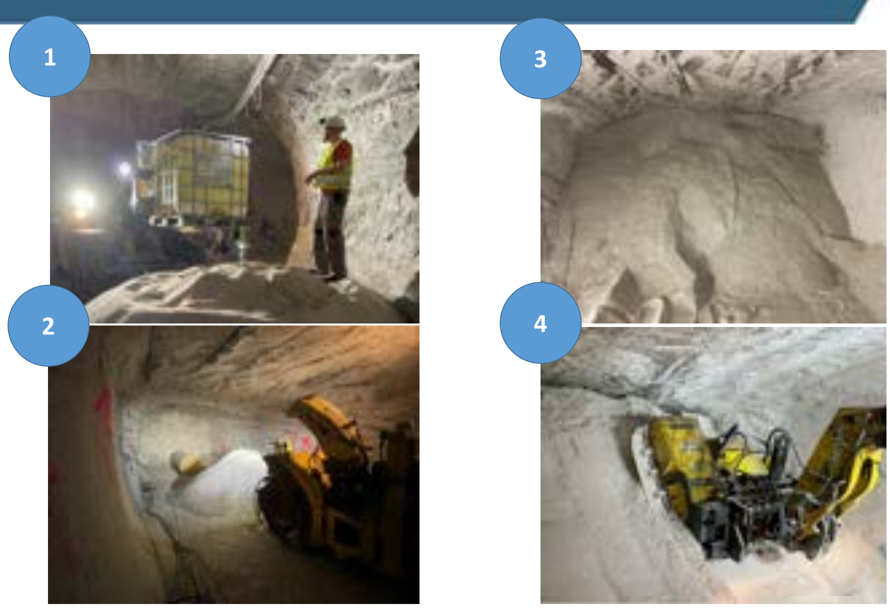


# Test Site Setup – Devices KOMPASS






# Backfill Body Building Process - KOMPASS



## Backfill Body Building Process - GESAV

1

2

3

4



## Backfill Body Building Process - Videos

## Retrieved Data – Settlement

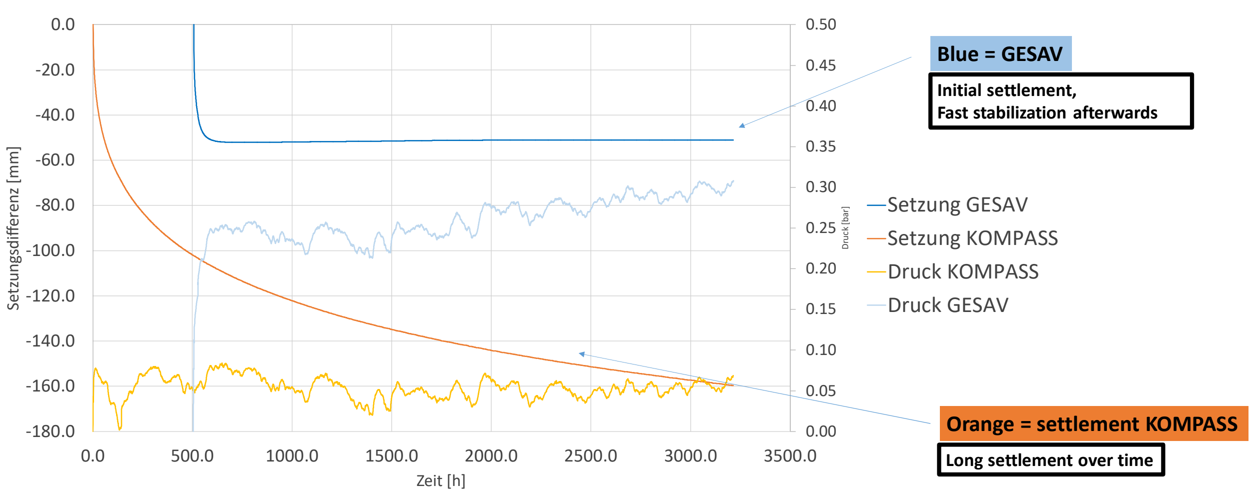
**GESAV body**

**KOMPASS body**

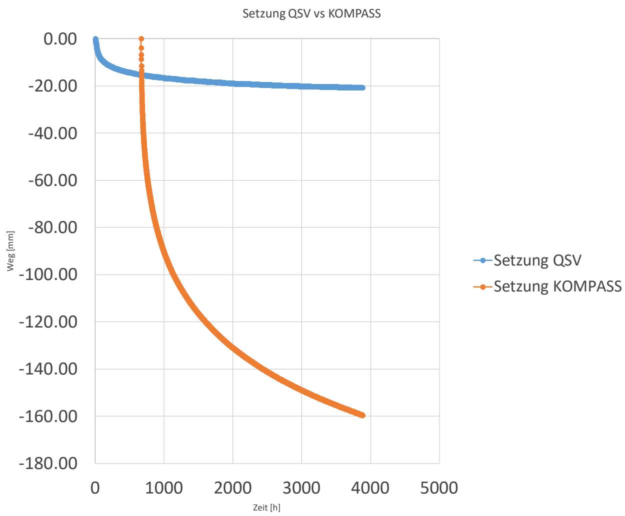
**GESAV backfill body highlights less settlement optically as well as in logged settlement data**



## Retrieved Data – Settlement



# Retrieved Data – Settlement




**Blue = Dry salt backfill**

**Initial settlement, stabilization after over short time period**

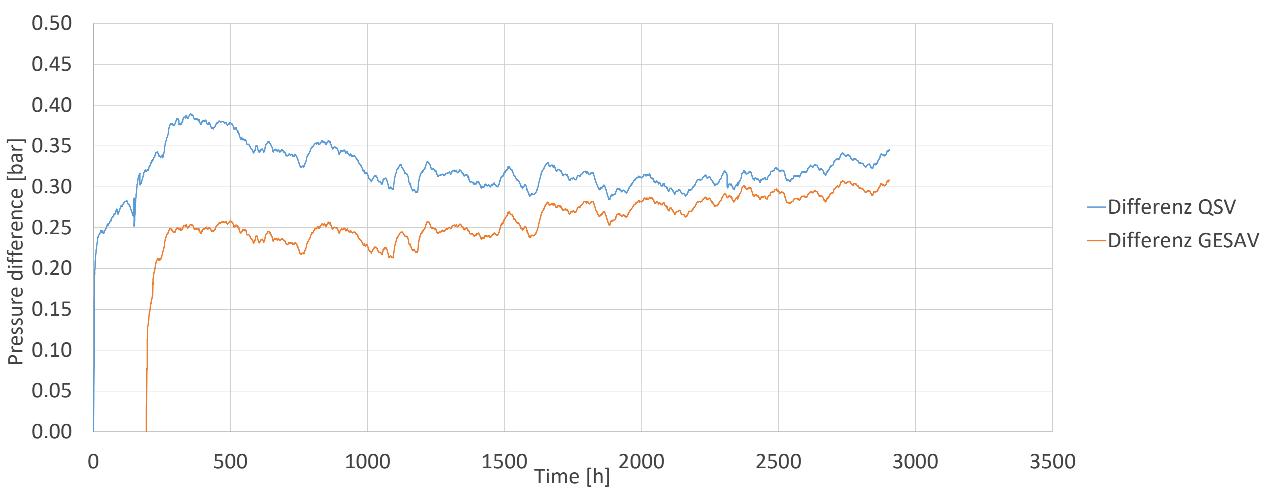
**Explanations:**
- different backfill methods
- different grain size distiributions

**Orange = settlement KOMPASS**

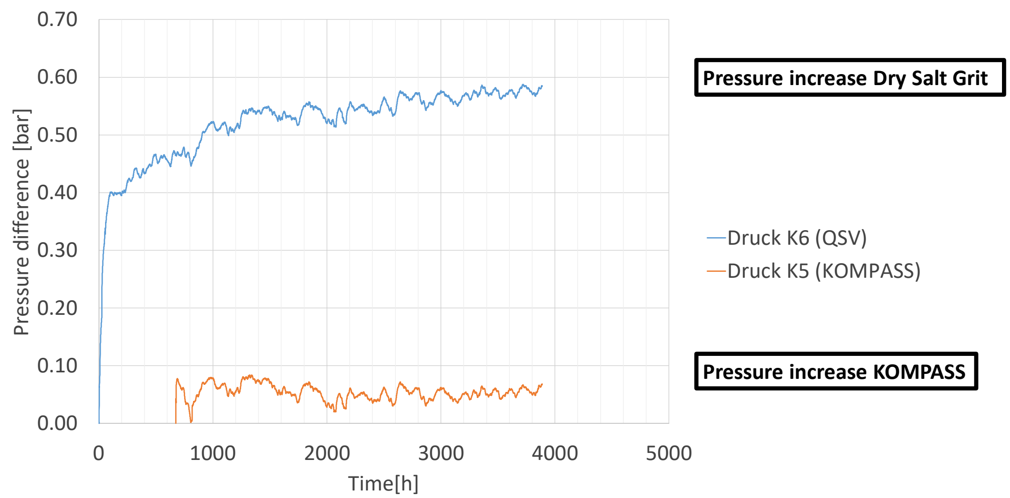
**High initial settlement, Long settlement over time**



# Retrieved Data – Pressure GESAV Body

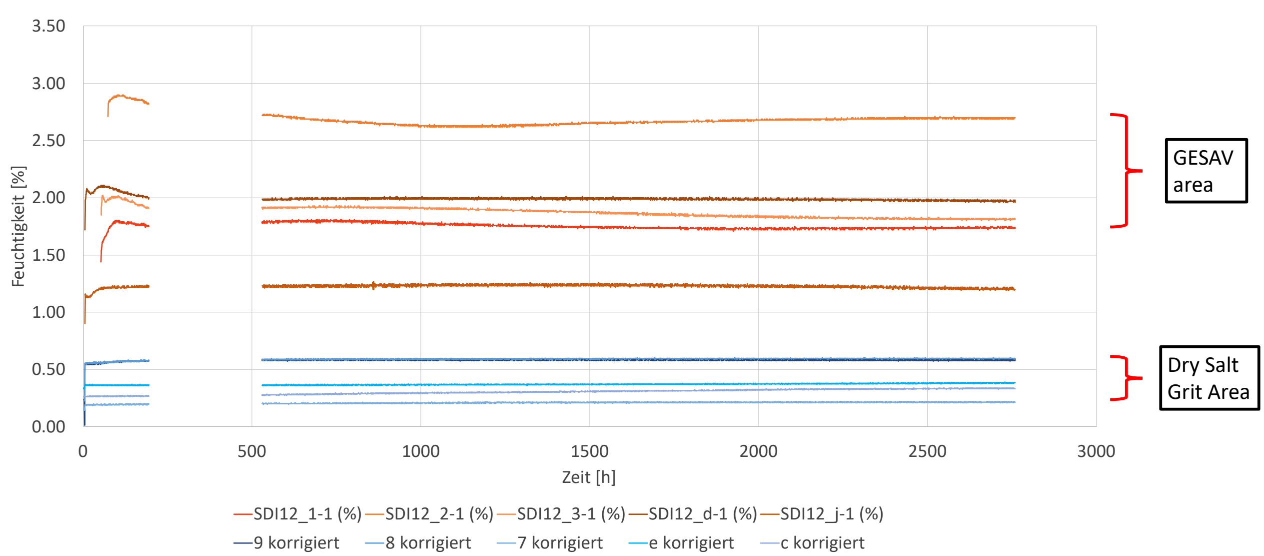


## Retrieved Data – Pressure KOMPASS Body

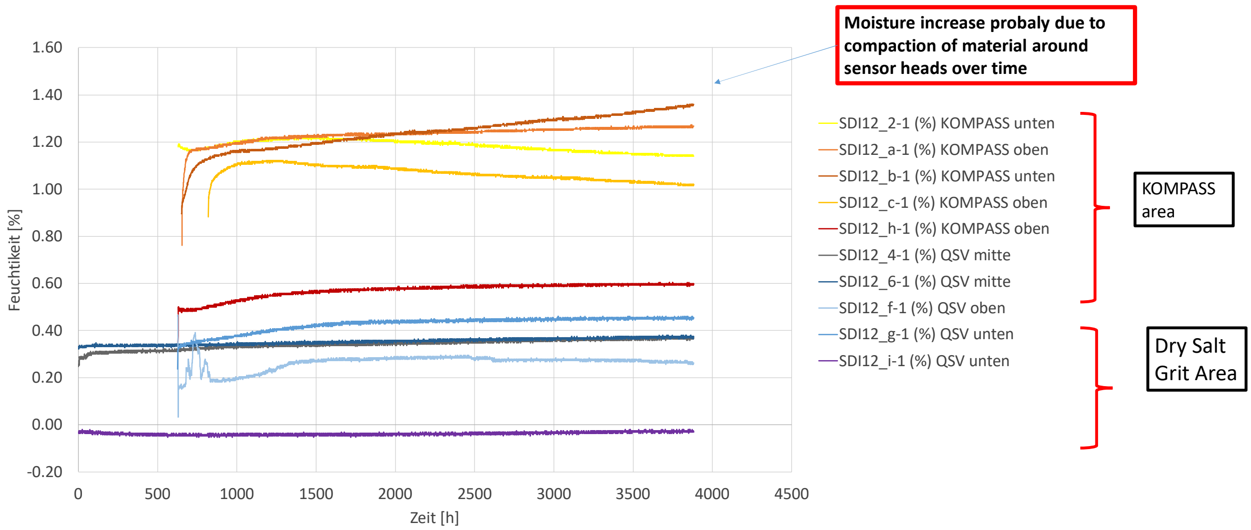





## Retrieved Data – Moisture GESAV



# Retrieved Data – Moisture KOMPASS



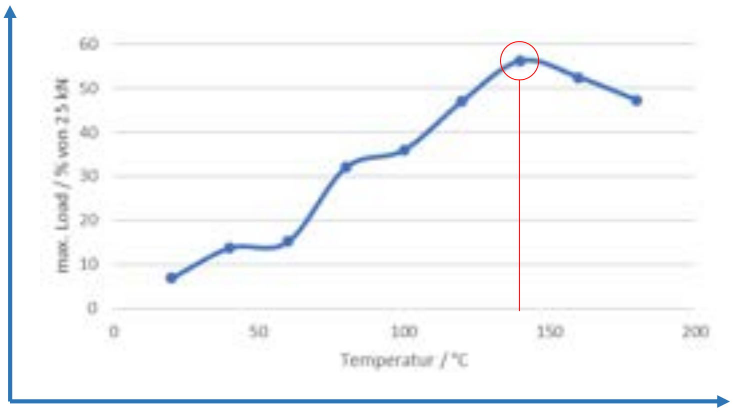



# Retrieved Data – In-Situ Density

| Material | Method | Density [g/cm3] |
|---|---|---|
| GESAV | Slinger-Vibration | **1.5** |
| Dry Salt Grit [GESAV BODY] | Slinger | **1.63** |
| KOMPASS | Slinger-Vibration | **1.62** |
| Dry Salt Grit [KOMPASS BODY] | Slinger | **1.67** |

# Ongoing Work

- **Currently assessing impact of thermal radiation on GESAV material stability**
- **Fresh GESAV material being heated in oven for 24h at different temperaturs; samples will then be tested for uniaxial compressive strength**




**Peaking at around 140°C**

**Geochemical results still pending**



# Achievements

- **Completion** of two in-situ real-life sized backfill bodies with fully monitored measurement setup
- **Succesful proof** that application of vibration backfill method works both on GESAV as well as on KOMPASS material
- **Cooperation** with KOMPASS-Project (FKZ.: 02E11708)
- **Creation** of a big data base based on logged data as well as in-situ sampling campaign
- **International presentations** about the project on several conferences and workshops
- **Support of scientific offspring** by providing the opportunity for thesis (PhD, MSc)

# Ongoing Work

- 2x PhD Thesis
- 1x Master Thesis
- Analysis of sampling campaign and logged data
- Constant geochemical analysis of in-situ samples



# Future Prospects

- Planning to continue SAVER I with SAVER II project starting in October 2023
- Increase scientific exchange between us and other countries with similar projects and/or shared interests
- Research relationship between temperature and GESAV structure development
- Continue monitoring and analyzing backfill bodies and in-situ samples

## THANK YOU FOR YOUR ATTENTION!

**We are open for questions and looking forward to network**

# RANGERS

## Summary of State-of-the-Art in EBS materials

Edward Matteo
Sandia National Laboratories

Eric Simo, Philipp Herold, Andreas Keller, Andree Lommerzheim, Paola Léon Vargas
***BGE TECHNOLOGY GmbH***

Edward Matteo, Kris Kuhlman, Rick Jayne, Melissa Mills, Ashley Machado-Lopez
***Sandia National Laboratories***




# RANGERS

- Methodology for design and performance assessment of geotechnical barriers in a HLW repository in salt formations
- Joint-Project of BGE TECHNOLOGY GmbH and Sandia National Laboratories

- Main goals:
  - Compilation of existing knowledge and experience to design salt-relevant:
    - Geotechnical Barriers
    - Engineered Barrier System (EBS)
  - Including their preliminary design and verification

- Secondary goals:
  - Optimization of EBS in salt repositories
  - Analysis of the safety assessment impact of gases on EBS
  - Coupling safety assessment simulations by BGE TEC and SANDIA

Edward Matteo, Kris Kuhlman, Rick Jayne, Melissa Mills, Ashley Machado

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. 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. Thanks to Heeho Park for review. **SAND2023-05280C.**

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

The research work that is the basis of this report was funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) represented by the Project Management Agency Karlsruhe (Karlsruhe Institute of Technology, KIT) under contract number FKZ 02 E 11839. The authors alone, however, are responsible for the contents of this study.

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# Speaking of Validation and Verification…


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## Purpose, objective, and approach of this talk

- Purpose:
  - Survey State of the Art of Engineered Barrier Materials to potentially enable credible design options to meet the site specific challenges

- Objective: Describe candidate materials that fall outside of the range of "conventional" seal/barrier materials normally under consideration

- Approach:
  - Provide some high level description from a repository design perspective
  - Then, describe the individual materials, highlighting pros and cons
  - Provide illustrative examples along the way



## Motivation, 1/2

Repository Design Concept in a Salt Host

- High Reliance on the Natural System
  - Low permeability
  - Self-healing via creep closure
- Salt backfill (e.g. run-of-mine salt) is an excellent barrier, once it is compacted

} Generic

- Multiple Barrier Concepts (~ engineered redundancy) are implemented in the Engineered Barrier System
  - Other barriers/materials are needed both for redundancy, but also to provide isolation from closure up until reconsolidated salt has reached sufficient permeability
  - Features, Events, and Processes (FEPs)

} Site specific

## Motivation, 2/2

Other barriers/materials must:

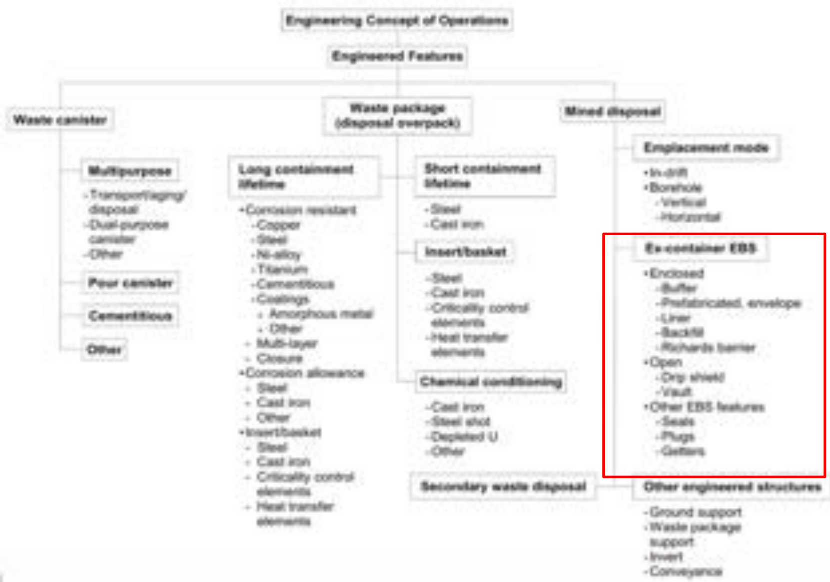
- Compatibility with the Natural System (e.g., bedded vs. domal, mineralogy, etc.)
  - Saturated/Partially Saturated (Scenarios)
    - Brine composition
    - Chemical durability /evolution
  - Unsaturated
    - Gas generation?
    - Mechanical durability/evolution
- Compatibility with materials in the EBS design
  - Have well-defined, reproducible, and predictable material properties
  - Material sourcing
- Be durable in the repository setting
- Not have a deleterious effect on the chemical and/or mechanical evolution of the repository system (e.g. near-field or far-field geochemistry)



## The EBS Design will be a function of Inventory and Geologic Setting

- Inventory – thermal output has key impacts on Repository Design
  - Who, What, Where of waste
- Geologic Setting
  - Host rock chemical and mechanical environment
- Engineering Decisions
  - Constructability
  - Emplacement
    - Drift and waste packing spacing (determined by thermal and geomechanical considerations)
    - Vertical vs. horizontal emplacement
    - Bentonite Buffer/backfill – pelletized vs. compacted vs. pre-fab
  - Materials selection
    - Overpack (e.g. corrosion allowance materials)
    - Buffer vs. backfill
  - Additional Engineered System Elements for Operational Safety (e.g. ground support)

## There are many Design Options for the Engineered System



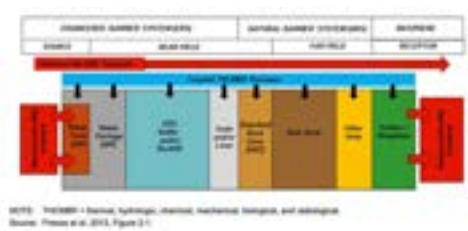

From Hardin et al. 2011



## Engineered Barrier System Components, 1/2

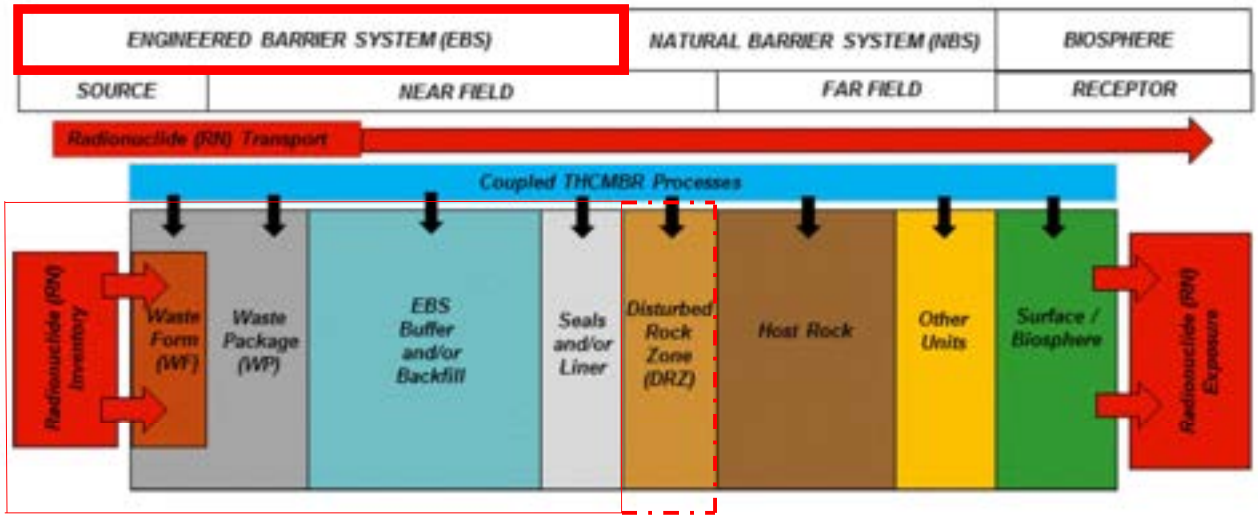
- Waste form
- Waste Canister/Overpack
- Buffer/Backfill
- Drift Seals
  - Access and Emplacement
- Shaft Seals
- Ground Support – e.g. liner, rock bolts, etc.
- Excavation Damaged Zone (EDZ)

**Seal System***
**a/k/a Geotechnical Seals**



*The Seal System functions to seal the drifts and shafts, and also takes into account the EDZ

## Engineered Barrier System Components, 2/2



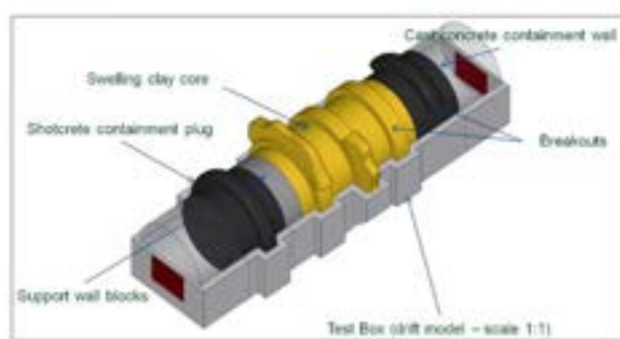

NOTE: THCMBR = thermal, hydrologic, chemical, mechanical, biological, and radiological.
Source: Freeze et al. 2013, Figure 2-1.



## Excavation Damage Zone (EDZ) and the Seal System

- A/k/a Damaged Rock Zone (DRZ)
- EBS Design must account for the EDZ and implement design features that prevent preferential transport along the fracture networks left behind from mining (Perras and Diederichs 2016)
- The EDZ features prominently into the design of the seal system, where break-outs and water stops are incorporated to interrupt potential transport pathways in the EDZ and/or at the Seal/Host interfaces
  - Liner – buffer/backfill
  - Liner- Host
  - Plugs – Host


From Perras and Diederichs 2016

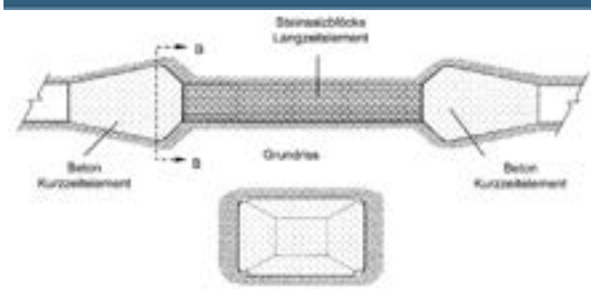



From DOPAS 2016 - Full Scale Seal Test conducted by ANDRA

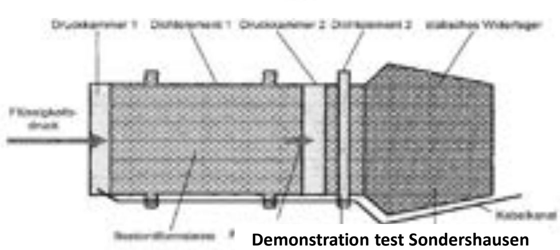
- Buffer/backfill
  - Crushed salt!!!
  - Extends waste package lifetime and secures waste package in emplacement
  - Helps conduct heat away from the waste package
  - Functional barrier that should compact and homogenize with the host rock
- Drift Seal Closures
  - Provide isolation from FEPs until backfill is sufficiently consolidated, or perhaps in specific water intrusion scenarios
  - "X" + bulkheads, X = low permeability binder material
  - Cementitious materials (low pH)
    - Ordinary Portland Cement (OPC)-based Salt Concrete
      - Autogenous shrinkage during curing can leave gaps that would allow fluid flow
  - Issues related to Mass concretes ->. OPC-alternative
    - e.g. Mg-O cement (Sorel cement)
    - "Specialty" cements and/or binders



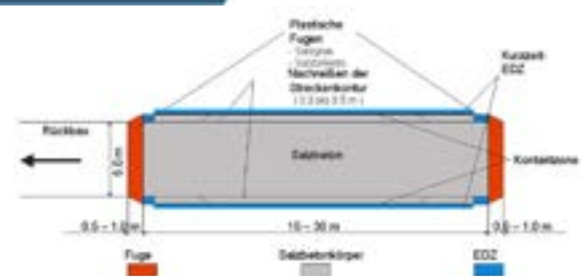
## Drift Sealing Concepts



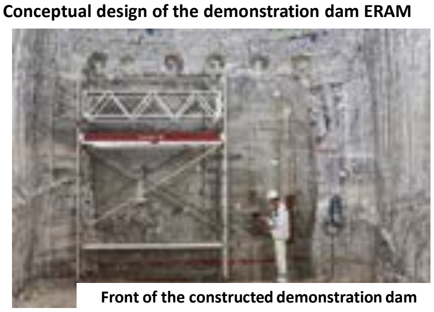
Conceptual design WIPP site



Demonstration test Sondershausen



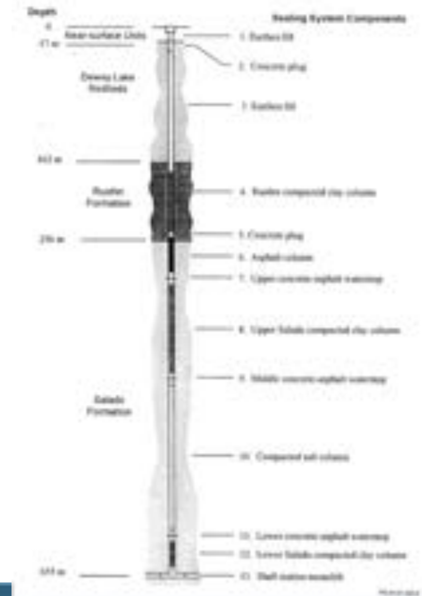
Conceptual design of the demonstration dam ERAM



Front of the constructed demonstration dam

## Excavation Damage Zone (EDZ) and Shaft Seals

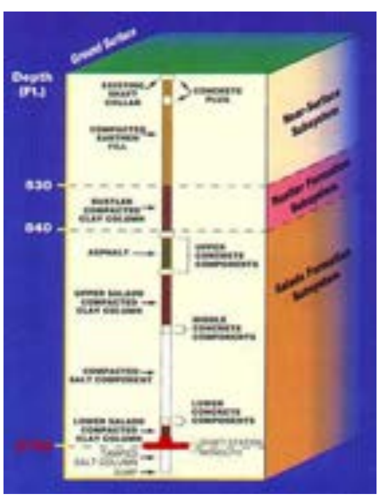
- In the Shaft, this also includes potential advective transport from disposal horizon to some other horizon that has potential to increase rate of transport to the biosphere
- Multi-barrier design, including “layers” composed of cementitious plugs, compacted swelling clay, backfill, and water stops.
- WIPP Shaft Seal Design often considered state-of-the-art of the multi-barrier design



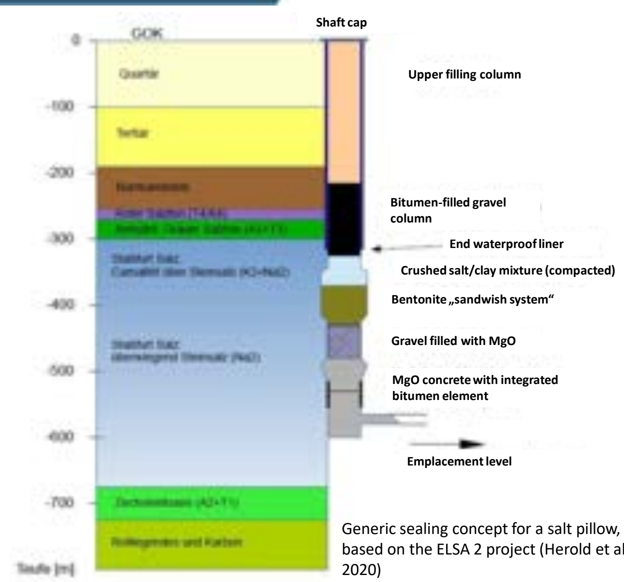
From Hansen and Knowles 1999



## Shaft sealing concepts



WIPP site https://www.cardnm.org/shaft_a.html




Generic sealing concept for a salt pillow, based on the ELSA 2 project (Herold et al., 2020)

## Discussion/see Break out session

- The design of (shaft) sealings depends on various factors and requirements

- In regard to the building materials following aspects seems important:
  a) Use as sealing element, abutment or filling column
  b) Mechanism of action/principle of action – technical bases for durability
  c) Aviailability
  d) Technical maturity of the construction
  e) Compatibility to the natural system and with other EBS materials

- The necessity to implement new materilas could result from „external“ aspects and the above named „internal“ aspects

- Most important seems b), d) and e)

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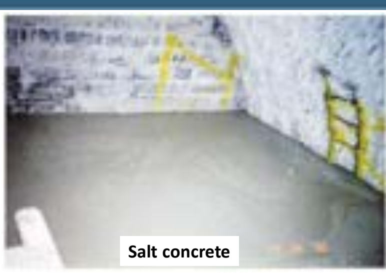
## Materials already in use


Salt concrete


Bitumen and Asphalt


Crushed Salt


MgO-concrete


Gravel and crushed hard rock


Bentonite

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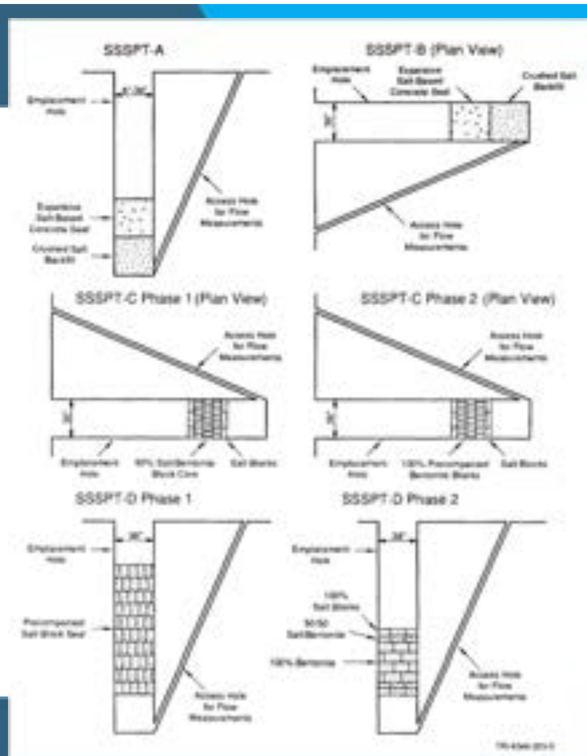
# Salt/Bentonite Mixtures for sealing

- The materials were tested against both brine and gas flow during the Small-Scale Seal Performance Tests at WIPP (late 1980's and early 1990's)
- There were fabrication inconsistencies with salt/bentonite blocks
- Crushed salt/bentonite mixtures have more recently been considered

- Pros:
  - may consolidate faster
  - Offers some potential for radionuclide retention

- Cons:
  - As a matrix material, mechanical evolution differs from salt and this introduces complexity for predicting material properties/behavior over repository timescales




From Finley et al. 1992



# Salt bricks

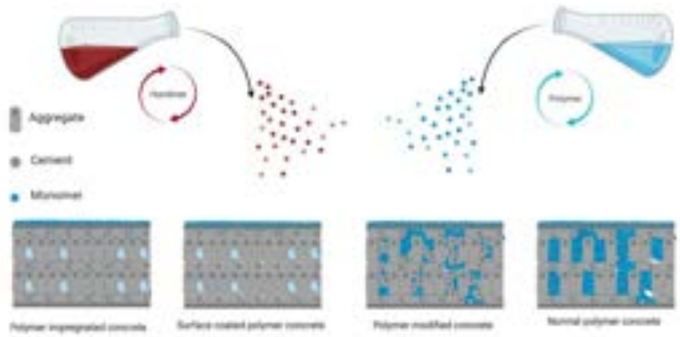
- Definition:
  - Bricks made of natural rock salt
  - Cut in different designs to fill the cross section and avoid overlapping joints
  - Use as sealing element for underground openings

- Expected Benefits:
  - A native material similar to the host rock can be used
  - The native rock provides a low porosity and the porosity of the sealing element is just defined by the technical voids or the joints
  - In comparison to crushed rock a significant reduction of the initial porosity can be achieved
  - Due to the low porosity compaction process could finalize faster and an earlier establishment of a bearing capacity is expected
- Drawback: emplacement logistics and impact on operational efficiency

**Düsterloh, 2022**

# Polymer Concrete

- Uses polymers to supplement/replace cement as a binder.
- Main categories include:
  - Polymer-cement concrete (PCC)
  - Polymer impregnated concrete (PIC)
  - Polymer concrete (PC)
- Made up of:
  - Liquid resin
  - Fillers (ex., silica flour or ground calcium carbonate)
  - Coarse aggregates (ex., gravel)
- Polymer increases material strength, adhesion, and water-tightness, which all are beneficial for sealant application. (Omaha, 2008)

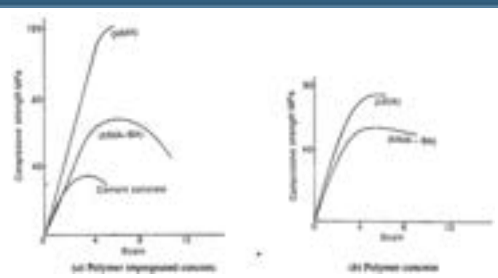



Different applications of polymer in producing concrete (Nodehi, 2021)

- Industry examples: bridge decking, surface overlays, road surfacing, floor toppings, sewer pipe, concrete repairs and patching



# Polymer Concrete: As a Grout/Sealant



PIC and PC stress-strength relationship using Methyl methacrylate (MMA) and Butylacrylate (BA) polymers at room temperature (Shraddhu, 2017)

Meyer Polycrete sewer pipes (left), JKT Group Polymer Concrete pipe, polymer modified concrete samples (Mohammed, 2022)

<u>Suitability:</u>

- Low porosity and increased adhesion
  → Reduces or eliminates water flow
- Chemical and abrasion resistant
  → Good compatibility with host rock
- Performs well under high loads
  → Ideal for salt repository with pressure from creep closure of drifts and shafts

<u>Challenges:</u>

- Significant increase in cost compared to Portland Cement
  - Cost rises by a factor of 7 (Bozkurt and Gencel, 2013)
- Requires specific care and curing temperature
  - However, 70% of maximum strength is fulfilled within one day of curing at room temperature (Niaki and Ahangari, 2022)
- Experiences thermal degradation beginning at 50ºC (Marschall and Frederick, 1987)
- Microbial interactions???

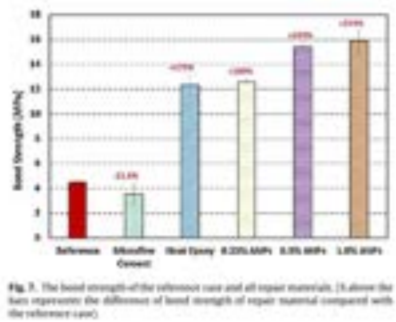
# Use case of polymer-concrete

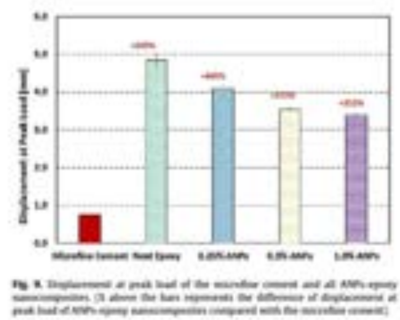
- Rheologic and bonding characteristics are tunable
- Example: Nanomodified Epoxy
  - Alumina nanoparticles can improve both viscosity and bonding
- Polymer modified concretes can bond well with geomaterials and engineered materials (steel, cement, etc.)
- Can be injected into micron-sized gaps, which can be important esp. where mitigation of gas flow is needed


International Journal of Greenhouse Gas Control

A new polymer nanocomposite repair material for restoring wellbore seal integrity

Moneeb Genedy, Usama F. Kandil, Edward N. Matteo, John Stormont, Mahmoud M. Reda Taha







# Materials – Molten Salts 1/2

- Definition:
  - Molten salts are salts that have been heated above their melting temperatures and have become liquid. They solidify when cooled down.
  - Simple salts or salt mixtures with a low viscosity are preferred
  - Melting temperatures typically range from 100°C to 1000°C.
- Expected Benefits:
  - Complete containment of radionuclides due to pure solid-state diffusion
  - Water free salts do not dissolve adjacent materials at their contact surface
  - The initial properties of the solid material are reached directly after cooling
  - Ease of installation in vertical sealing elements
  - Free flowing liquid reaches gaps and cavities
  - Incompressible media without porosity
  - Possibility to mix salts with another and to add aggregates to influence properties

Figure …: HITEC salt (Coastal Chemical) with 53% $KNO_3$; 40% $NaNO_2$; 7% $NaNO_3$ and a melting point 142°C (Minkley, 2018) – Not to be used in a rock salt underground repository environment due to chemical behavior.

## Materials – Molten Salts 2/2

- Particularities and Processing (incl. Constraints):
  - Occupational health and safety challenges arise from handling hot liquids
  - The melting temperature needs to be selected such that the host rock remains solid and low enough to exclude thermal cracks in the host rock or in other sealing elements
  - Cooling material may have decrease in volume on the order of a few percent. Therefore the filling of the remaining space must be done in a continued process or as a secondary step

- Potential Application Areas - for repository closure tasks – if permeability is low enough
  - Feasibility of molten salts with low melting point is currently under investigation (German Project SalVE: TU BA Freiberg, BGE TECHNOLOGY, IfG Leipzig)
  - Not to be used as a backfill due to the energy intense processing, large required volume and less chemical similarity with the host rock compared to crushed salt
  - In a shaft the molten salt will fill gaps of the prior layer and the contour easily.
  - For low perm candidates, the material can be used in vertical and horizontal seals



## MgO shotcrete

- Definition:
  - Non-hydraulic cement based on magnesia chloride (solution) and magnesia oxide plus different aggregates – similar to established MgO concrete
  - Pre-mixed and pneumatically installed

- Expected Benefits:
  - MgO-concrete as well established building material in cast in place construction method
  - Shotcrete offers an alternative installation method to reduce the hydration heat inside the construction and thus a limitation of thermal induced stresses
  - Flexible in shape of the cross section and contour
  - No additional drilling required, no working from upper levels
  - Uniform connection to the rock, no roof gap and thus suitable for drift seal construction


Knoll et al. (2010)


Arendt (2022)

# Summary / Next Steps

- Repository Design Concept in Salt and conceptual underpinnings of the Natural System and the EBS have been summarized
- Novel materials for implementation in the EBS Design in a Salt Host have been reviewed
- Pro and Cons were discussed
- RANGERS Project and the SOTA Report #2 will be completed at the end of 2023.

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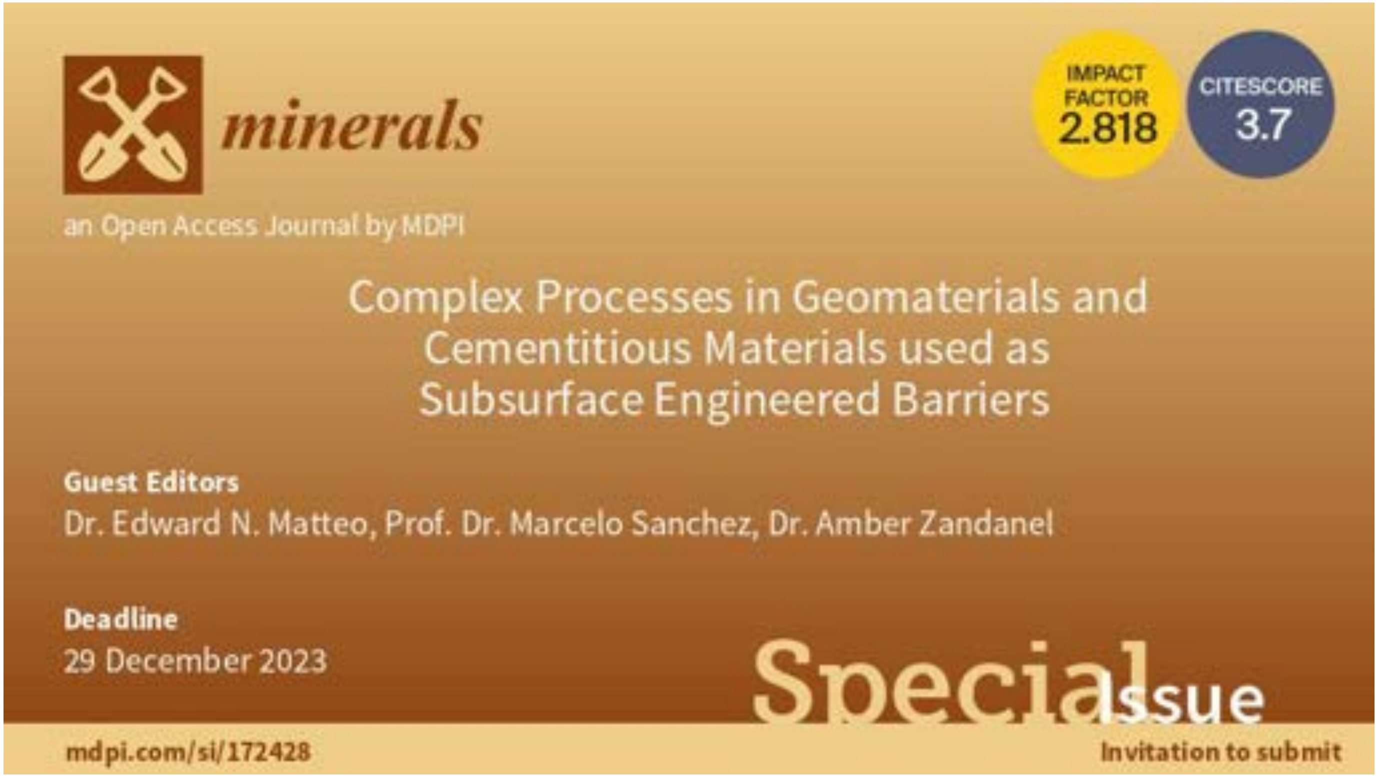


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# MgO concrete: “MgO-C3”: New building material for long-term & fast-acting closure elements


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# Agenda



2

## Motivation

- Shaft seals = the most important technical measure
  to ensure the integrity of a repository,
  **however, the permeability is initially high when installed ……**

  MgO building materials offer unique advantages:
  - Long-term stability under saliferous conditions
  - Favorable hydro-mechanical properties

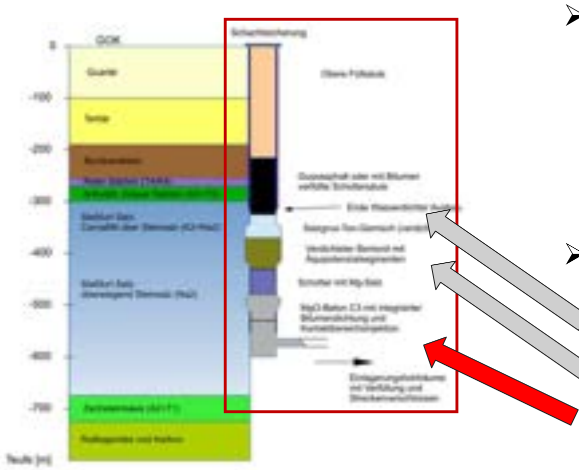
  **But: the potential of MgO building materials for HAW repositories is not yet fully exploited ……**


**MgO-C3 Concrete** → A large-scale test with the MgO-C3 formulation is being carried out in the Teutschenthal mine ….



## Application I: closure of a radioctive waste repository

**ELSA II shaft closure concept**



Abschlussbericht ELSA-Phase II (TU Bergakademie Freiberg und BGE TECHNOLOGY GmbH, BMWi-FKZ 02E11193A/B)

- The technical barriers should fulfill their sealing function at the beginning of the post-closure phase,

  **however, due to the excavation damage or disturbed zone in the salt convergence must act to restore the salt tightness.**
- For safety reasons the shaft closure elements are (at least) diverse as (geo)technical barriers, e.g.
  - **Crushed salt /clay mixture at the salt top**
  - **Bentonite seal**
  - **MgO-C3 at the shaft bottom**

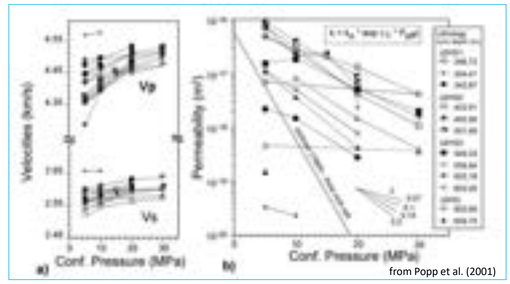
# MgO-C3 – site concrete

## Formulation type „3-1-8“


**Why the MgO-C3 - concrete …?**

→ Development of an high expansion pressure

⇨ effective "immediate sealing“ of the EDZ (ELSA II)




from Popp et al. (2001)

Recovery of tightness as a function of pressure (and time)

**Aim of the study: Demonstration of**
**+++ high and long acting expansion pressures**



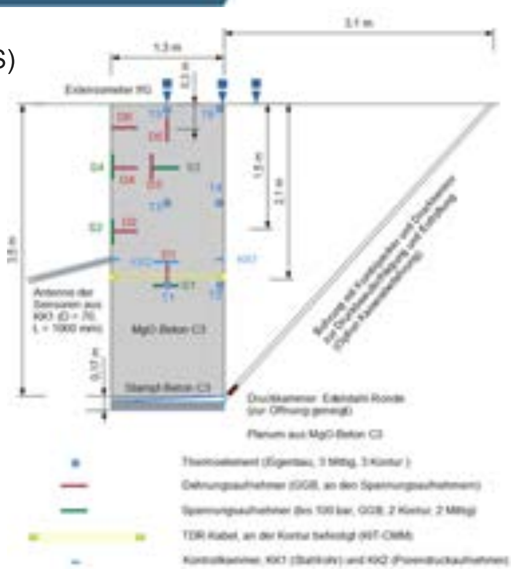
# State of knowledge

**Large bore hole test 1** (Salt mine Sondershausen - GSES)

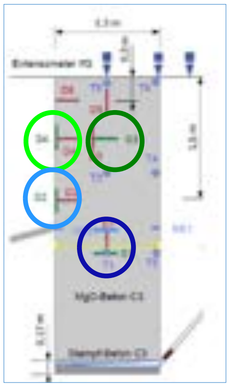
➢ First technical realization and first data on heat development

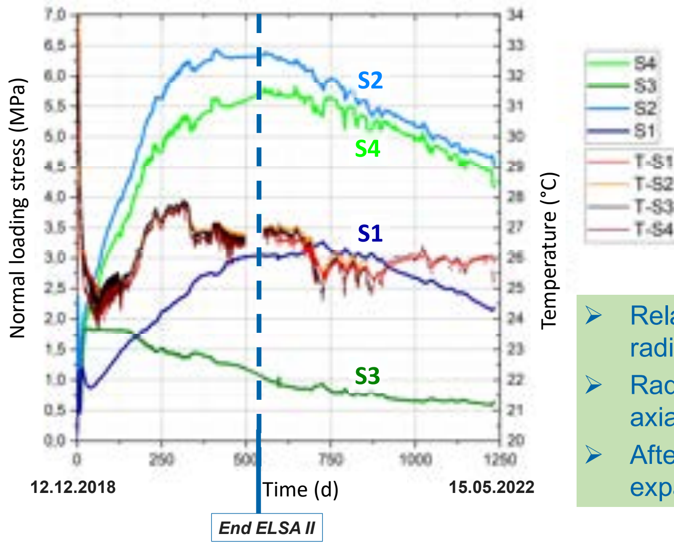
**Large bore hole test 2** (Salt mine Teutschenthal - GTS)

➢ more sensors, measurement data on heat development, radial and axial pressure development in connection with the two-phase long-term setting process (3-1-8 - MgO-type): **ca. 5 $m^3$ MgO - C3 concrete**



## Outcome of the 2n test – expansion pressure



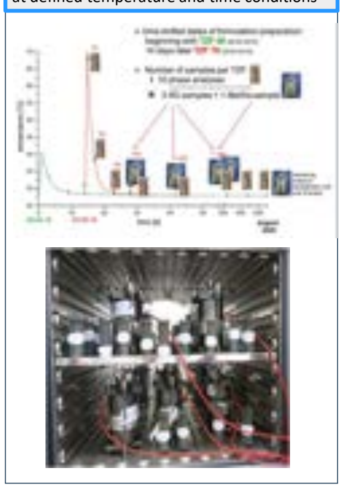



- Relatively rapidly increasing radial contact pressures
- Radial pressures are higher than axial (probably end-effects)
- After about 2 years, the expansion pressure decreases

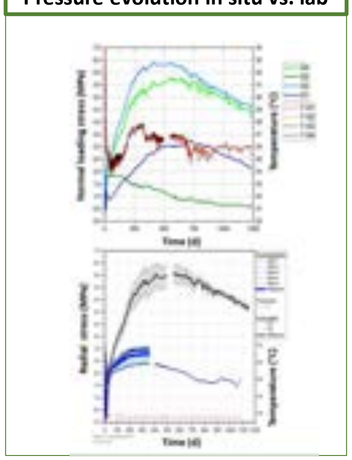


## Verification of the test results in the lab

**Investigation approach:** Investigation of the mineral phase development in pressure cells at defined temperature and time conditions

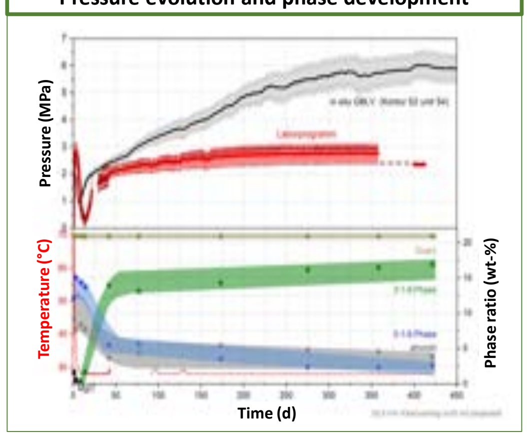


**Pressure evolution in situ vs. lab**



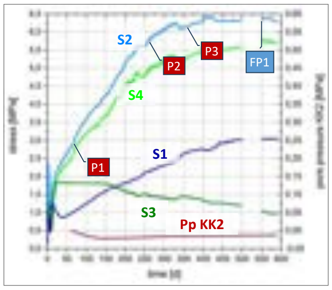
- Lab pressures are lower than in situ: Scale effect?

**Pressure evolution and phase development**




- Pressure evolution corresponds to the development of 3-1-8 phase
- Pressure decrease with time: Texture effect?

# Outcome of the 2n test – Permeability



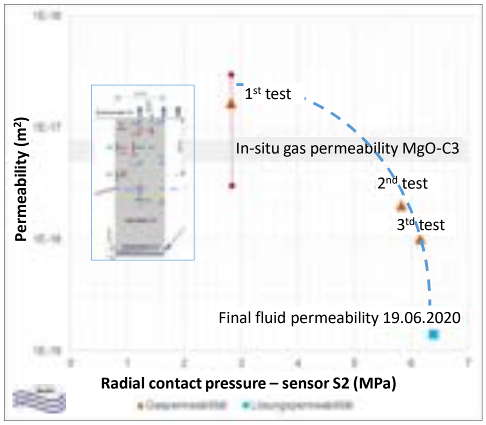

(1)Testing with gas

- P1: Day 61 (12.02.2019)
- P2: Day 264 (03.09.2019)
- P3: Day 355 (03.12.2019)

(2) Flooding with brine (03.2.2020)

(3) Contiously pressurisation with brine

- FP1: Fluid perm. day 539 (03.06.2020)




- ➢ With increasing radial stress the permeability of the plug decreases

- Establishment of fast working sealing element
- If the pressure is decreasing the convergence of the salt will overtake (➔ long-acting seal)

- ➢ The evolution of the permeability and pressure state in the MgO-C3-plug has to be monitored further
- ➢ The physical-chemical and microstructural understanding of the underlying mechanisms has to be improved

**New – research project**

12/2022 – 11/2025
**MgO-C3**
BMUV funding code 02E12072A/B



12/2022 – 11/2025
**MgO-C3**
BMUV funding code 02E12072A/B

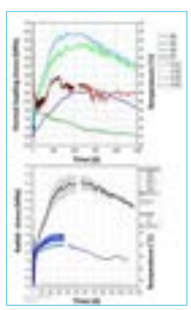
# Joint Project – Partners / WP

**TU Bergakademie Freiberg**,
Departement of Inorganic Chemistry,
Salt and Mineral Chemistry
Daniela Freyer, Iris Paschke, Matthias Gruner

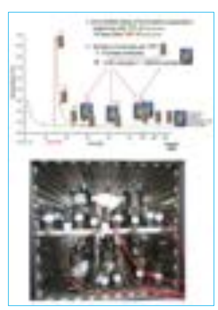
In Subcontract **IfG Leipzig**
Institut für Gebirgsmechanik GmbH
Untersuchung Prüfung Beratung Begutachtung
Dirk Naumann, Till Popp

and
**Departement Reactive Transport**
in Leipzig
Johannes Kulenkampf

In situ



Lab



Microstructure

12/2022 – 11/2025
MgO-C3
BMUV funding code 02E12072A/B

# WP1 Investigation of the contact pressure

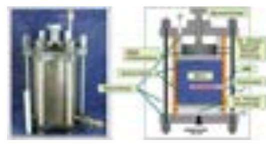
WP 1.1 Continuation of the monitoring of the large borehole test (i.e. stresses, temperatures, humidity)

AP 1.2 Investigation of the expansion pressure and phase composition in pressure cells along the temperature path

AP 1.3 Measurement of the fluid permeability as a function of the radial contact pressure (stationary measurement)

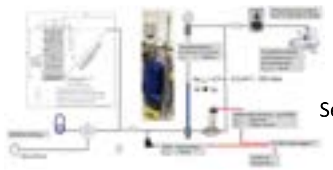
Test site Teutschenthal mine 07/2019

Drying oven



Sample size:
100mm Height,
100 mm Diameter

- Test program with 24 big test cells (for the pressure monitoring)
- smaller cells for phase investigations



Set up for the permeability measurements



12/2022 – 11/2025
MgO-C3
BMUV funding code 02E12072A/B

# WP2 Investigation of fluctuations of the C3 formulation

**Influence of the aggregate proportion on the development of contact pressure (variations of the sand/gravel proportions)**

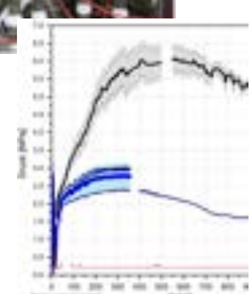
WP 2.1 Investigation of the delivered MgO

WP 2.2 Aggregate components (proportion, particle size distribution, particle shape)

WP 2.3 Laboratory program with IfG-sample cells (pressure development) and IfAC-sample cells for phase analysis

WP 2.4 Determination of geomechanical parameters (strength, relaxation, gas permeability)

WP2.5 Investigation of structural changes / differences of the C3 variations: CT-Measurements (HZDR)



12/2022 – 11/2025
MgO-C3
BMUV funding code 02E12072A/B

# WP3 Optimisation of the C3 formulation

- WP 3.1 Possible substitution of quartz powder M300 with another inert powder component
- WP3.2 Checking the preservation of the long-term contact pressure
- WP 3.3 Determination of mechanical parameters
- WP3.4 Assessment of the fluctuation effects and the quality of the improved C3 formulation for the mgO-C3 building-material, acting as fast seal

**WP 4 Reporting**

| *Components* | *Amount* |
|---|---|
| MgO | 7 % |
| Quartz powder M300 | 21 % |
| Silikate aggregates 0-8 mm | 56 % |
| $MgCl_2$-Solution (5 molal) | 16 % |



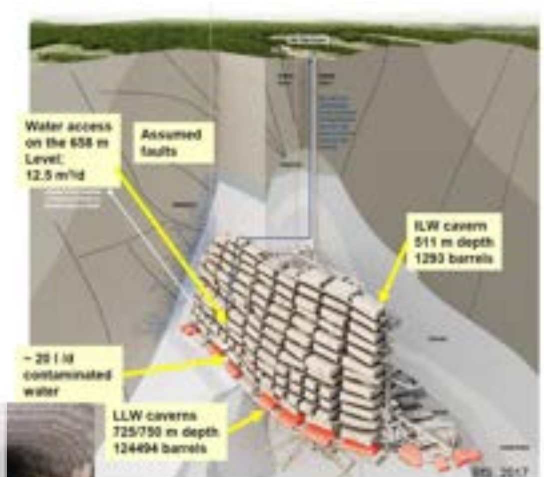
# Application II: Asse salt mine – part of emergency measures

- At least since 1988 inflow of salt solutions into the Asse II mine.
- Salt rock and overburden continue to deform. Thus, it cannot be ruled out that the inflowing brine volumes increase to the extent where this can no longer be controlled.

As part of the emergency measures in order to minimize the risks resulting from a design-exceeding inflow of saliferous solutions,

**fast acting shaft seals are required, to avoid**

- an uncontrollable inflow of water into the repository
- to reduce the consequences of the event, i.e. impeding the outsqueeze of contaminated fluids from the Asse mine.




**The MgO-C3 - concrete can act as an emergency seal!**

## Summary

12/2022 – 11/2025
MgO-C3
BMUV funding code 02E12072A/B

**MgO-C3 is a promising new building material for shaft seals**

- Construction of fast acting seal elements with development of contact pressures in the order of several MPa = active closure of the EDZ
- The material corresponds to the long-term stable 3-1-8 formulation
- The capability of properties (e.g. development of contact pressures) was demonstrated with the Teutschenthal test, **but**

☹ **the contact pressures decreases with time … ,**

☺ **however, with time the radial pressure effect will be replaced by the effect of convergence of the surrounding salt.**

➢ **Open questions will be investigated in the joint project MgO-C3.**

➢ **One topic is optimization of the building material properties.**

# Session 6 Breakout EBS

## An Impulse to start discussion

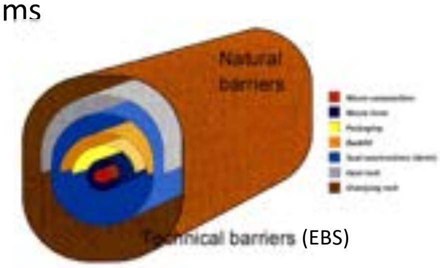
Till Popp, IfG
Philipp Herold, BGE TEC
Jörg Melzer, KIT



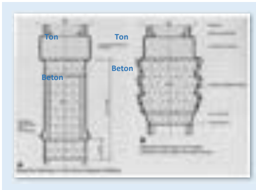

Development of a guide for the interpretation, review and further development of

## Summary Session 5

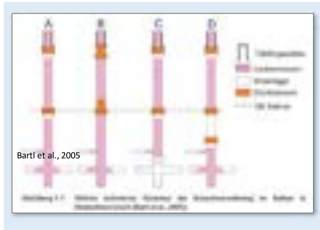
- Impact of T-H-M-C processes on the integrity of sealing elements
- Cement Seals in Salt
- MgO concrete types and MgO concrete reception C3
- Investigation of crushed salt behavior also in large scale In-Situ Application
- Development of a guide for the interpretation, review and further development of Engineered Barrier Systems



# Learning from past salt mining practice ?

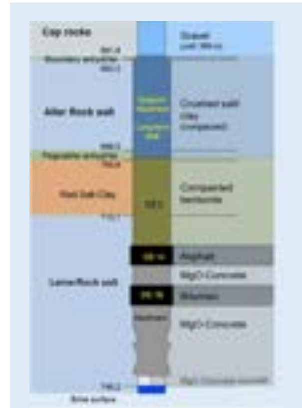


Clay-/Concrete plugs after Bodenstein et al., 2002



Bartl et al., 2005

Rumphorst, 2012



Prototype shaft seal concept „Shaft Saale“

| | |
|---|---|
| **before 1990** | Save keeping of salt mining shafts in the GDR |
| **Status in the nineties** | Shaft sealing in the south harz potash region |
| **State of the art 2012** | Shaft seals for conventional salt mines |

More than 20 shaft seals were realized in the German South Harz potash mining region between 1990 and 2005

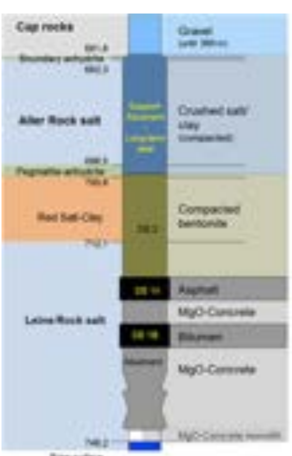
Some of them, which were dedicated to be long-term safe, failed (shafts GEBRA and LOHRA) - **Errors in technical execution and quality management**

The shaft Saale closure concept is dedicated to be the „prototype“ concept, for repositories for hazardeous waste.



# Design of „improved“ shaft sealing systems

**Sealing concept shaft Saale**
(developed in 2008 /under realisation)



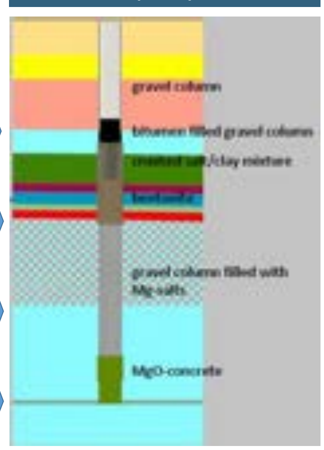
Crushed salt / clay mixture = Long term sealing element

Bentonite = sealing element

Asphalt / Bitumen = sealing elements

MgO-abutment / Long tem-stable seal

**Sealing concept RANGERS (2022)**



## Many elements with the same function …. Why?

**.. Belt and braces means more safety?**

- Are the function of each engineered component (e.g. position, thickness, materials … ) and the reasons, why it was selected, clear ?
- Is the decision process about the different design aspects documented ?
- How is the function demonstrated ? Generally, the feasibility and properties of EBS has to be demonstrated in large-scale (1 : 1) tests ….
- Does it mean, that a complete shaft (or only elements) has to be tested and which testing time is required ?

# Tool box of building materials

**Bulk building materials:** Depending on the application, abutment / sealing element

| | **Cement-based** (hydraulic binder) | | **MgO-based** (Sorel-Binder) | |
|---|---|---|---|---|
| | **Salt concrete**<br>• Crushed rocksalt<br>• Water/ -NaClmixing liquid<br>• Cement binder | **Brine concrete**<br>• **standard silicate additives**<br>• Water / -NaCl mixing liquid<br>• Cement binder | **3-1-8 formulations**<br>**Examples:** A1 (Asse), C3 (TU-BAF), DBM2 (K-UTEC)<br>• Aggregates: sand / salt<br>• MgO-Binder<br>• $MgCl_2$-mixing liquid | **5-1-8 formulations**<br>**Examples:** MB10 (CARLA)<br>• Aggregates: sand / salt<br>• MgO-Binder<br>• $MgCl_2$-mixing liquid |
| Placing | In-situ concrete | In-situ concrete | In-situ concrete | In-situ concrete / shotcrete |
| Chemical resistance | In the NaCl environment - stable<br>With $MgCl_2$ – solut.: not stable (corrosion) | | Long-term chemical stability in contact with $MgCl_2$ solution | In contact with $MgCl_2$ change in the 3-1-8 phase (indirect stable) |
| Tightness | - depending on the building material recipe and the technology used | | | Self-sealing |
| Strength | - depending on the building material recipe and the technology used | | | Extremely high |
| Dis-advantages | • Shrinkage / no chemical Long-term stability | | • Soluble with water / low solubility against NaCl-solutions | |
| Advantages | ➢ many mining experiences for shafts<br>➢ Brine concrete – standard aggregates<br>➢ Classified crushed salt easily available | | ➢ At least volume-constant<br>➢ Properties adjustable via formulation / e.g. for 3-1-8 formulation (MgO-C3) temporary expansion pressure | |

**Sealing materials**

**Bentonite**
- Granules
- Molded bricks
- Binary mixture

➢ Abutment required
➢ Stable in salt formations (salz clays)

**Asphalt ($\rho_A > \rho_{fl}$)**
- Asphalt-mastic
- Feather-asphalt
- Asphalt-mats

➢ Abutment required
➢ Inert in salt formations

**Bitumen ($\rho_B < \rho_{fl}$)**
- Hot bitumen
- Injektion bitumen
- Injection Bit.-emulsion

➢ Inert in salt formations
➢ Abutment required
➢ Problem admission

**Backfill materials**

**Sand fractions**
➢ Pure filling column
➢ Possibly not stable to settlement / refilling
➢ Graded grain fraction according to groundwater horizons

**Crushed salt/GESAV**
- Dry or wetted

➢ Abutment required
➢ Acting as seal after long-lasting consolidation

**Gravel**
➢ backfill column
➢ Stable settlement
➢ load transfer (abutment)
➢ Backfilling the shaft bottom

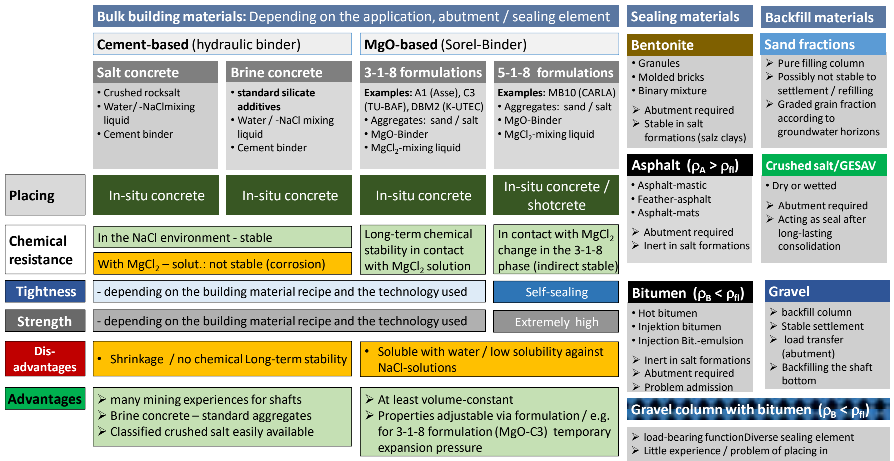
**Gravel column with bitumen ($\rho_B < \rho_{fl}$)**
➢ load-bearing functionDiverse sealing element
➢ Little experience / problem of placing in



**So everything looks nice…**


**But is this the End of the road?**

# Tool box of building materials



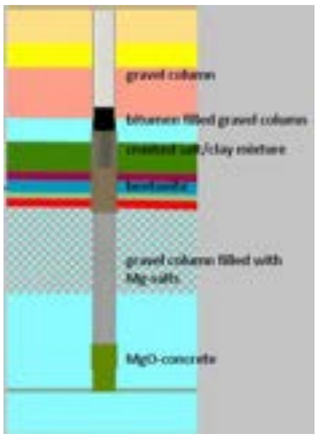

- Is enough practical experience regarding technical emplacement of the various materials available?
- Do we have functions in the EBS which are not fulfilled by the actual materials, e.g. capability of salt melts.
- Are short- and long term interactions (e.g. HM-loadings, chemical barrier degradation) sufficiently considered?



# Tool box of building materials (2.0)

# Do we finaly have a sealing concept?

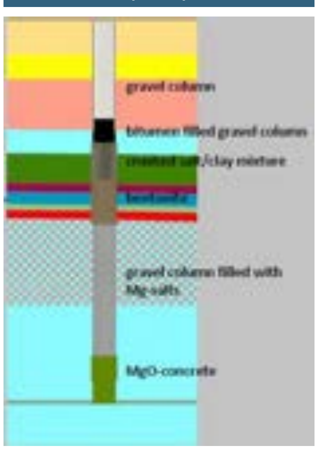
**Sealing concept RANGERS (2022)**

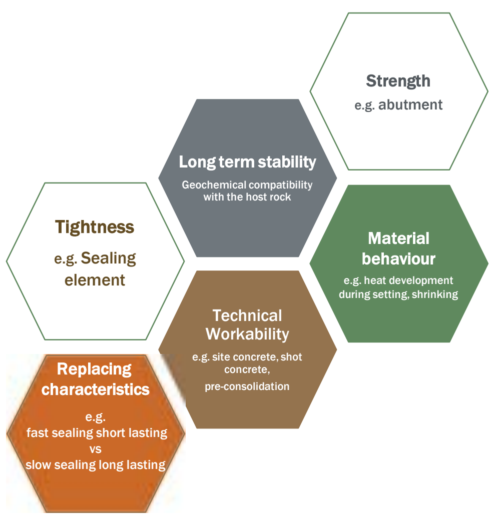





# Time-dependent functions of building materials

**Sealing concept RANGERS (2022)**




**Several building materials with different properties corresponding to different functions for EBS are available:**

Is the knowledge regarding the different materials sufficient

## Discussion




## What are possible next Steps

- More Research to find new / better Material for EBS to extend /complete the tollbox?
- Further development and investigation of behaviour of the known Material?
- Further investigation of time depending and replacing charachteristics of Material and EBS systems?

# SESSION 7: Insights on Operating Facilities

Chair: Melissa Mills (SNL)

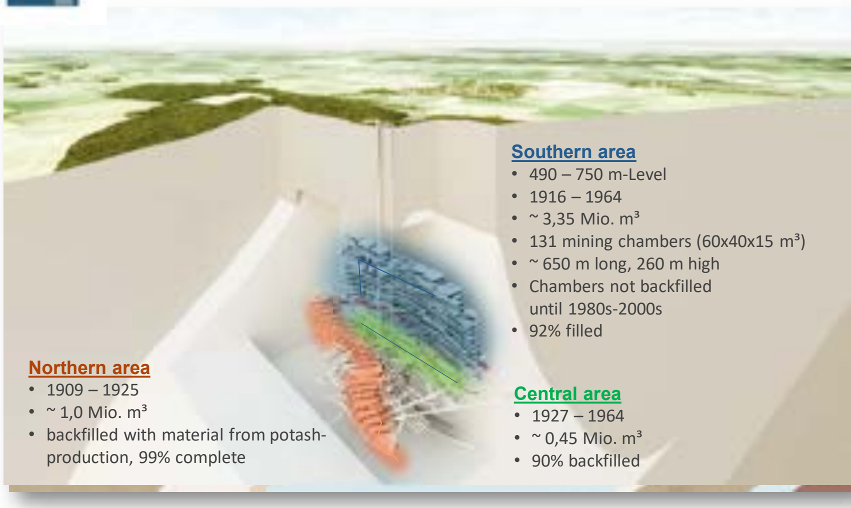
BGE TEC Sandia National Laboratories PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG


1


2

# HISTORY



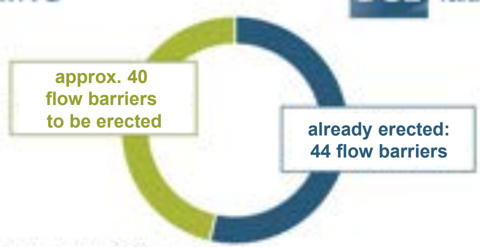




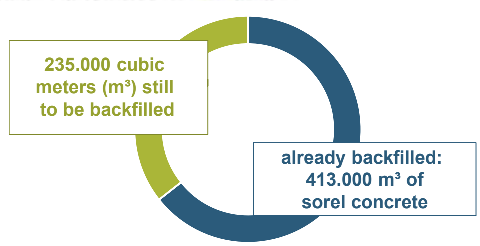
# STATUS – EMERGENCY PLANNING

achieved project goals (excerpt)

- *erected:* more than 1/2 of flow barriers
- *stabilized:* approx. 2/3 of remaining caverns
- *completed:* 4 cavern sections for intermediate storage of brine
- *ready for operation:* collection point for brine




Erection of flow barriers




Backfilling of residual cavities

## STATUS – RETRIEVAL

achieved project goals (excerpt)

- *explored:* salt structure in the east of the existing mine
- *signed:* contracts for approval planning of retrieval shaft, surface facilities, waste treatment plant/interim storage, retrieval procedures and retrieval technology
- *acquired:* operational areas for retrieval shaft and waste treatment plant/interim storage
- *started:* regional planning procedure and nuclear licensing procedure
- *under construction:* drilling site for last exploratory drilling to confirm location of retrieval shaft



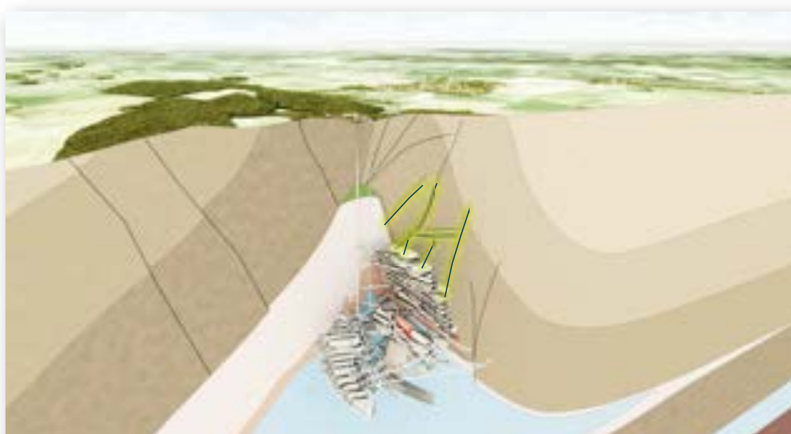
## BRINE INFLUX FROM SOUTHERN FLANK

- extraction ratio > 60%
- broken overburden rock
  → halo-kinetic processes
  → geolocical faults
- long periods of open mining chambers (75 years)
- short distances to overburden rock (< 10 m)

→ instability of the geomechanical system

→ subsidence of up to 7 m

→ brine influx in southern district since 1980s: 12 m³/day



## Retrieval

- Process of waste retrieval
- Surface infrastructure
- 3D view
- Timeline and costs

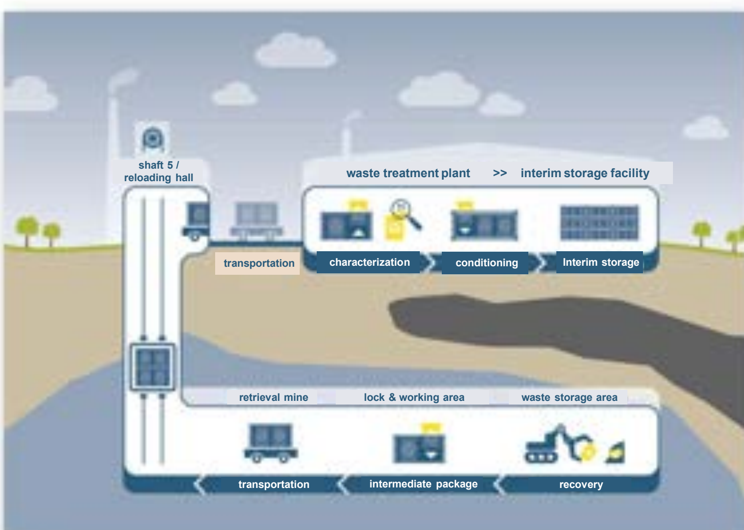
# 02



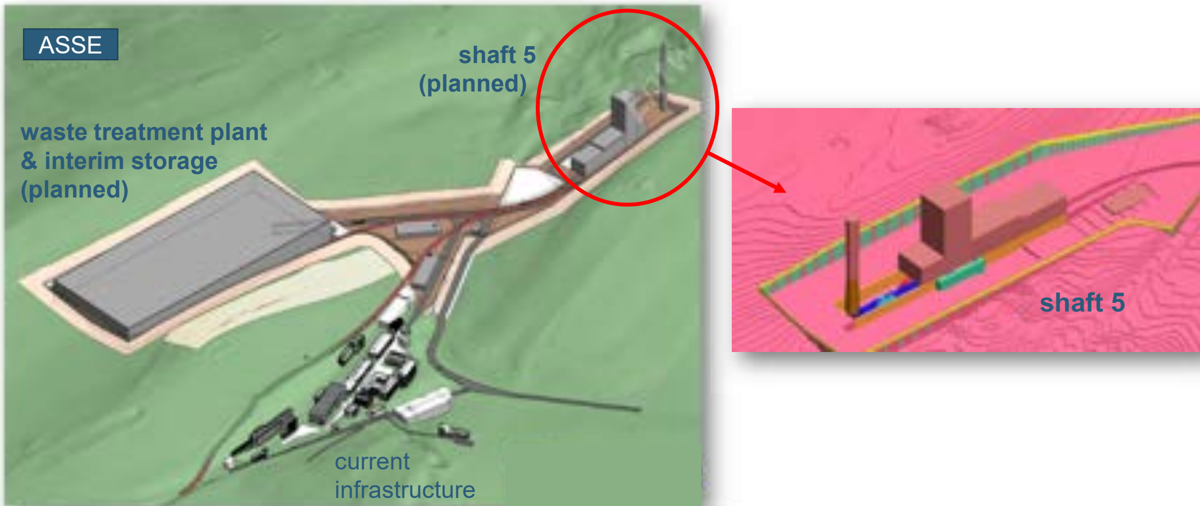


BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

# PROCESS OF WASTE RETRIEVAL



## SURFACE INFRASTRUCTURE






9

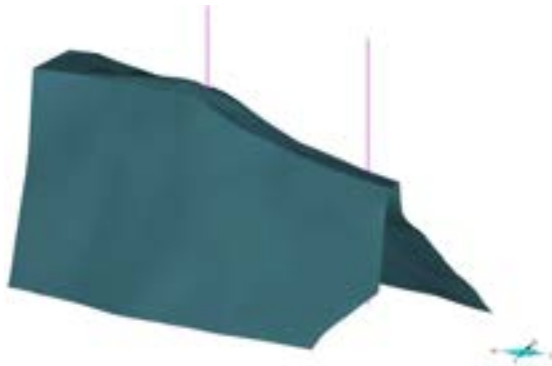
## 3D-VIEW



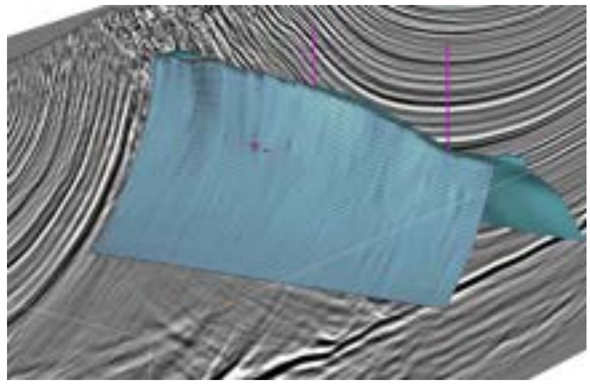
10

# SEISMIC-BASED STRUCTURAL MODEL
## SALT CONTOUR

Former, schematic salt contour



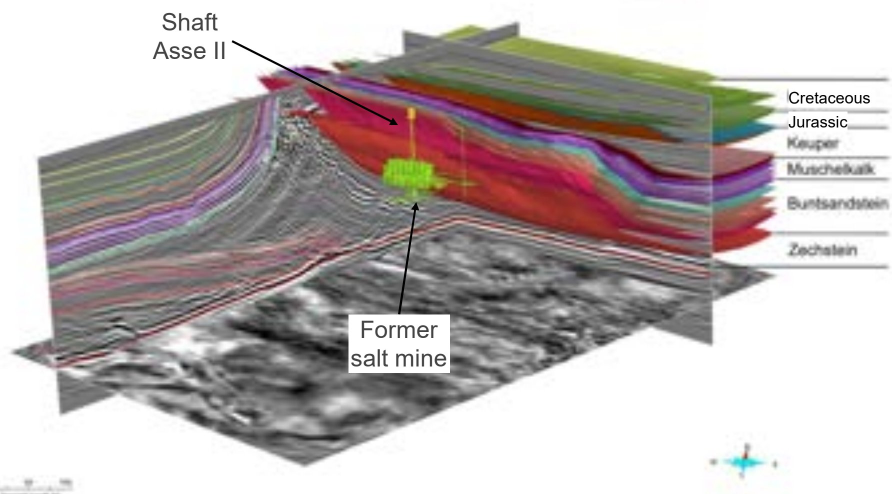
New, seismic-based salt contour





# SEISMIC-BASED STRUCTURAL MODEL
## MAIN RESULTS

- Full 3D subsurface image
- Better understanding of overburden structures
- High-resolution shape of the salt contours for better risk assessment
- Detailed structural analysis for location of retrieval shaft



# ASSE
# TIMELINE AND COSTS

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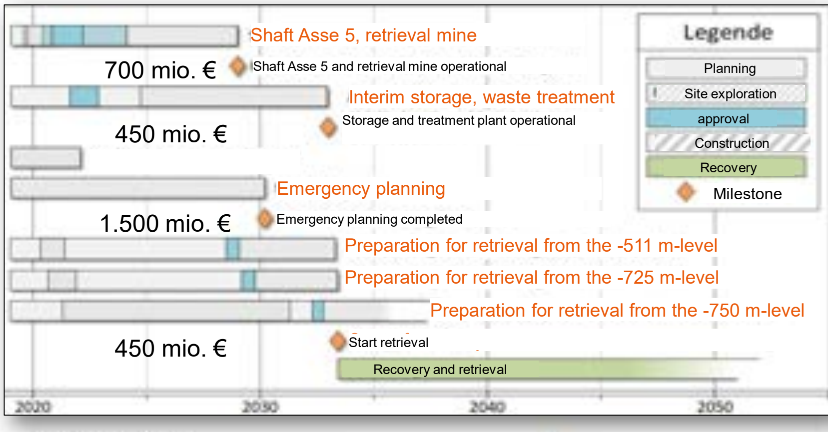



+ 250 million €
infrastructure + properties → ∑ 3,35 billion € + 400 million € administration



## INTENDED OPERATION AND INCIDENTS

- Additional radioactive discharges during opening of the chambers
- Incidents in the emplacement chamber during recovery due to uncontrolled movement of the rock (collapse of the chamber) and/or of the casks (cask stack slides)
- Incidents during handling of open radioactivity in the airlock between the chamber and the mine, as well as in the waste treatment facility



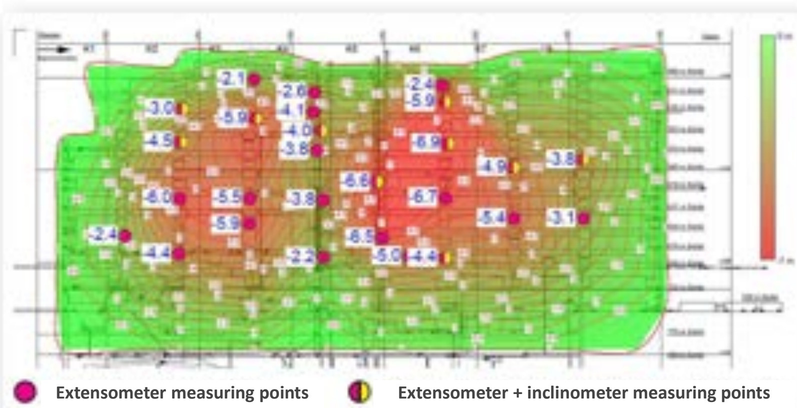
## BRINE INFLUX COULD BECOME UNCONTROLLABLE

### Probability of occurence

- We bring movement into a highly stressed and sensitive system.
- We create new cavities.
- We give the southern flank at least another 30 years of movement.

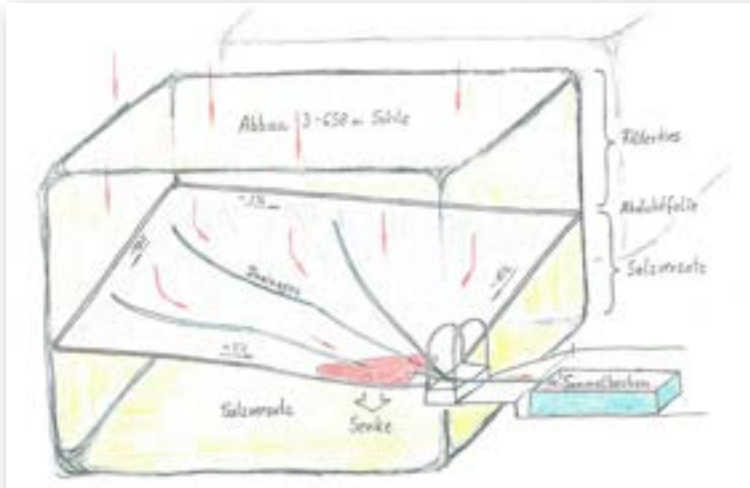
### Extent of damage

- We are expanding the handling with open radioactive substances.
- Possibility of faster release of radionuclides into the biosphere.



## MAIN COLLECTION POINT 3/658 – DYSFUNCTIONAL

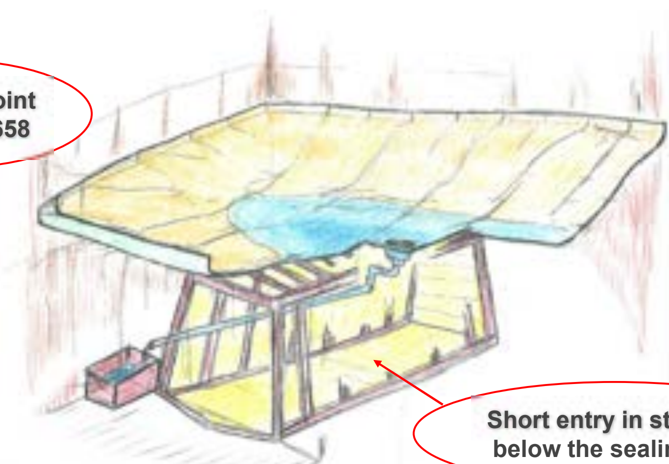
- Deformation of sealing foil due to rock movements
- Formation of sinkholes, leading to accumulation of brine
- Pumping required
- Only 1 of 3 drainage pipes still available
- Expert group set up to develop measures



schematic drawing



## MAIN COLLECTION POINT 3/658 – PREFERRED OPTION



## CONCLUSION

- THE ASSE RETRIEVAL PROJECT IS EXTREMELY COMPLEX, LENGTHY AND TECHNICALLY DEMANDING.
- IN SOME CASES, WE HAVE TO DEVELOP COMPLETELY NEW PROCESSES, FACILITIES AND MACHINES IN ORDER TO BE ABLE TO CARRY OUT THE RETRIEVAL SUCCESSFULLY.
- WE HAVE TO DEAL WITH SIGNIFICANT RISKS.
- WE HAVE TO PREPARE AS QUICKLY AS POSSIBLE FOR THE EMERGENCY OF UNCONTROLLED WATER INFLOW.
- WE HAVE TO DEAL WITH UNEXPECTED PROBLEMS AGAIN AND AGAIN AND FIND CREATIVE SOLUTIONS.
- **THE ASSE PROJECT IS THEREFORE A PARADISE FOR ENGINEERS AND SCIENTISTS.**





BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

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# Human Intrusion Scenarios

## for deep geological repositories in salt rock

Jens Wolf
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH


1

# Agenda



2

## Definitions: FHA and IHI

- Future human actions (FHA)
  - cannot be predicted over long time frames
  - have the potential to disturb the disposal system

*Future human actions of concern are those occurring after repository closure that have the potential to disrupt or impair significantly the ability of the natural or engineered barriers to contain the radioactive wastes.*

NEA 1995: Future Human Actions at Disposal Sites

- **Human Intrusion (HI)**: FHA affecting the integrity of a disposal facility and potentially giving rise to radiological consequences (IAEA SSG-23)
  - FHA resulting in the disturbance of the host environment beyond the disposal facility and its immediate proximity are not categorized as HI
  - while it is widely accepted that a society that generates radioactive waste bears the responsibility for developing a safe disposal system (…), the present society still cannot protect future societies from their own actions
    → **inadvertent** (unintentional) **HI (IHI)** is considered in the safety case
    - No knowledge at all
    - No knowledge about the health risk

*Those in which either the repository or its barrier system are accidently penetrated or their performance impaired, because the repository location is unknown, its purpose is forgotten, or the consequences of the actions are unknown.*

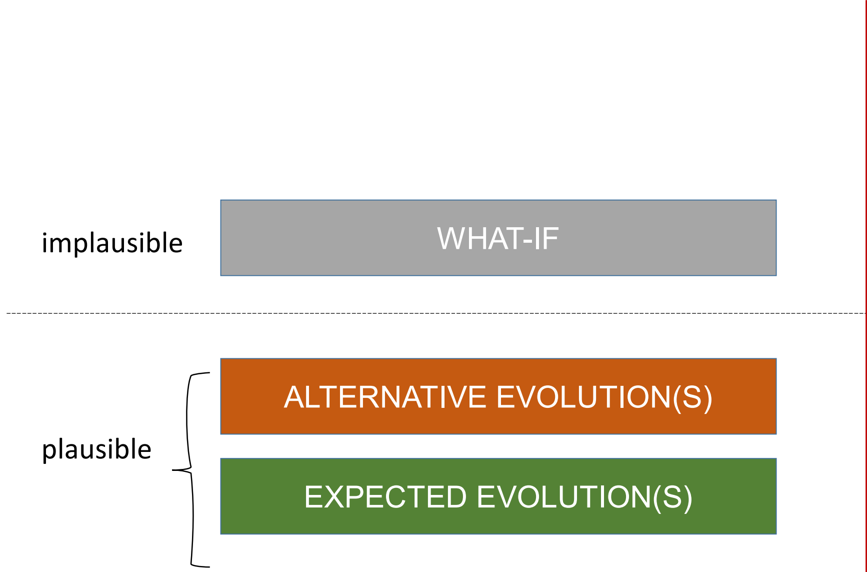
NEA 1995: Future Human Actions at Disposal Sites



## Unpredictability of IHI

- Uncertainties
  - Development of EBS and geological barrier → plausible scenarios vs. implausible what-if
  - When will the knowledge about the DGR be lost?
  - When will HI occur?
  - What technology will be used?
  - What are the future habits acting people?
- → HI scenario cannot be predicted
- → **stylized scenarios**:
  based on the premise that the practice of future societies correspond to current practices

## Scenario uncertainties and IHI




IHI

unpredictable (FHA)
plausible (existing action)
[reduced probability (depth)]

**stylized scenarios**

**→ regulation!**

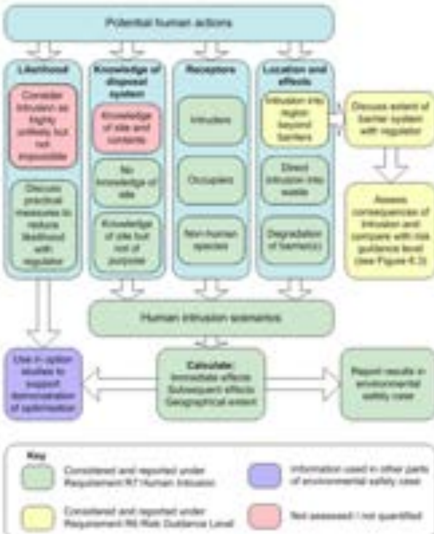


## Importance of regulation for HI

- FHA have the potential to significantly impair the performance of a disposal system and can be envisaged as **particular types of plausible scenarios**
- FHA are **unpredictable** and scenarios that involve them need to make stylised assumptions → considered as a specific scenario category
- Treatment of uncertainties which cannot be quantified, like those associated to human intrusion is a useful area for the regulatory guidance
- IHI that directly damage the isolation/confinement performance are often systematically treated in regulations
- Several regulations require considering the radiological impact on the intruder
- The absence of regulatory limits for that particular situation is somehow compensated by the necessity to minimise the likelihood of intrusion through deep disposal, site selection or by means of markers (optimization)
- In addition some regulators may accept the possibility of human intrusion and its potential consequences on the condition that it is demonstrated that the repository has been placed at a sufficiently **great depth** and **away from natural resources**, the two main counter measures against human intrusion. Also, the repository may be designed to reduce the likelihood of human intrusion or the possible consequences.

NEA 2012: MeSA, IAEA 2017: HIDRA

# Regulation [GRA, 2009, UK]




GRA 2009: Geological Disposal Facilities on Land for Solid Radioactive Waste

- Requirement R7: **Human intrusion after the period of authorisation**
- 6.3.35 The developer/operator of a geological disposal facility should assume that human intrusion after the period of authorisation is highly unlikely to occur. The developer/operator should consider and implement any practical measures that might reduce this likelihood still further. The developer/operator should also assess the potential consequences of human intrusion after the period of authorisation.
- (…)
- 6.3.44 Human intrusion scenarios should be based on human actions that use technology and practices similar to those that currently take place, or that have historically taken place, in similar geological and geographical settings anywhere in the world. (…)



# Regulation [EndlSiAnfV, GER]

- In total four classes of scenarios defined (called evolutions in German regulations). Plausible scenarios are
  - Expected evolutions or
  - Deviating (alternative) evolutions
- In addition to the expected and deviating evolutions, hypothetical evolutions and evolutions based on future human activities shall be described, provided that their consideration can serve to further optimise the disposal system or to test the robustness of the disposal system.
- Evolutions based on FHA are evolutions that can be initiated by FHA, particularly by IHI into the disposal facility, and that can be relevant for the safety of the disposal system. As reference evolutions for this serve those evolutions that can be initiated by current human activities.

## Explanatory Memorandum to the EndlSiAnfV

- Evolutions based on FHA cannot be systematically derived **due to their unpredictability**, both in terms of their specific characteristics (e.g. technologies used) and the probability of their occurrence.
- Therefore stylized scenarios should be considered, for example
  - deep drilling in ignorance of the existing repository,
  - construction of dams
- Precisely **because of the unpredictability of FHA as described above, these cannot be sensibly classified in the categories of expected/deviating developments**
- In this respect, a <u>subordinate consideration</u> of the effects of possible human activities in the course of optimizing the repository system is recommended internationally.
- Irrespective of this, however, the fundamental decision in favor of DGR of HLW (in contrast to e.g. permanent storage at or near the earth's surface) represents an effective measure to reduce the impact of FHA on the repository.
- FHA that intentionally affect the repository, in particular intentional field of view into the repository, are not to be considered. These activities are necessarily carried out with knowledge of the existing repository and therefore at least indirectly also its potential for danger. They are therefore entirely the responsibility of the future living people who plan and carry out these activities.



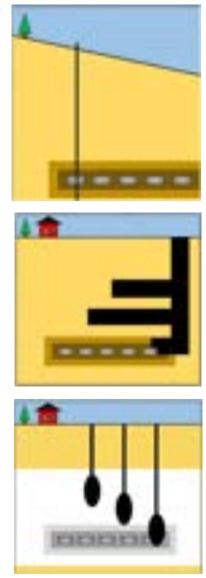
## Regulation [US]

- 40 CFR 194.32
- requires direct incorporation of HI into the WIPP compliance calculations:
  - (a) Performance assessments shall consider natural processes and events, **mining, deep drilling, and shallow drilling** that may affect the disposal system during the regulatory time frame.
  - (b) (…)
  - (c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.
  - (d) Performance assessments need not consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years.

- 10 CFR 63.322
- definition of a stylized scenarios:
  - (a) There is a single human intrusion as a result of exploratory drilling for groundwater
  - (b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository;
  - (c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for groundwater in the region surrounding Yucca Mountain;
  - (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole;
  - (e) (…)
  - (f) (…)
  - (g) No releases are included which are caused by unlikely natural processes and events.

## HI Scenarios: Hidra project [IAEA]

- **Human Intrusion in the Context of Disposal of Radioactive Waste (HIDRA)**
- Member States developed an approach for identifying HI scenarios to be assessed, and protective measures to reduce the potential for and consequences of IHI.
- The HIDRA project developed an approach that supports operating organizations, regulatory bodies and government organizations as they work uphold safety in a consistent and structured manner in line with the IAEA safety standards. The approach is flexible and enables the consideration of different disposal concepts, site conditions, regional habits, and stages of development.
- First phase: 2013-2015, focused on potential scenarios, societal factors and protective measures.
- Second phase: 2016-2018, focused on practical implementation of the HIDRA approach and documentation of country-specific examples.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M(S)
M(D)

IAEA 2017: HIDRA



## Workshop: HI in Salt Repositories

- Online Workshop
  - 01/10/23, 15:00-18:30 GMT (8:00-11:30 MST, 16:00-19:30 CET)
  - 01/11/23, 15:00-18:30 GMT (8:00-11:30 MST, 16:00-19:30 CET)
- 40 Participants from Australia, Germany, The Netherlands, Switzerland, UK, US

- Day 1:
  - HI in National Regulations
  - The IAEA project HIDRA
  - Nagra approach (Opalinus Clay)
  - Yucca Mountain

- Day 2
  - WIPP
  - Morsleben
  - Discussion

## Summary of presentations

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| HLW [GER] | EndlSIANfV (2020) | IHI | 500 to $10^6$ | yes | no | Clay, Salt, Crystalline | Drilling, Mining etc. |
| HLW [CH] | SGT (2014) | IHI | 500 to $10^6$ | yes | yes | Clay (OPA) | Drilling |
| HLW [NL] | no regulation regarding HI | | | | | | |
| HLW [UK, w/o Scotland] | GRA (2009) | IHI | | yes | no | Clay, Salt, Crystalline | |
| **TRU WIPP [US]** | **40 CFR 192.32 (1985-96)** | **IHI** | **10.000** | **no** | **yes** | **Salt (Salado)** | Drilling, Mining |
| HLW Yucca Mountain [US] | 10 CFR 63.322 (2001) | IHI | $10^6$ | yes | no | Volcanic Rock | Drilling |
| HIDRANIA [IAEA] | - | IHI | 500 to $\infty$ | yes | no | Generic | Drilling, Mining |



## Important results from the Workshop (I)

- Since Salt has been an important resource during the history of mankind, HI in salt requires special attention in comparison to other host rocks (clay, crystalline, tuff).
- To reduce the probability of HI, the depth of the repository is substantial: the deeper, the better. The footprint of the repository also plays a significant role. Both aspects are valid for repositories in salt. But in contrast to other host rocks, the value of the resource is so high, that these general strategies to reduce the probability of HI is limited. In salt, technical options, such as dissolution mining, allow the profitable exploitation even at great depth and structures with a small footprint.
- Since the regulations address HI in general (not specific for one specific host rock), the particular role of HI in salt is not addressed in national regulations. The only exception is the regulation for the WIPP (bedded salt), where HI is prominently addressed and drilling of boreholes at different times during their assessment period of 10.000 years define the main disturbed scenario.
- The FEP on future human actions listed in the IFEP of NEA are often not used as (bottom-up) basis for the consideration of HI scenarios. Except of the FEP approach of the WIPP-Site, the common (top-down) approach is to define directly stylized scenarios for HI.

## Important results from the Workshop (II)

- The stylized scenarios for HI are disruptive events. The most common stylized scenario is the drilling of a borehole into a displacement area. This scenario is seen to cover all other relevant HI scenarios.
  → international agreement on HI scenarios
- With the exception of WIPP the consequences of human intrusion are analyzed separately in stylized scenarios and the consequences of HI scenarios are excluded from comparison with safety indicators. The reason is the unpredictability of future human behaviour. The exclusion from the "classic" comparison with safety indicators does not mean that the consideration of HI is of low priority.
- On the contrary, experience in the different programmes shows , that a thorough consideration of HI plays a key role for the communication of a safety case with different stakeholders and is seen as an important element for confidence building in the safety case.
- **Knowledgement management** about disposal facilities is a key factor in assessing the role of IHI in a safety case.

- The thorough implementation of the handling of HI scenarios is of high importance for the Safety Case for DGR in Salt

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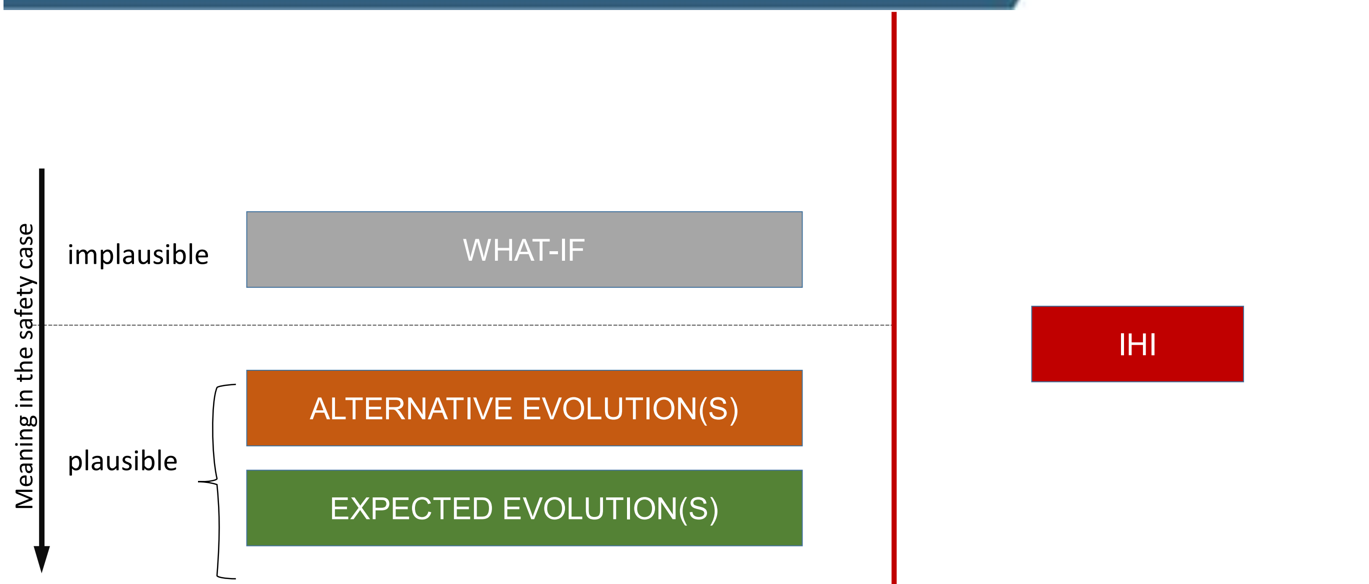
## Results and Recommendations

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- NEA 1995: Future Human Actions at Disposal Sites, Nuclear Energy Agency, NEA-No. 6431, OECD/NEA, Paris, France
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- U.S. Environmental Protection Agency (EPA). 1996. 40 CFR Part 194.32: Scope of performance assessments
- U.S. Nuclear Regulatory Commission (NRC). 2016. 10 CFR Part 63.322: Human Intrusion Scenario




## Acknowledgements


PTKA Projektträger Karlsruhe, Karlsruher Institut für Technologie

Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection

Sandia National Laboratories

COVRA

CSIRO

nagra

Nuclear Waste Services

Niemeyer Umwelt

BGE TEC, BGE Technology GmbH

# WIPP Lessons Learned

## Compliance (Re)Certification Applications

Andy Ward
U.S. Department of Energy, Carlsbad Field Office


1

## What is WIPP?

- Repository in salt
  - Defense waste : Transuranic (TRU) & TRU Mixed
  - 650 m below ground level
  - Mined in Permian Salado Formation (bedded)

- Major Milestones
  - 1975 – selected current location
  - 1984 – waste shaft completed
  - 1999 – accepted first waste
  - 2022 – mining Shaft #5
    - – new filter building
  - 2023 – Emplacing in new Panel 8
    - – Mining west drifts to replacement panels


2

## Lessons Learned

- A lot can be learned about improvements to future waste management and disposal efforts

- ChatGPT summarized these as:
  - Operational Safety
  - Regulatory Compliance
  - Community Engagement
  - Monitoring and Long-Term Performance
  - International Collaboration

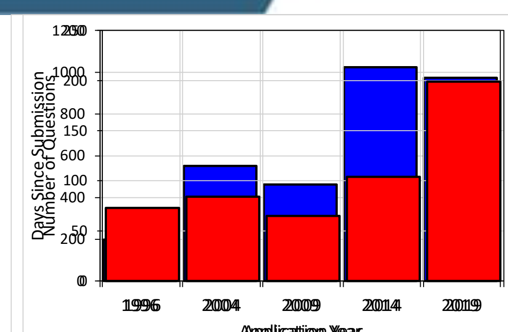
- Regulatory Compliance
  - *Discuss collaboration between the DOE and the EPA to ensure compliance with regulations*
  - *Highlight the need for clear communication and coordination between different stakeholders to meet regulatory requirements*




## Compliance Recertification Applications

- CRA-2019 Decision, May 3, 2022
  - Completeness determination ~974 days (2.7 yr)
  - ~100% increase in number of questions (~200)
  - Geochemistry + Actinide Chemistry ~40%

- The EPA identified 57 issues to be addressed "*before the next PA*"
  - Dissolved Actinides ~33%
  - Chemical Conditions ~25%
  - Colloids ~ 14%
  - Gas Generation ~11%

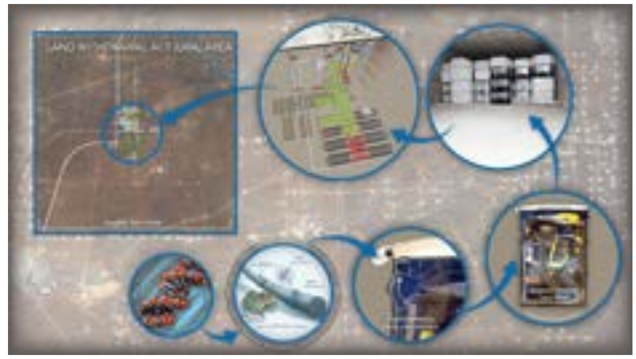



| SECTION | CCA | 2004 | 2009 | 2014 | 2019 | Total |
|---|---|---|---|---|---|---|
| Appendix MON | | | | | 20 | 20 |
| Appendix SCR | | 1 | | | 16 | 17 |
| Appendix SOTERM | | 1 | 12 | 6 | 16 | 35 |
| Geochemistry | | 3 | 21 | 17 | 57 | 98 |
| Consideration of Drilling | 2 | 2 | 10 | 1 | 16 | 31 |
| Models & Computer Codes | 30 | 36 | 10 | 24 | 13 | 113 |
| Scope of PA | 7 | 2 | 1 | 34 | | 44 |
| Results of PA | 2 | | | | 31 | 33 |
| **Grand Total** | **73** | **84** | **65** | **104** | **199** | **525** |

## Radiolysis

- Radiolysis is known to:
  - occur at very small temporal and spatial scales
  - involve complex radiation chemical system
  - show strong dependence on secondary reactions
  - result in nonhomogeneous chemistry
  - occur in SNF exposed to H2O(g), (aq)

- The NAS in 1996 opined:
  - "auto-oxidation" by alpha bombardment is possible
  - WIPP pH and $E_h$ controlled by geology and waste constituents (Fe, organics)
  - a slight change caused by alpha bombardment *is expected to be negligible*
  - oxidative corrosion in SNF by alpha radiolysis is minor, ***therefore***
  - alpha-radiolysis *is expected to be an even more minor concern* at WIPP





## Chemical Conditions Conceptual Model

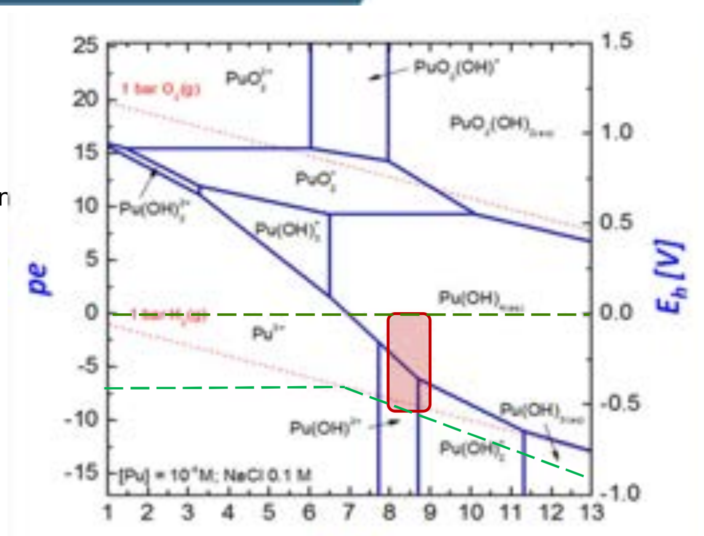
- Thermodynamic but not $E_h$ equilibrium

- Range of $E_h$ known
  - system reducing so upper $E_h \leq 0$
  - lower $E_h$ dominated by [Fe(0), Fe(II)]
  - radiolysis oxidants react rapidly with Fe corrosion products without affecting upper $E_h$

- Corrosion of cannisters starts immediately
  - system is assumed to be well mixed

- $\alpha$-radiolysis implemented as a source of $H_2$ per the EPA

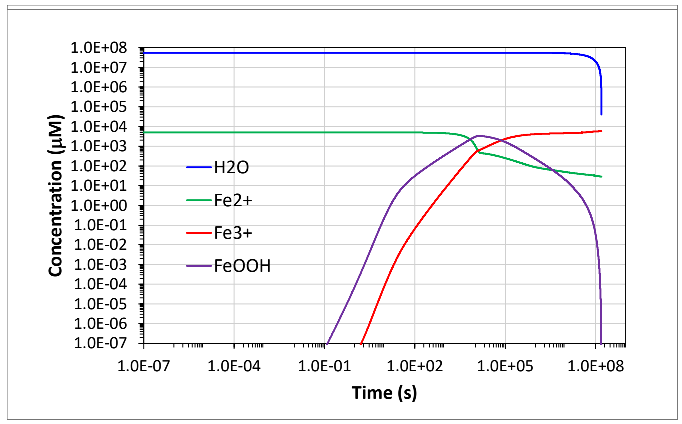
- Predictions of An oxidation state and solubility could be based on an incomplete description of chemical conditions




Altmaier et al., 2017

# Effects of α-radiolysis

- Implemented as a source of $H_2$ generation at request of the EPA
- Concomitant production of oxidizing species with $H_2$, including $H_2O_2$ initially at similar concentrations
- Radiolysis products don't show steady state
- Products of anoxic corrosion of Fe(0) unknown, but
  - decrease in [$Fe^{2+}$] due to reaction with $H_2O_2$ (Fenton reaction)
  - oxidation to $Fe^{3+}$
  - An(III) could be oxidized
  - formation of $FeOH_2^+$ and FeOOH, which could react with An
- Evidence of $H_2O$ depletion ≥ ~30yr
- Radiolysis products could affect An oxidation state and solubility






# DOE Order 435.1, Radioactive Waste Management

**OBJECTIVE:**
- To ensure that all Department of Energy (DOE) radioactive waste is managed in a manner that is protective of worker and public health and safety, and the environment

**APPLICABILITY:**
- Requirements in this Order *that duplicate or conflict with the WIPP Land Withdrawal Act* of 1992, including the U.S. EPA's Certification of the WIPP, *do not apply* to the operation of WIPP or the disposal of waste therein.

**REQUIREMENTS:**
- DOE radioactive waste management activities shall be systematically planned, documented, executed, and evaluated.


DOE M 435.1-1

RADIOACTIVE WASTE MANAGEMENT MANUAL

U.S. DEPARTMENT OF ENERGY

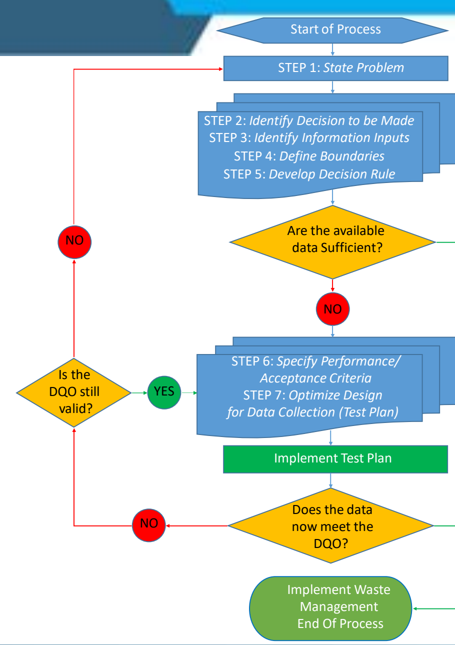
# Performance Assessment Maintenance

- The performance assessment *shall be maintained* to evaluate changes that could affect the performance, design, and operating bases for the facility…
- Maintenance *shall include* the *conduct of research*, field studies, and monitoring needed *to address uncertainties or gaps in existing data:*
  - …*shall be reviewed and revised when changes* in waste forms or containers, *radionuclide inventories*, *facility design* and operations, closure concepts, or *the improved understanding of the performance of the waste disposal facility* … or may alter the conclusions or the conceptual model(s) of the existing performance assessment
  - …*shall be made on an annual basis, and shall consider the results of data collection and analysis from research, field studies, and monitoring*
  - *Annual summaries* of waste disposal operations shall be prepared with respect to the conclusions and recommendations of the performance assessment and a *determination of the need to revise the performance assessment*



# Data Quality Objective (DQO) Process

- A systematic planning process for generating data *that will be sufficient for their intended use*
  - basis for balancing decision uncertainty with available resources
  - define *appropriate* types of data to collect and quality requirements to support decisions
- Required for ***all significant*** data-collection projects within DOE, per a September 7, 1994 memo from Thomas P. Grumbly, Assistant Secretary for Environmental Management: "*Institutionalizing the Data Quality Objectives Process for EM's Environmental Data Collection Activities*"
- *The DQO process is required by CBFO Quality Assurance Program Document (DOE/CBFO-94-101)*
  - *"By using the DQO process, DOE will assure that the type, quantity, and quality of data used in decision making will be appropriate for the intended application*
  - *"DOE will guard against committing resources to data collection efforts that do not support a defensible decision"*



# Design Thinking and Better Questions

- Put serious effort into improving the quality and sharpness of the question being asked
  - “*If I were given an hour in which to do a problem upon which my life depended, I would spend 40 minutes studying it, 15 minutes reviewing it, and 5 minutes solving i*t”, Albert Einstein.
  - "*Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise“,* Tukey J.W (1962). The Future of Data Analysis, Ann. Math. Statist. 33(1): 1-67.
- Project goal is to move to the right hand side
  - look at existing data (***no need to reinvent the wheel***)
  - consider context, resources, SMEs
  - Include different approaches (not all are ideal)
  - two-way communicate




# Low-quality Questions?

- *“… report does not provide sufficient detail for the oxidation state assessment…*
- *“ …the data themselves are incompletely described and are perhaps not internally consistent with what is said…”*
- *“Corrosion was localized therefore rates could not be calculated using mass loss…”*
- *“Data quality indicators point to underlying difficulties with data collection...”*
- *“The quality of these data are not sufficient to support any definitive conclusion…”*
- *“Despite the solver demonstrating some speedup for the flow model, no such enhancement was observed for the transport simulations…”*

## Summary

- Conceptual models are "living" constructs and must be updated
  - changes that could affect performance, design, and operating bases for the facility
  - improved understanding of the performance of the disposal facility
  - anticipated by the regulations, which describe when and how it should be done
  - for reasons unknown, contractors appear reluctant to implement

- The DQO process is a systematic planning process for generating data *that will be sufficient for their intended use*
  - must start with high quality focused questions
  - ends with the most effective investigation design that will make good use of time and money to generates information that is useful in making decisions



# Questions


1

# CONTENTS

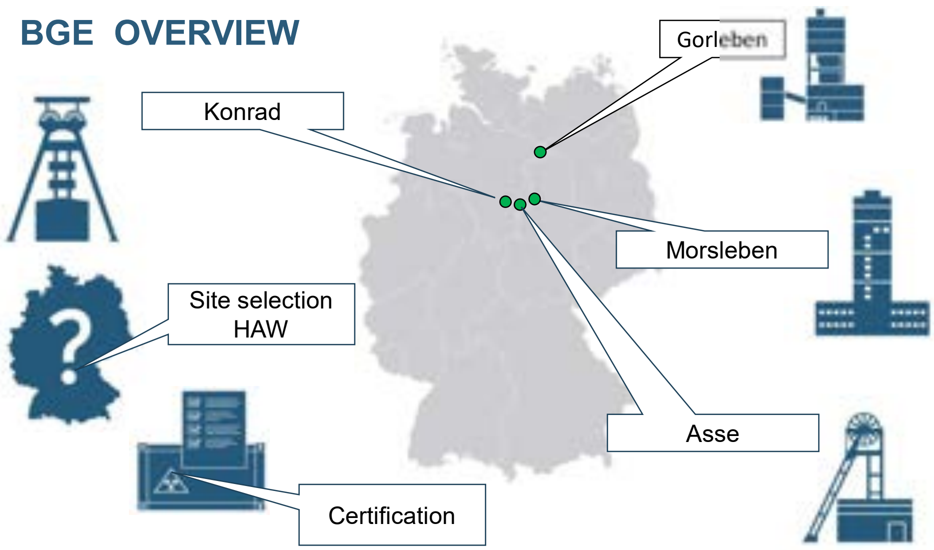
Lessons Learned





2

# BGE OVERVIEW




**BGE**

founded 2016
merger completed 2018

~ 2.200 employees
~ 540 Mio. € turnover

Management:
- Stefan Studt
- Thomas Lautsch
- N.N.

Source: BGE





# FOCUS ON

- The BGE and its predecessor organizations:
  → more than 40 years of experience in repository projects
- Many lessons learned in the **Gorleben**, **Konrad**, **Asse**, **Morsleben** and **site selection** projects
- Topics:
  - **approval procedure**
  - **planning**

## APPROVAL PROCEDURES

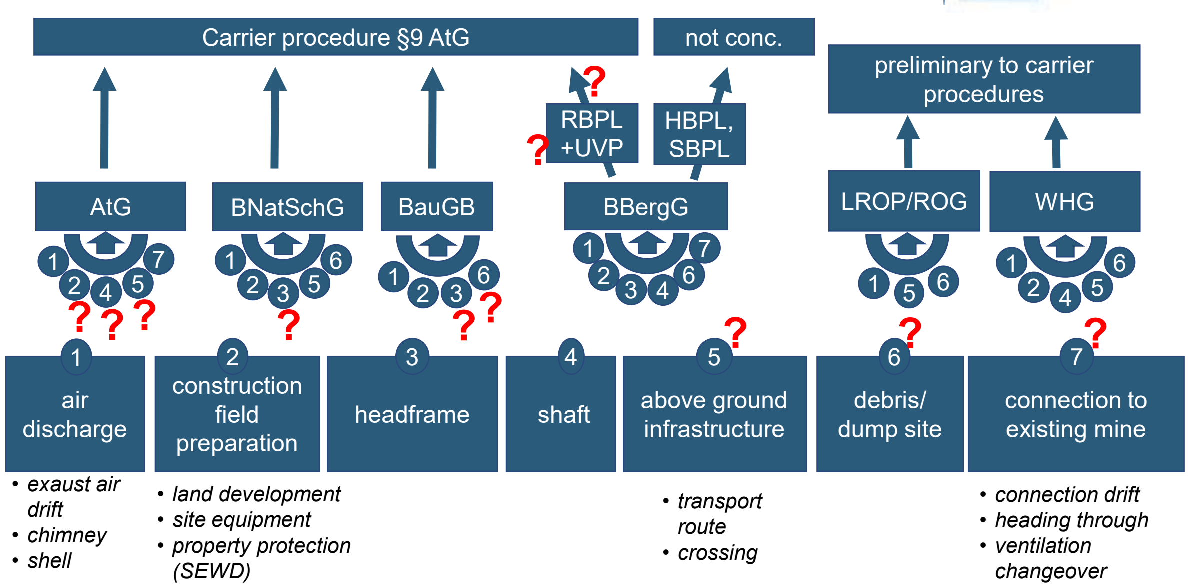
Approval procedures are the most **time-critical** processes (in Germany), therefore:

- Plan the duration of approval procedures realistically
- Develop a licensing strategy, involve the authorities at an early stage and keep them continuously involved.
- Build trust with the licensing authorities and create commitment between applicant, licensing authorities, experts and the public
- Encourage authorities to build up the necessary resources and know-how in good time and to bundle technical expertise.



5

## Asse: draft of application complex I (as of 09.06.2021 – in progress)

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## APPROVAL PROCEDURES

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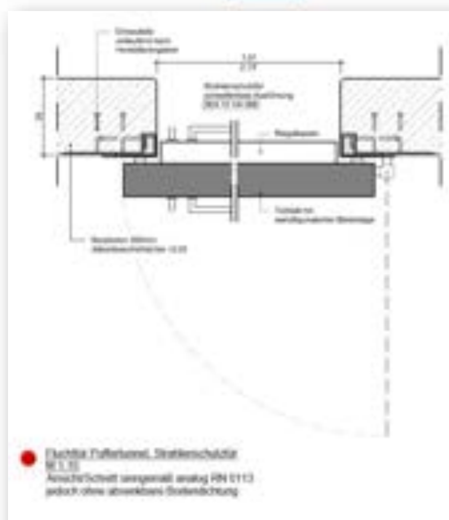
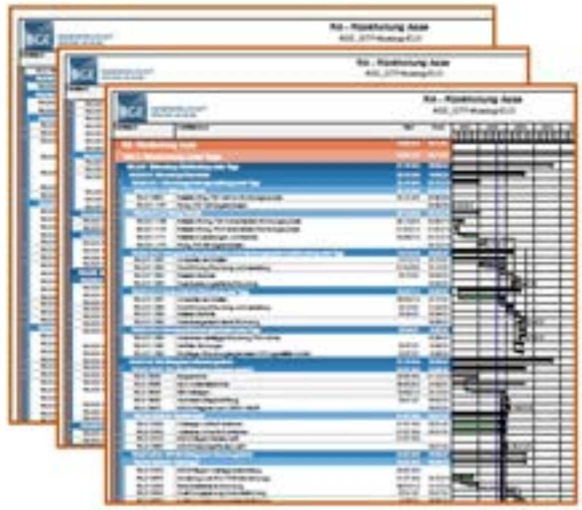
## APPLICATION DOCUMENTS

- Coordinate **structure**, **scope** and **depth** with authorities in advance
- Do not make application documents more detailed than absolutely necessary - instead, plan until the project is ready for implementation, then reduce the **level of detail** in the application documents.
- Classify equipment, systems and components in the application documents restrictively: avoid classification as a nuclear system where possible.
- Have application documents prepared by **experts** who are familiar with the requirements of the **nuclear licensing procedures**.



## PLANNING

- Planning from the end, the end is **long-term safety**
- **Realistic** process and schedule planning
  - Take the actual duration of **comparable processes** as a basis
  - Do not always plan in the earliest position
- Do not pile up conservatisms
- Plan intermediate construction stages
- **Standard solutions** with equipment, systems and components wherever possible







## GORLEBEN: INFRASTRUCTURE ROOMS NEAR SHAFT

## PLANNING

- Planning from the end, the end is **long-term safety**
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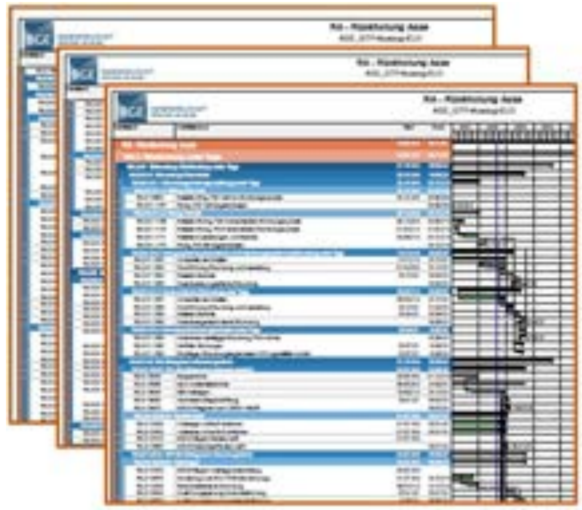
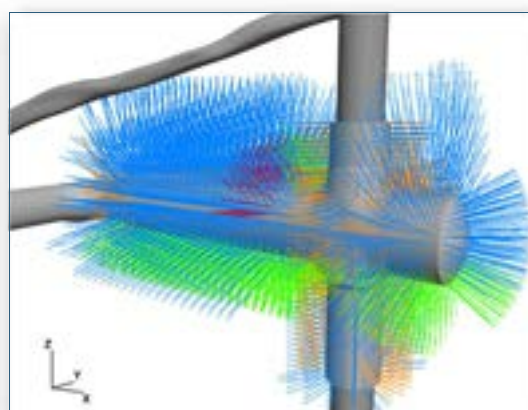




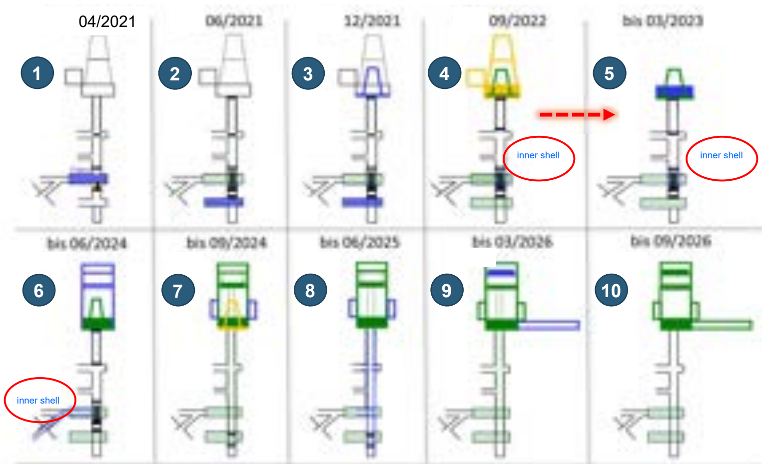
## REPOSITORY KONRAD: CONSTRUCTION SITE UNDERGROUND

Shaft Konrad 2, -850 m-level under construction



Shaft Konrad 2, 3-D-Model of rock bolting in the 2nd bottom

## REPOSITORY KONRAD – SHAFT KONRAD 2: INTERMEDIATE CONSTRUCTION STAGES




Configuration Management

- demolition
- under construction
- finished





## REPOSITORY KONRAD – SHAFT KONRAD 1: RENOVATION WORK

Exchange of northern and southern ropeways

## PLANNING

- Planning from the end, the end is **long-term safety**
- **Realistic** process and schedule planning
  - Take the actual duration of **comparable processes** as a basis
  - Do not always plan in the earliest position
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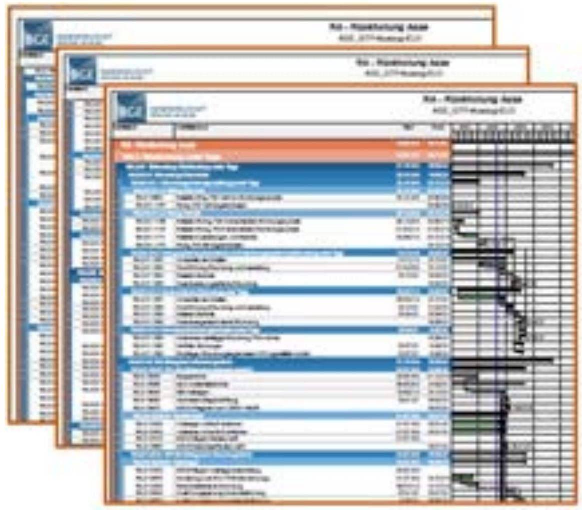
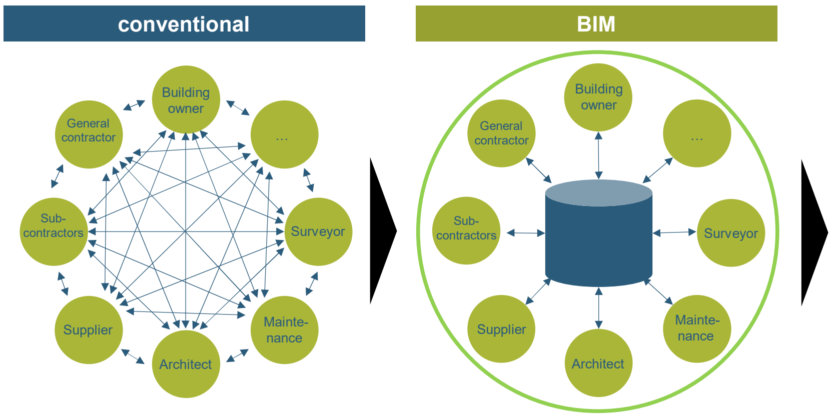




## STANDARD HEAVY DUTY FORKLIFT VS. HEAVY DUTY FORKLIFT FOR KONRAD REPOSITORY

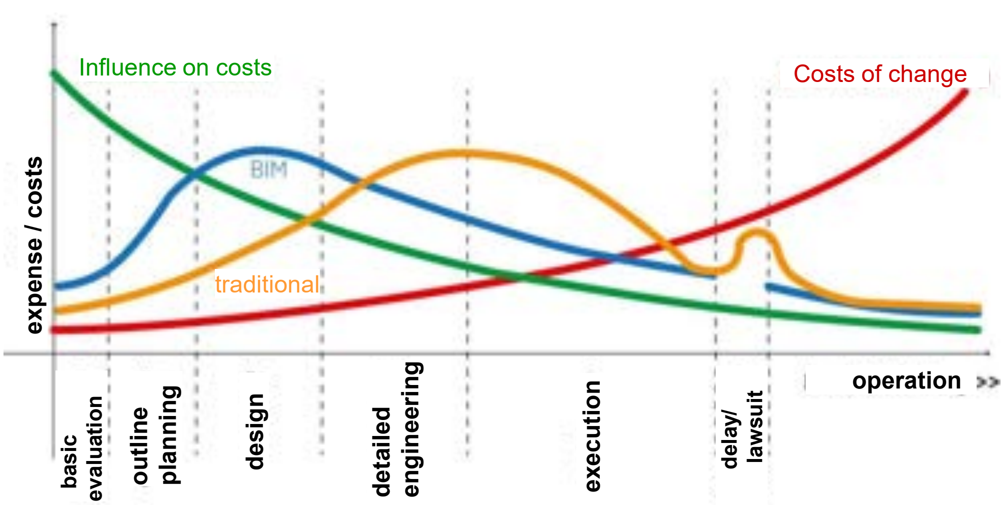
# BUILDING INFORMATION MODELING (BIM)




- ✓ secure future state of the art
- ✓ increase planning quality
- ✓ improve transparency
- ✓ simplify operation & maintenance



# COST EFFECTS OF BIM



## KONRAD REPOSITORY: DIGITAL TWIN FOR COMMISSIONING



## CONCLUSION

- REPOSITORY PROJECTS ARE TECHNICALLY HIGHLY COMPLEX AND EXTREMELY LENGTHY PROJECTS
- LAWS AND REGULATIONS ARE ADDITIONAL CHALLENGES
- COMPLEXITY AND LONG PROJECT DURATION CAN LEAD TO MISTAKES
- LEARNING FROM MISTAKES IS IMPERATIVE
- BETTER COLLABORATION AND COMMUNICATION CAN HELP US PREVENT MISTAKES
- DIGITALIZATION OFFERS THE OPPORTUNITY TO OPTIMIZE COOPERATION, COMMUNICATION AND COSTS


BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

"On behalf of the Federal Government I declare open the final nuclear repository for the next 1 million years"

Germany in the year 2350:
it is done!

Source: Frankfurter Allgemeine Zeitung





BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

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# Outlook


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## Proceedings

**We are looking for Volunteers!**

Session 1 – National Projects

Session 2 – Modelling

Session 4 – Special Topics

Session 5 – EBS, Materials and Backfill

Session 7 – Insights on Operating Facilities

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## 2024

**In person or virtual?**

**NWS offered to host the workshop in the UK (London or Manchester)**

**PTKA will host the workshop**

**Other hosts?**
**Somewhere else?**



## Future Sessions

**What topics should be addressed 2024?**

**More room for disussions/breakout sessions and working groups?**

**Should we establish a call for papers?**

## Organisational Information

**Field trip**

- **Leaving 8 AM from Drury**
- **Lunch provided at Bandelier Nat'l Monument**
- **Return to Drury ~5 PM**

**What to bring/wear:**

- **Walking shoes (sneakers)**
- **Hat or sun protection**
- **Water**