Proceedings of the 10th US/German Workshop on Salt Repository Research, Design, and Operation

Spent Fuel and Waste Disposition

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PROCEEDINGS OF THE 10TH US/GERMAN WORKSHOP ON SALT REPOSITORY RESEARCH, DESIGN, AND OPERATION

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EXECUTIVE SUMMARY

The 10th US/German Workshop on Salt Repository Research, Design, and Operation was hosted by RESPEC and South Dakota School of Mines & Technology, both located in the Black Hills of South Dakota. Over 60 registered participants representing Germany, United States, the Netherlands, and the United Kingdom availed themselves to excellent facilities on the School of Mines campus. As the 10th annual workshop, this occasion is a milestone of the modern era of collaboration between the US and Germany, which has extended to other countries with potential for radioactive waste disposal in salt.

Thrust areas covered in the annual workshops are selected by participants and typically include elements of continuity from year to year. This year's themes included siting, modeling challenges, seal systems and materials, operational safety, and special topics. Two major breakout sessions addressed test sample conditioning and natural closure of salt openings. When the new-generation US/German workshops were conceived, one goal was to identify challenging issues related to salt repository sciences and then conduct open discussions in special breakout sessions. These timely sessions achieve the workshop paradigm and provide in-depth dialogue on important salt repository considerations.

In many respects, general themes of these salt repository workshops reflect advances in the scientific basis for nuclear-waste disposal in salt formations and develop naturally as a consequence of unremitting attention largely as a result of the workshop commitment. Technical capabilities in the laboratory and field continue to improve in concert with accumulating experience. Because we are working together, mechanical deformation at the micro-scale can be interpreted at a large scale, which is fundamental to predictive modeling of salt repository evolution.

This document records the Proceedings of the 2019 gathering of salt repository nations and has been compiled by RESPEC, demonstrating an adopted protocol in which the host organization creates that year's Proceedings. To assist with organization and compilation, individual chapters are summarized by volunteer subject-matter experts from the participatory audience; these contributors are recognized in the Acknowledgements. All formal presentations are included in this document, thus providing a resource for referencing and many excellent photographic images. Appendices include the agenda, list of participants, abstracts, and presentations. A primary purpose for recording workshop activities is to create and sustain an accessible record of salt repository research. These archives also illustrate transparent development of research areas each year. The list below identifies topics that were emphasized at the 10th US/German Workshop on Salt Repository Research, Design, and Operation. A brief summary of each major topic is provided in the following text.

- Ten-Year Summary of Annual Workshops
- National Site Selection Processes
- Modeling Challenges
- Natural Closure of Salt Openings
- Engineered Barrier Systems
- Laboratory Salt Test Sample Conditioning
- Technical Barriers and Operational Safety

A brief look forward to the 2020 workshop in Braunschweig, Germany, concludes these Proceedings.

Ten-Year Summary of Annual Workshops

The 10th salt repository workshop symbolizes a new-age milestone. By comparison, a well-recognized international conference on the mechanical behavior of salt has been held ten times since initiating in 1981. Conspicuously, many of the issues facing science and engineering of salt repositories are not new, as the beginnings can be traced back decades. Through collaboration, we have been able to move the technical agenda forward; increased knowledge leads to better investigative techniques, more solid understanding and consistency of data interpretation, improved instrumentation and parameter control, and especially how these research areas apply to radioactive waste disposal in salt.

This chronological milestone is simply a demarcation of how far we have come but does not imply how far is yet to be traveled. Therefore, accomplishments of 10 years' work represent beginnings that, in their achievement, illuminate the actual distance remaining. Brief summaries of each annual workshop are woefully insufficient to capture the amount of work and advancement of science undertaken and accomplished. Self-imposed emphases—pertaining to salt repository research, design, and operation—still embrace enormous breadth and depth. Principal themes of the ten most productive and important areas covered in the last 10 years are as follows:

- Constitutive modeling
- Laboratory testing
- Seal systems
- Materials, including reconsolidating salt and concretes
- Operational safety
- Natural analogues
- Features, events, and processes
- Safety case
- Knowledge preservation
- Salt Club outreach.

These topics are all vital to a successful repository program and represent the ten most important enterprises undertaken. Several other research areas that involve arising challenges or special interests were also addressed on a timely basis. Many abstract goals, such as promoting interest, education, access, and outreach, are also organic to conducting the workshop. During assembly of these brief annual summaries, the above items recur at the forefront of workshop content, and their pursuit often spurred the next generation of investigations.

National Site Selection Processes

National policy most often represents the starting point for geological repository investigations. Governing legislation establishes rules of engagement, and site selection has proven to be a challenge in many countries. In this workshop, perspectives from the United Kingdom, the Netherlands, and Germany were represented with respect to salt repository potential. In the national context, site selection may involve other geological formations, and countries with a salt repository option are usually required to include other geomedia in their evaluations.

The United States program has seen delays implementing repositories in the national interest. Similar to the national programs showcased in this workshop, the United States reconsiders geological repository considerations by empaneling a "Blue Ribbon Commission" to evaluate America's nuclear future. The discourse here is widely applicable and revolves around a thesis of volunteer siting. As our international programs advance, these workshops may provide essential guidance and input to the national processes.

Modeling Challenges

Since Project Salt Vault in the late 1960s, effort has been made to model features of salt repositories. In this workshop, geomechanics and hydrologic modeling challenges were discussed. Geomechanics modeling has been a primary focus in all workshops and remains a key technical issue. Participants in these workshops have carefully examined constitutive models and their application to large-scale field tests. Interestingly, at the initial workshop in Mississippi, Professor-Dr. Karl-Heinz Lux provided a review of significant steps in structural analysis of rock-salt mass. For centuries, an empirical method of trial-and-error represented the state of the practice. In more recent generations (say from 1960 to 1980), modeling by analogy took hold. Evolution of analytical approaches and numerical modeling emerged as computational capabilities gathered. Many of the advancements regarding damage mechanics, healing, coupling, and demonstrating reliability have been developed in these workshops.

Hydrological modeling is also part of performance evaluation. Presentations from this session included a wide range of topics relevant to brine migration through and near salt deposits, which share a theme that brine migration requires careful consideration. Predicting brine migration in many scenarios is complicated by hydromechanical coupling, two-phase flow considerations, density-dependent flow, and flow through an evolving damaged rock zone.

Natural Closure of Salt Openings

The Waste Isolation Pilot Plant is abandoning former disposal areas with potentially little mitigation or engineering measures to ensure predictable future conditions as rooms and haulage ways close. The topic of if or how this additional void space alters the basis for long-term safety assessment from that approved for compliance certification by the US Environmental Protection Agency was raised. The current basis assumes that the rooms and haulage ways remain open, which is contrary to natural analogs of mined salt excavations. Natural closure of salt excavations occurs as a function of many contributing variables, such as size and shape of openings, extraction ratio, depth, temperature, moisture, and mechanical response of nonsalt units.

Assumptions within the compliance analysis for the Waste Isolation Pilot Plant assumes mostly static conditions, which is conservative compared with current knowledge that open rooms will close over time and damaged salt surrounding the excavations will heal. Examples from the Teutschenthal Mine indicate that under certain conditions (dictated by the salt mineralogy, humidity, and stress conditions), unfilled rooms can fully close and reconsolidate within decades, particularly when fast-creeping salts were present. Other examples of completely closed rooms were discussed in the breakout session. Evolution of the un-backfilled Waste Isolation Pilot Plant underground will involve substantial volume reduction and porosity decrease. The Waste Isolation Pilot Plant site is also statutorily obligated to 100 years of institutional control. Geotechnical information gathered over the operational period documents closure rates that can bring roof and floor into contact within a few decades for the fastest closing rooms in the facility and even the slowest closing rooms at WIPP are expected to fully closure within a century. On a local scale and perhaps a global scale, reconsolidation will advance toward native conditions and reserve little porosity for future brine introduction by human intrusion. The breakout session concludes that the Waste Isolation Pilot Plant performance assessment assumption warrants revisiting in a formal setting to more accurately represent future states of the underground.

Engineered Barrier Systems

Engineered barrier systems and materials have been evaluated extensively, especially in German operations at the Asse II Mine and Morsleben repository. In this workshop, barrier construction, stabilization, and evaluation are described for the purpose of ensuring long-term safety and operational efficiency. Laboratory studies substantiate large-scale construction demonstrations and monitoring results. A review of several experiences was provided in this workshop to identify mixtures of salt-based concrete and Sorel concretes using construction materials with magnesium oxide as a binding agent and magnesium chloride solution as a mixing liquid. Multiple field-scale demonstrations provide assurance that important roles in mine stabilization and sealing of drifts, shafts, and boreholes are readily achievable. Several full-scale mixing and placing operations have demonstrated construction feasibility and upscaling of laboratory results to in situ performance. Engineered barrier systems are vital to licensing and operations because closure systems must be practically constructed and shown to meet performance requirements to the satisfaction of licensing authorities, as well as stakeholders. Comprehensive knowledge regarding magnesium oxide-based construction materials has established industrial handling practices, mechanical and hydraulic material properties, and long-term stability.

Laboratory Salt Test Sample Conditioning

Sample integrity at the moment of testing is one of the most interesting technical developments illuminated by joint salt research. Sample material can endure wide variations of care in the process of acquiring, packaging, transporting, storing, preparing, and preconditioning for testing. The impetus for this breakout session was to identify and discuss influences of sample conditioning on the mechanical behavior. In particular, the breakout session emphasized pressurization or annealing practices employed to heal unintended damage from external influences.

Sample conditioning (as these practices have become known) is a relatively new research area for workshop collaboration. As joint testing efforts progress, minimizing unintended disturbance of samples and, in the process, summarizing standard procedures and best practices, is vital. Routine procedures for sample handling and preparation may have accounted for spurious definition of argillaceous and clean salt at WIPP, for example. Conditioning temperature and hydrostatic pressure were compared because initial volumetric strain appeared to be sensitive to these variables. As salt testing becomes more exacting, sample conditioning immediately preceding execution of planned test procedures has been identified as a key area to establish standards.

Technical Barriers and Operational Safety

Operational safety was bookmarked by Sandia National Laboratories' Vice President Dr. Steve Rottler in Santa Fe, New Mexico, at the 2015 workshop. As a nuclear-weapons laboratory, Sandia National Laboratories has institutionalized a dictum of safety by design, also known as operational safety. In these workshops, we have exposed the importance of operational safety as superseding predictions of long-term safety. These workshops have illuminated how operational safety, if properly undertaken, can be integrated with long-term safety. These ideals are especially pertinent to salt repositories, because salt safety measures in terms of barriers are readily attainable, as documented in this session of the workshop.

Technical barriers relate directly to operational safety; a systems approach that integrates operations and long-term safety has been emphasized in the US/German salt repository workshops in recent years. These issues have many perspectives, and the Waste Isolation Pilot Plant provides an example of how operations and long-term safety are inextricably linked. As noted in this workshop, the safety-by-design principle applies to all geological disposal media. Germany has developed a project to provide design criteria beginning with generic container concepts and evaluating international state-of-the-art waste container design criteria.

Concluding Remarks and Outlook

These Proceedings record the 10th annual workshop on salt repository research, design, and operation, which restarted after Germany emerged from a moratorium in 2010. The main technical areas involve constitutive modeling and engineered barriers, and highly technical laboratory testing has contributed to both model evaluation and barrier performance. Principal investigators continually examine details of the advancing salt science to reset the research agenda. The results and status are reviewed annually and recorded in the Proceedings of these workshops. Thus, the research is approached for the common benefit—sharing the burden distributes cost and enhances time effectiveness, and documenting the work provides a transparent and readily available record.

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Salt science advances by timely and cost-effective collaboration, especially in the most recent 10 years. Each attendee contributed with diverse input to enhance the workshop. Chapter summaries are provided by the combined efforts of volunteer authors listed below.

CONTRIBUTING AUTHORS

Chapter	Title	Authors[a]
1	Introduction	F. Hansen
2	Ten-Year Summary of Annual Workshops	F. Hansen
3	National Site Selection Processes	J. Riemaecker-Burschil J. Bartol A. Shelton
4	Modeling Challenges	B. Reedlunn K. Kuhlman
5	Natural Closure of Salt Openings	E. Keffeler T. Popp
6	Engineered Barrier Systems	N. Müller-Hoeppe
7	Laboratory Salt Test Sample Conditioning	S. Buchholz U. Düsterloh T. Popp J. Hladysz W. Graesle A. Hampel
8	Technical Barriers and Operational Safety	W. Bollingerfehr
9	Concluding Remarks and Outlook	F. Hansen

(a) For those chapters with more than one author, the lead author is listed first.

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Appreciation is a wonderful thing. It makes what is excellent in others belong to us as well.

(Voltaire)

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REVISION HISTORY

Document Number/Revision	Date	Description
RSI-2948/Rev. 0	August 8, 2019	Draft report for Sandia National Laboratories' review/approval
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ACRONYMS

BAM	Bundesanstalt für Materialforschung und-prüfung (Federal Institute for Materials Research and Testing)
BAMBUS	Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt
BGE	Bundesgesellschaft für Endlagerung mbH (Federal Company for Radioactive Waste Disposal)
BGE TEC	BGE TECHNOLOGY is a wholly owned subsidiary of BGE
BfE	Federal Office for the Safety of Nuclear Waste Management
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMWi	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy)
CMS	constant mean stress
COVRA	Centrale Organisatie Voor Radioactief Afval (Central Organization for Radioactive Waste)
DBEIS	Department for Business, Energy & Industrial Strategy
DECOVALEX	DEvelopment of COupled models and their VALidation against Experiments
DIKOSA	Diffusion in Kompaktierten Salzgrus (Diffusion in the pore water of compacted crushed salt)
GESAV	Gefügestabilisierter Salzgrusversatz (microstructure stabilized crushed rock salt backfill material)
ERAM	Endlager für radioaktive Abfälle Morsleben (Morsleben repository for radioactive waste)
FEPs	features, events, and processes
GDF	geological disposal facility
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Society for Plant and Reactor Safety) GmbH
HLW	high-level waste
IAEA	International Atomic Energy Agency
IfG	Institut für Gebirgsmechanik (Institute for Rock Mechanics)
KoBrA	requirements and concepts for disposal containers for heat-generating radioactive waste and spent fuel in salt, clay and crystalline rock
KOMPASS	Kompaktion von Salzgrus für den sicheren Einschluss (reconsolidation/ recompaction of crushed salt backfill)
KOSINA	Konzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flach lagernden Salzschichten in Deutschland sowie Entwicklung und Überprüfung eines Sicherheits-und Nachweiskonzeptes (concept development for a generic final repository for heat-generating wastes in flat-bedded salt layers in Germany as well as development and examination of a safety and verification concept)

LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LILW	low- and intermediate-level radioactive waste
MoU	memorandum of understanding
MOX	mixed oxide
NBG	National Advisory Board
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NWP	Nuclear Waste Partnership (WIPP management and operations contractor)
OPERA	Onderzoeks Programma Eindberging Radioactief Afval (Research Programme on Geological Disposal of Radioactive Waste)
PA	performance assessment
PCS	panel closure system
PMDA	Plutonium Management and Disposition Agreement
PVC	polyvinyl chloride
RD&D	research, development, and demonstration
RWM	Radioactive Waste Management Ltd.
SDSM&T	South Dakota School of Mines & Technology
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
StandAG	German Repository Site Selection Act
TUBAF	Technical Bergakademie Freiberg
TENORM	technically enhanced naturally occurring radioactive materials
THM	thermal, hydrological, and mechanical
TUC	Technische Universität Clausthal
UK	United Kingdom
US	United States
US DOE	US Department of Energy
US EPA	UA Environmental Protection Agency
WEIMOS	Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz (Collaborative project: Further development and qualification of rock mechanics modeling for final storage of HAW in rock salt).
WIPP	Waste Isolation Pilot Plant

1 INTRODUCTION

A multinational collaboration on salt repository research, design, and operation has enjoyed remarkable success since reinvigorating efforts in 2010. Nations now engaged in the shared salt repository research agenda include Germany, the United States (US), the United Kingdom (UK), the Netherlands, and Poland. The scientific basis for safe and permanent nuclear-waste disposal in salt formations has been strengthened by annual workshops that recognize and address contemporary research, including breakout sessions to stimulate open discussion and focus planning for ongoing investigations. Collaboration not only identifies pertinent technical issues but facilitates timely, expert, and cost-effective consideration. Contemporary workshops have been held annually since 2010 and are documented in yearly Proceedings, which summarize content and conclusions. The Proceedings help preserve scientific understanding and provide timely source references. These workshops often produce valuable joint publications coordinated with the Nuclear Energy Agency (NEA) and other suitable external forums for dissemination. Nuclear-waste management programs face growing challenges, while permanent disposal in salt formations provides a robust, safe option for several nations. Workshop format and publications provide a cost-effective insurance against loss of scientific expertise and institutional memory. This report summarizes ten US/German workshops since formal reinitiation, reexamines key technical issues, discusses the evolving research agenda, and highlights successes and challenges.

Researchers and practitioners in Germany and the US have shared expertise in salt science for many years, including evaporite mineral mining, hydrocarbon storage, and long-term nuclear-waste isolation. These relationships rejuvenated in 2010, when Germany emerged from a 10-year moratorium. Researchers restarted salt repository workshops and adopted a more formal approach. In 2011, a Memorandum of Understanding (MoU) between the US Department of Energy (US DOE) offices of Environmental Management and Nuclear Energy and the German Ministry of Economics and Technology officially sanctified the workshop relationship and broadly described its aspirations.

Favorable attributes for radioactive waste disposal in salt include zero far-field permeability and self-healing of fractures and openings, which combine to ensure that materials placed within salt formations will remain isolated from the biosphere for regulatory timescales. Because salt has been conventionally mined for mineral industries and solution mined for storage caverns, great hands-on resources of knowledge exist for everyday salt-mining operations. Repositories for chemo-toxic waste (Germany) and transuranic nuclear waste (US) have operated for many years. Heat-generating nuclear-waste disposal introduces new factors to the practical knowledge base and thus necessitates a rigorous research, development, and demonstration (RD&D) program. Joint international projects share financial burden and combine technical expertise to address pressing issues. Nuclear-waste disposal is also fraught with highly debated societal issues, which further support the need for international collaboration. Improved public perception can be derived from world-wide, transparent, and safety-oriented approaches. The US/German workshops on salt repository research, design, and operation also provide tangible preservation of knowledge and opportunity to develop requisite human capital for an extremely long-term life cycle.

The 10th workshop denotes a modern milestone in the sense of a significant event, yet a milestone also represents a new chapter and literally provides a measure of distance to a destination. Therefore, accomplishments of 10-years' work represent beginnings that, in their achievement, illuminate the actual distance remaining. Brief summaries of each annual workshop are woefully insufficient to capture the amount of work and advancement of science undertaken and accomplished. Self-imposed emphases—pertaining to salt repository research, design, and operation—still embrace enormous breadth and depth. Principal themes of the ten most productive and important areas covered in the last 10 years are as follows:

- Constitutive modeling
- Laboratory testing

- Seal systems
- Materials, including reconsolidating salt and concretes
- Operational safety
- Natural analogues
- Features, events, and processes
- Safety case
- Knowledge preservation
- Salt Club outreach.

It is a matter of opinion which of these is singly most valuable or if they represent the ten most important enterprises undertaken. Several other research topics were covered, including arising challenges or contemplation of special subjects. Many abstract goals, such as promoting interest, education, access, and outreach, are organic to conducting the workshop. During assembly of these brief annual summaries, the items above recur at the forefront of workshop content and their pursuit often spurred the next generation of investigations.

2 TEN-YEAR SUMMARY OF ANNUAL WORKSHOPS

2.1 Introduction

Repositories for nuclear waste, regardless of geology, comprise a breadth of challenging issues. Recent collaboration on salt repositories addressed mostly technical aspects, but the specialized practitioners fully acknowledge that public acceptance and national policy often overwhelm scientific discourse. Collaborative research efforts have evolved considerably in the last 10 years. Knowledge accumulates and state-of-the-art modeling improves analysis of operations, sealing, geomechanics, and a host of related details that are all aimed at reducing uncertainty. Knowledge also begets discovery. As science naturally advances, experimental methods mature and improve, test control and procedures become finer, fundamental mechanical processes are identified, modeling capabilities grow, and the overall discipline advances. Because the landscape of salt repository science is vast, collaborators streamlined and concentrated efforts to yield maximal impact and optimal resource utilization. Therefore, primary workshop focus shifted each year as emphasis changed and, in some cases, conclusions were drawn. As recollected here, certain main themes pervade the workshop agenda—geomechanics, sealing systems and materials, performance assessment (PA) and the attendant features, events and processes (FEPs) rubric, licensing, operations and operational safety, underground research facilities, and attention to arising issues or related areas of interest.

The annual US/German workshops dedicated to salt repositories benefit from many sources, including federal and independent research groups, industry, national laboratories, and universities. Advances in understanding the mechanical behavior of salt were on full display at the 2018 Conference on the Mechanical Behavior of Salt held in Hannover, Germany (BGR, 2018). The Solution Mining Research Institute has contributed significantly to salt research for many years. Laboratory proficiency and techniques are improving every day, computational capability has increased exponentially, and more-and-more full-scale mining experience often links related research avenues. Today, we remain actively engaged in basic salt research with better tools, deeper understanding, and accumulated experience.

2.2 Summaries

Highlights of these extraordinary 10 years of cooperation are presented in the following text.

1st Workshop

In 2010, changes and developments in US and German radwaste policy combined to stall repository progress. These circumstances were clear to leading organizations in both countries and gave rise to a new dedication for salt repository collaboration with an added emphasis on sustainability. One general impediment to nuclear-waste disposal has been a lack of sustaining effort. A commitment to meet yearly and examine an agreed-to research agenda was conceived as an institutional blueprint for continuity.

The 1st workshop of the new era was hosted by Mississippi State University and held in Canton, Mississippi. At this formative stage, organizers decided to emphasize research, design, and operation of salt repositories and produce a Proceedings of each workshop. Other research areas that could relate to salt repositories, such as the potential for microbial activity and actinide solubility, already had dedicated cooperative efforts. To help accommodate the overall breadth of scientific inquiry, workshop organizers further resolved to petition the NEA for recognition of and support for a Salt Club where a broader reach of ancillary issues might be adopted.

2nd Workshop

In 2011, the 2nd workshop was held in Peine, Germany, and embraced a more rigorous, formal agenda. In part, collaborators wanted to foster a "workshop" atmosphere—vetting of issues were encouraged and visions toward resolution were identified. The initial content of five sessions included safety analyses, sealing concepts, backfilling, deformation and healing of rock salt, and natural analogues. The concept of an NEA-sponsored Salt Club was further advanced. Germany, the US, Poland, the Netherlands, and England have salt formations that may be candidate hosts for deep geological disposal. The proposed Salt Club was officially acknowledged by the NEA in spring 2012. Almost immediately, joint activity on natural analogues and a consolidated FEPs catalog was initiated. A successful international workshop on natural analogues was organized in Germany in September 2012 and the presentations were published by the NEA (Sandia National Laboratories, 2013).

3rd Workshop

In 2012, the 3rd workshop was held in Albuquerque, New Mexico. Three main salt repository topics were covered: the safety case, benchmark modeling, and reconsolidation of granular salt. A safety case or safety analysis involves long-term PA. At this juncture, Germany had issued its preliminary safety analysis for the Gorleben salt dome (Gesellschaft für Anlagen- und Reaktorsicherheit [GRS], 2012). These discussions and recognition of transient national policy helped reveal terms of a collaborative research agenda, as exemplified by an overview of the US' ability to develop a safety case for bedded salt. The discussion of domal and bedded salt repositories was perceptive and served as an example of how international collaboration can illuminate emerging issues. Discussion of the safety case for different salt formations led to further testing and modeling research.

Spurred by collaborative spirit, several initiatives emerged. German salt modeling researchers and Sandia National Laboratories (SNL) signed an agreement to participate in a joint project to formulate a strategy for generic modeling of thermomechanical field-scale tests. Examination of extant data immediately identified the need for additional laboratory testing. Concomitantly, German researchers proposed that to fill this void, specific types of mechanical data were needed, which gave rise to the possibility of testing Waste Isolation Pilot Plant (WIPP) salt and evaluating constitutive models for bedded salt.

Reconsolidation of granular salt was identified as a key technical issue for German repositories, WIPP panel closure options, and design and performance of salt repositories for heat-generating waste in the US. Based on these findings, a review paper was prepared by leading field experts and submitted as another joint report under the auspices of the NEA Salt Club (Hansen et al., 2014). This report was an example of a mutually derived benefit for advancing salt repository science. Looking forward, this benchmark report illuminated remaining questions, including the ability to model permeability of reconsolidated salt at low porosity. Ensuing discussions and publications brought forth additional collaboration in the study of granular-salt consolidation.

4th Workshop

The 4th workshop was held in Berlin, Germany, and coordinated with the NEA Salt Club meeting in September 2013. More than 50 salt repository research scientists from Europe and the US met to discuss selected aspects of the safety case for salt disposal of high-level waste, plugging and sealing, salt-mechanics modeling, and repository design. Additional discussion from the Salt Club included geochemistry, microbiology, and hydrogeology. The FEPs database assembly continued with joint publications at appropriate venues (e.g., Freeze et al., 2017).

Sealing capability was being demonstrated at full scale at the Morsleben repository and the Asse II Mine. Salt-mechanics modeling engendered by the joint project was officially extended to include two additional full-scale tests conducted at WIPP. Modeling was projected to compare isothermal Room D to heated Room B. These modeling studies identified a suite of laboratory testing to be conducted on WIPP bedded salt. Hundreds of tests that addressed fundamental material behavior were identified at this time and set the stage for long-term collaboration on constitutive modeling.

5th Workshop

In September 2014, the 5th workshop was held in Santa Fe, New Mexico. Forty-seven registered participants were equally divided between the US and Germany with one participant from the Netherlands. Following precedent, the agenda began to be established at the close of the 4th workshop, including facets of thermomechanical testing and modeling, plugging and sealing, and PA. However, the most interest by far pertained to operational safety. An underground fire and radiological release at WIPP in February 2014 gave operational safety a new sense of relevance and urgency. This example illustrates how the workshops provide flexibility and means to address emerging issues. Operational safety was undertaken as a new topic.

Operational events at WIPP introduced unprecedented uncertainty regarding the mission and compromised other underground activities. One suggested demonstration to deploy at WIPP concerned early evolution of salt excavations. If planned appropriately, this mining demonstration could characterize host-rock evolution before, during, and after excavating test rooms. This work was proposed to link model prediction and confirmation of geophysical phenomena that are basic to the goals of the US/German salt workshops.

Collaborators continued to compile an international FEP catalog that pertained to the safety case for disposing heat-generating nuclear waste in salt. This effort is expected to be published under the aegis of the NEA Salt Club. For several reasons, a new effort to examine differences and similarities of bedded and domal salt was initiated, along with recognizing and including pillow salt formations. This example also illustrates how arising issues are identified and addressed by international collaboration.

6th Workshop

In 2015, the 6th workshop was held in Dresden, Germany. Collaboration naturally continued between workshops and helped reveal future research directions. Remaining among previous research issues were the minimum stress criterion, granular-salt properties at low porosities, constitutive model development, and other matters of mutual interest and pertinence to the salt safety case. The overall goal of the joint project was to further develop tools for demonstrating safe, final disposal of heat-generating, radioactive waste in salt formations. Tools in this context included constitutive models, numerical codes, and modeling procedures. Previous joint project activities evaluated proficiency against isothermal and thermal in situ test results. The most recent simulations of unheated Room D and heated Room B examined large-scale thermomechanical effects on closure. In concert, a large laboratory testing program on Salado Formation bedded salt provided additional parameter quantification.

Large-scale demonstrations of concrete placement and performance provide important operational functions as well as contribution to final closure. Many drift seals made of salt-saturated concrete have been evaluated at full scale using specialty concretes with cement or MgO (magnesium oxide) as the binding agent and brine saturated with NaCl (sodium chloride) or $MgCl_2$ (magnesium chloride). Investigations of pilot drift seals encompassed the primary elements of drift seals: construction materials, excavation damage zone, and contact zone.

The US and Germany continued to collaborate on characterizing bedded, pillow, and domal salt formations as applied to heat-generating, nuclear-waste disposal. Heretofore, the US concentrated on bedded salt, while similar efforts in Germany emphasized domal salt. In 2015, each nation was once again considering possible repository choices, which presented a need and an opportunity to compare repository-relevant differentiating characteristics of various salt formations.

Events in February 2014 at WIPP sharpened the focus on operational safety. One means to mitigate risk level is to minimize exposed areas during operations. Knowledge gained regarding salt reconsolidation, together with analogues examples, support a concept of modular design, sequential licensing, certification, and closure in large-scale salt repositories. Part of the optimism regarding modular-build-and-close design philosophy derives from acceptance by the US Environmental Protection Agency

(US EPA) of the premise that crushed-salt panel closures will return to a physical state that is comparable to native salt.

Priorities for underground testing (if possible) were also discussed in a breakout session. The basis for salt repository science and engineering benefited from several full-scale field experiments. Currently, no defined test is mandated before a safety case can be prepared for disposing heat-generating nuclear waste in salt. Nonetheless, if an underground facility were to become available, the salt repository community can define high-value test priorities. Based on the breakout sessions of this workshop, the consensus for highest priority field testing included large-scale consolidation and drift-seal demonstrations.

7th Workshop

In 2016, the 7th workshop was held in Washington, DC, with over 50 participants. The lineup of issues had a familiar ring: safety case, operational safety, geomechanics, and plugging and sealing. A new and sensational issue of percolation was added and addressed in a breakout session.

Comparisons were made between the German and US approaches to establishing robustness in the safety case. A connection between operational and long-term safety was again discussed in terms of WIPP recovery following the underground fire and radiation release. Engineered safety was at the forefront of concerns, and safety-by-design principles were identified that could add robustness and minimize risk exposure during operations (e.g., Gadbury and Hansen, 2016).

Collaboration in geomechanics included laboratory and field testing, constitutive model development and comparisons, benchmarking calculations, case study experiences, and analogues. All of these topics have been discussed in terms of salt repositories over the last few years. However, new WIPP test results were available that allow modelers to fine-tune approaches, including salt creep at low-deviatoric stress states.

Historical seal experiences in Germany were summarized for the most common seal materials. Construction practices and performance measures provide assurance that large-scale, high-performance seals of readily available materials can be constructed in salt formations. Performance measures include strength, permeability, chemical stability, and healing of the damage zone. Granular-rock reconsolidation was not revisited at this workshop but would be reengaged as a new research agenda was developed.

A potentially pertinent issue, called deformation-assisted fluid percolation in salt, was broached in the technical literature. Its presentation into the literature claimed that salt formations are permeable, which challenges a long-held fundamental tenet of salt disposal. Several experts contributed to open discussion in the breakout sessions and pointed out limitations of the published experiments as well as selective interpretation of the recently published results. However, workshop participants were not able to state definitively that deformation-assisted enhancements in percolation should not be anticipated in salt repository host rocks. Debate was expected to continue.

8th Workshop

In 2017, the 8th workshop was hosted by the Centrale Organisatie Voor Radioactief Afval (COVRA) at their headquarters near the operating storage facility in Nieuwdorp, the Netherlands. Fifty-five registered participants efficiently conducted the technical program at COVRA’s premises, which was an excellent venue to present, discuss, and advance the basis for radioactive waste disposal in salt formations.

Continuity of purpose had been established over recent years, and the scientific breadth continued to call for teamwork. Themes and emphases arise progressively because of advancing investigations and discussion, while new test results help define near-term research. Contemporary research agendas are documented periodically in external publications and in annual Proceedings and are often integrated into requests to the German Ministry and the US DOE for financial support.

Research themes frequently feed information between and among activities. As an example, constitutive modeling efforts have been examining apparent underprediction of creep deformation at low-deviatoric stress. In terms of modeling Rooms B and D at WIPP, this apparent effect would apply to a large portion of the grid space. Until recently, no experiments with precise instrumentation and absolute control over state variables at the low strain rates of interest were conducted. The experimental door was opened by Dr. Pierre Bérest and coworkers (Bérest et al., 2005; 2018), and similar investigations now constitute significant emphasis in our collaborative research.

A dedicated project to develop a generic repository for heat-generating waste in bedded salt formations in Germany as well as developing and testing a safety and demonstration concept was launched in the summer of 2015. Bedded salt was not previously considered to host a high-level waste repository in Germany. The project included developing generic geological models including deriving model parameters, developing a safety demonstration concept, developing technical repository designs for four emplacement alternatives, analyzing geomechanical integrity, evaluating operational safety, and analyzing radiological consequences.

9th Workshop

In 2018, the 9th workshop was held in Hannover, Germany, in concert with the international conference on the mechanical behavior of salt, the NEA Salt Club meeting, and a regular meeting of a collaborative project to further develop and qualify rock-mechanics modeling for final storage of radioactive waste in rock salt. New test results and analyses of WIPP core, including shear strength of salt/clay and salt/anhydrite interfaces, were presented. The first results from microstructural investigations by optical and scanning electron microscopy core samples tested at low-deviatoric stress were shown.

Germany completed several pilot applications of drift seals in the Asse II Mine and Morsleben repository. Batching, casting, and monitoring a variety of concrete materials were successfully demonstrated. Monitoring included crack formation, gaps on the seal/salt interface, permeability, and porosity. Other drift-seal strategies were outlined, including dynamic compaction of granular salt and a sealing system of cut salt bricks.

A project called KOSINA (Konzeptentwicklung für ein generisches Endlager für wärmeentwickelnde Abfälle in flach lagernden Salzschichten in Deutschland sowie Entwicklung und Überprüfung eines Sicherheits-und Nachweiskonzeptes) was jointly undertaken by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), GRS, Institut für Gebirgsmechanik (IfG), and Bundesgesellschaft für Endlagerung mbH (BGE TEC). KOSINA was funded by the Bundesministerium für Wirtschaft und Energie (BMWi) for the purpose of concept development for a generic repository for heat-generating waste in bedded salt formations in Germany. The contribution of KOSINA collaborators to the workshop included results from generic geological modeling, technical repository concepts, a safety and demonstration concept, numerical simulations on barrier integrity, and an analysis of radiological consequences.

10th Workshop

The 10th workshop was held in Rapid City, South Dakota, and cohosted by South Dakota School of Mines & Technology (SDSM&T) and RESPEC. The remainder of these Proceedings includes chapters dedicated to the technical topics addressed. National policy was discussed because several nations have a salt repository option, and national policy dictates rules of engagement. Engineered and technical barriers (including operational safety considerations) were reviewed. Of special note are two breakout sessions concerning natural closure of salt openings and laboratory test sample conditioning. The breakout session format differentiates these workshops from more familiar conferences and adds problem-solving open discussions, which was envisioned when these new-generation workshops were restarted.

2.3 Conclusions

This cooperation has come a long way since reconvening US/German salt repository investigations in 2010. The ongoing effort of the US and Germany provides a vivid example of benefits of international teamwork between peers for mutual advantage. The most obvious advantage has been optimizing scarce human resources. Workshop participants strive to advance the technical basis for disposal in salt formations and jointly publish accomplishments in the open literature. Yearly Proceedings can be found by a simple internet search and are included on several organizational websites, such as BGR and SNL. A vital outcome of the 10-year cooperation is knowledge preservation. The workshop Proceedings are also a great resource for background material, photographs, and a history of salt repository experience.

The geological repository life cycle stretches beyond a single lifetime and could easily exceed a century. Evidence in the US and Germany suggests that resolving the final disposition of nuclear waste has an uncertain future, and repository projects in both countries have required much more time than initially anticipated. At the same time, widespread skepticism about nuclear power has, perhaps, rendered the waste-management field uninviting for young scientists and engineers and further complicates knowledge preservation and transference. This series of workshops provides a vehicle to stimulate early-career scientists in an imperative mission to remove nuclear waste from the biosphere.

Thus, the 10th anniversary milestone has arrived; a milestone indicating how far we have come, but not how far we must go. As these collaborations move forward and deepen, with motivated leadership and focused workshops, our nations will be ready to license, operate, and close a nuclear-waste repository in salt.

3 NATIONAL SITE SELECTION PROCESSES

National repository programs begin with a law or policy that describes the processes and goals to be used in geological waste disposal in that particular country. The national law also promulgates rules of engagement that define organizational structure and implementation. A regulatory component prescribes the framework and standards to achieve environmental and human protection. The hierarchy of national disposal approaches gives rise to systematic methods because basic components are common to all programs. Disposal manifests as a system, which combines properties of waste inventory, waste form, selected host environment, engineered barriers, and facility operations. Together, these components of the disposal system provide required safety functions that ensure containment and isolation of the radioactive waste.

The hierarchy of national disposal from top down is as follows: national law, waste inventory, disposal decision, regulatory paradigm, development of technical basis, site selection, license application, site preparation, transportation, storage, disposal operations, monitoring and performance confirmation, and closure. Each of these steps can be complicated for a variety of reasons, but fundamental elements such as these are encountered in every nuclear-waste disposal program. This workshop discussed programs of the UK, the Netherlands, and Germany.

3.1 United Kingdom Process

3.1.1 Introduction

The UK has accumulated radioactive waste from a range of activities including nuclear-power generation, medicine, research, and defense-related nuclear programs. Most of the waste can be disposed of safely in facilities on the surface, but a suitable facility is still needed for the remaining higher activity radioactive waste; some of this waste will remain hazardous for hundreds of thousands of years. The UK policy is that higher activity waste will be disposed of in a Geological Disposal Facility (GDF) (Department for Business, Energy & Industrial Strategy [DBEIS], 2018).

Radioactive Waste Management Ltd. (RWM) is a public body and a wholly owned subsidiary of the Nuclear Decommissioning Authority (NDA). One of RWM's roles is to develop a permanent, safe solution to manage the UK's higher activity radioactive waste. Implementing geological disposal and providing long-term radioactive waste-management solutions are primary responsibilities of the RWM.

Geological disposal involves placing waste deep underground and containing it within multiple barriers to ensure that the hazardous materials are isolated from the surface environment and no harmful quantities of radioactivity ever reach the surface environment. Geological disposal is internationally recognized as the safest and most secure permanent solution to managing higher activity radioactive waste.

The following specific types of radioactive waste make up the UK inventory for disposal in a GDF (DBEIS, 2018):

- High-level waste from reprocessing spent nuclear fuel at the Sellafield site
- Intermediate-level waste from existing nuclear-licensed sites and defense, medical, industrial, research, and educational facilities
- Small proportion of low-level waste that is not suitable for disposal in the UK's national low-level waste repository
- Spent fuel from existing commercial reactors (yet to be declared waste) and from research reactors that is not reprocessed
- Spent fuel (yet to be declared waste) and intermediate-level waste from a new-build program (up to a defined amount)

- Plutonium stocks that are not reused in new fuel manufacture (yet to be declared as waste)
- Uranium stocks from enrichment and fuel fabrication activities (yet to be declared waste)
- Irradiated fuel and nuclear materials (yet to be declared waste) from the UK defense program.

Information below provides an update on the process to identify a suitable site and a willing community to host a GDF in the UK.

3.1.2 Siting Process

Radioactive waste management is a devolved matter in the UK. Therefore, the Welsh government, Northern Ireland Executive, and Scottish government each have responsibility for this issue in their respective countries. England, Wales, and Northern Ireland have adopted the policy of geological disposal (DBEIS, 2018; The Welsh Government, 2019) and note that future policy decisions regarding geological disposal in Northern Ireland would be a matter for the Northern Ireland Executive, which is currently suspended. While the Scottish government remains committed to responsibly addressing Scotland's radioactive waste, its policy is that the long-term management of higher activity radioactive waste should be in near-surface facilities, and those facilities should be located as near as possible to the sites where the waste is produced (The Scottish Government, 2011; 2016).

The safety and security of a GDF is paramount, and the RWM is responsible for demonstrating the high standards of safety, security, and environmental protection required by the Environment Agency and Office for Nuclear Regulation. The process of identifying and selecting a suitable site will be based on detailed technical work and could take approximately 15–20 years. Therefore, the English and Welsh governments recently launched policy frameworks for working in partnership with willing communities to build trust and understanding of the GDF development throughout this process before any commitment to host a GDF is required. The frameworks are similar and involve establishing working partnerships with communities over the duration of the technical and characterization activities and in the long term through the construction and operational phases of the facility. Support, such as scientific and technical information and advice or input from independent experts, will be available to communities, and funding will be provided to support access to these resources. Community investment funding will also be available up to £1 million per year rising to £2.5 million per year for communities that progress to the stage where deep borehole investigations are undertaken.

The overall siting process is summarized in Figure 3-1, and detailed guidance for communities seeking additional information on the GDF program has also been developed by the RWM.

3.1.3 National Geological Screening

The host geological environment in which a GDF will be built will provide an important element of the multibarrier system, and the UK has a range of potentially suitable geological environments for a GDF. Previous public consultation revealed a strong desire for considering geology in the early stages as a way of building public understanding and confidence in the siting process for a GDF. The RWM has, therefore, undertaken a national geological screening exercise across England, Wales, and Northern Ireland to publish high-level information that is relevant to the safety of a GDF.

The geological reconnaissance is not expected to determine if sites are definitely suitable for a GDF; rather, the results of the national screening exercise provide geological information that may be of potential interest to the RWM across England, Wales, and Northern Ireland. The following five features have been considered:

- Rock type
- Rock structure – the locations of major faults and highly folded zones

- Groundwater – including the presence of aquifers and the geological features and rock types that may indicate the separation of deep and shallow groundwater systems
- Natural processes – the distribution of earthquakes and extent of past glaciations
- Resources – the locations of existing deep mines, intensely deep-drilled areas, and the potential for future exploration or exploitation of resources.

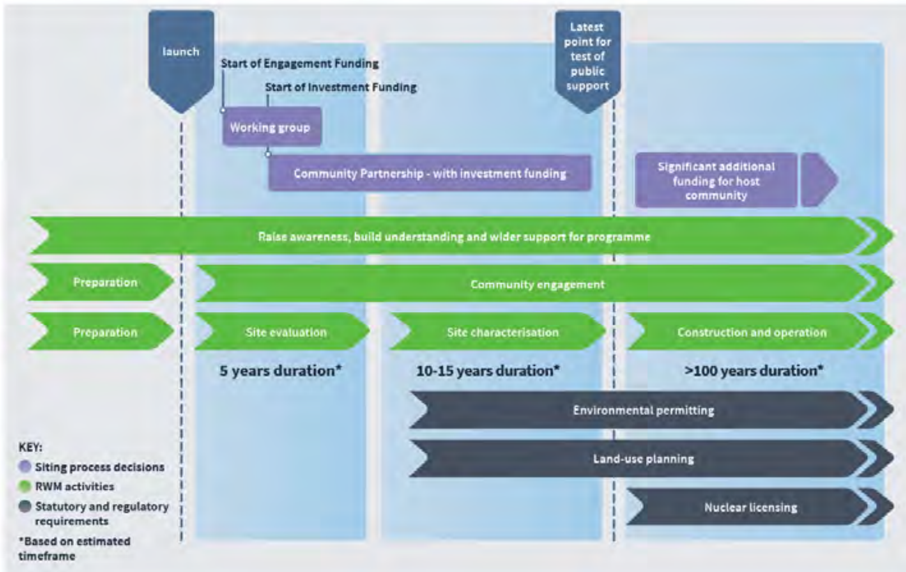


Figure 3-1. Timeline for the Siting Process.

The RWM has published this information in a variety of formats for each of the geological regions of England, Wales, and Northern Ireland. Information includes a series of documents that describes the geological features stated previously and considers their relevance to the safety of a GDF. The documents are published in various levels of detail so that the information is accessible to a greater range of audiences and are accompanied by maps and short video clips that summarize the conclusions for different regions.

An emphasis is made that no national exercise will be able to definitively rule all areas as either suitable or unsuitable, which is why the national geological screening exercise has not sought to target individual sites for development. Rather, existing, national-level information is available in an accessible form to support engagement with communities across the country on early questions regarding their potential to host a GDF safely.

3.1.4 Summary

The RWM is the dedicated waste-management organization that is responsible for implementing government policy on developing a GDF and engaging directly with communities to raise awareness and build relationships. The process of site identification, based on detailed technical work, will require a significant amount of time. Government policy frameworks are established to work in partnership with communities over the duration of the technical and characterization activities. Throughout the construction and operational phases, investment funding will support the community to realize the benefits that a nationally significant infrastructure project—such as a GDF—could bring to their area.

The RWM has undertaken a national geological screening exercise across England, Wales, and Northern Ireland to publish high-level information that is relevant to the safety of a GDF. This information is accessible in a layered manner that is designed for people of all knowledge levels to seek answers to questions and is publicly available via RWM's web portal in a variety of presentation formats.

3.2 The Netherlands Process

3.2.1 Introduction

Radioactive substances and ionizing radiation are widely used and generate radioactive waste. The current policy in the Netherlands is that radioactive waste is collected, treated, and stored above ground by the COVRA. Following interim storage of at least 100 years, all of the radioactive waste in the Netherlands is intended for disposal in a single deep GDF in 2130 (Verhoef et al., 2017). The goal of geologic disposal is to isolate radioactive waste from our living environment so that future generations are not exposed to ionizing radiation from the waste.

During the interim storage period, the geological disposal option (either in a rock-salt or clay formation) must be prepared financially, socially, and technically. This summary, based on the presentation given at the workshop, describes a new potential disposal concept in the Zechstein domal rock salt as a research guide. The Onderzoeks Programma Eindberging Radioactief Afval (OPERA) is the Dutch research program on geological disposal of radioactive waste. Using the OPERA initial safety case (Verhoef et al., 2017), examples of research areas to further develop this new disposal concept are presented as well as a new research program.

3.2.2 Disposal Concept for Domal Rock Salt

In the Netherlands, radioactive waste is classified as low- and intermediate-level radioactive waste (LILW), technically enhanced naturally occurring radioactive materials (TENORM), and nonheat-generating high-level waste (HLW). LILW arises from operating and decommissioning nuclear-power plants and related facilities and from activities using radioactive materials or radioisotopes in medicine, industry, and research. The majority of LILW packages can be handled and transferred directly to a GDF without significant additional shielding. In total, 152,000 drums (45,000 m^3) of LILW are expected for disposal. TENORM waste originates from ores (and other raw materials) that are generated in processing industries that may have high natural radioactivity concentrations. TENORM includes radioactive waste that originates from the URENCO uranium-enrichment facility. Following repackaging and conditioning, 9,060 Konrad Type II containers (40,000 m^3) are expected for disposal in the Netherlands. The HLW consists partly of heat-generating waste (e.g., vitrified waste from reprocessed spent fuel from the nuclear-power plants in Borssele and Dodewaard, spent fuel from the research reactors, and spent uranium targets from molybdenum production), and nonheat-generating waste (e.g., hulls and ends from fuel assemblies that have been disassembled and cut into smaller fragments during reprocessing). Following conditioning, 533 super-containers of heat-generating HLW and 700 super-containers of nonheat-generating HLW are destined for disposal.

All radioactive waste will be disposed in a single, deep GDF in the Netherlands; thus, no separate facilities for LILW and HLW are envisaged. In this disposal concept for Zechstein domal rock salt, the deep repository consists of two levels: a disposal section for LILW-TENORM (upper level) and a separate section for HLW (lower level). The LILW-TENORM section of the repository will be located at a depth of 750 m in the center of a salt dome, and the HLW section will be located at a depth of 800 m (approximately 50 m lower). The depth (> 750 m) of the repository is currently determined by the requirement that the depth of the GDF be sufficient to protect the facility from the effects of geomorphological processes (e.g., subglacial channels). New insights could potentially change this requirement.

The HLW section will cover an area of approximately 420 × 390 m. Depending on how the waste will be disposed, between 42 (Figure 3-2(b) disposal within galleries) and 60 (Figure 3-2(c) vertical disposal holes) galleries will be needed. Disposal in the gallery is the preferred option because emplacement and retrievability, which is a requirement in the Netherlands, would be easier and simpler. In the HLW section of the GDF, mining and waste emplacement will alternate. A disposal gallery will be mined first, followed by emplacing waste within the newly mined gallery. A new disposal gallery will then be mined, and the previous disposal gallery and part of the ventilation shaft will be backfilled. In this manner, the repository can easily be extended in a modular way, similar to the modular-build-and-close concepts discussed in these workshops. After waste emplacement, only the main shaft remains open until the final closure of the GDF to ensure that HLW is retrievable.

The LILW-TENORM section of the repository (at a depth of 750 m and built after HLW emplacement) will have a width and length of approximately 420 and 580 m, respectively (Figure 3-3). The different LILW-TENORM waste types will be separated into groups and emplaced in separate sections of the GDF to prevent potential influence of products generated by degradation of waste matrices and packages. Each disposal room will have a length of 115 m, a width of 10 m, and a height of 4.5 m; in total, 36 disposal rooms are required (Figure 3-3). Following waste emplacement by (heavy) forklift trucks, the LILW-TENORM section will remain open until the final closure of the GDF to ensure that LILW-TENORM is retrievable.

3.2.3 Further Research

The initial safety case (Verhoef et al., 2017) is an overall summary of the achievements of OPERA, which is the latest national program on geological disposal in the Netherlands. Within the initial safety case, current knowledge on performance and evolution of different compartments (e.g., repository, host rock, overburden, and the biosphere) of a GDF was assessed. Based on this assessment, key topics for future research were prioritized and are illustrated in Figure 3-4. For a GDF in rock salt, the host rock has been given the highest priority followed by the engineered barrier system and society, surrounding rock formations, and biosphere.

Based on the repository concept discussed in the previous section, specific research questions were identified. For example, subrosion needs to be addressed for disposal concepts in a salt dome. Subrosion can be described as groundwater dissolution and erosion that could possibly disturb the GDF. However, the subrosion rates dataset in the Netherlands is small and the uncertainties are large. Other geological features that warrant attention include present-day depth and distribution of subglacial channels (also known as tunnel valleys or buried valleys) as well as their formational genesis.

To address these research questions and expand the knowledge on geological disposal, COVRA is currently working on a new long-term, continuous research program, as shown schematically in Figure 3-5. The first 10 years (i.e., 2020–2030) are dedicated to expanding knowledge on a repository in clay and salt. The results of this research (in 2030) will be an initial safety case similar to the OPERA initial safety case (Verhoef et al., 2017) for salt. In the following 20 years (between 2030–2050), knowledge on a repository in clay and salt will be further expanded and the end results will be reported in safety cases.

3.2.4 Summary

To expand the knowledge on a repository in clay and salt, COVRA is currently working on a new long-term, continuous research program. Likewise, a new potential disposal concept in Zechstein domal rock salt was developed to guide research on salt. In this new disposal concept, a two-level repository is envisaged to dedicate separate levels for LILW-TENORM and HLW. The upper level of the GDF is for LILW-TENORM, and the lower level will be used for nonheat-generating HLW where disposal options will be evaluated.

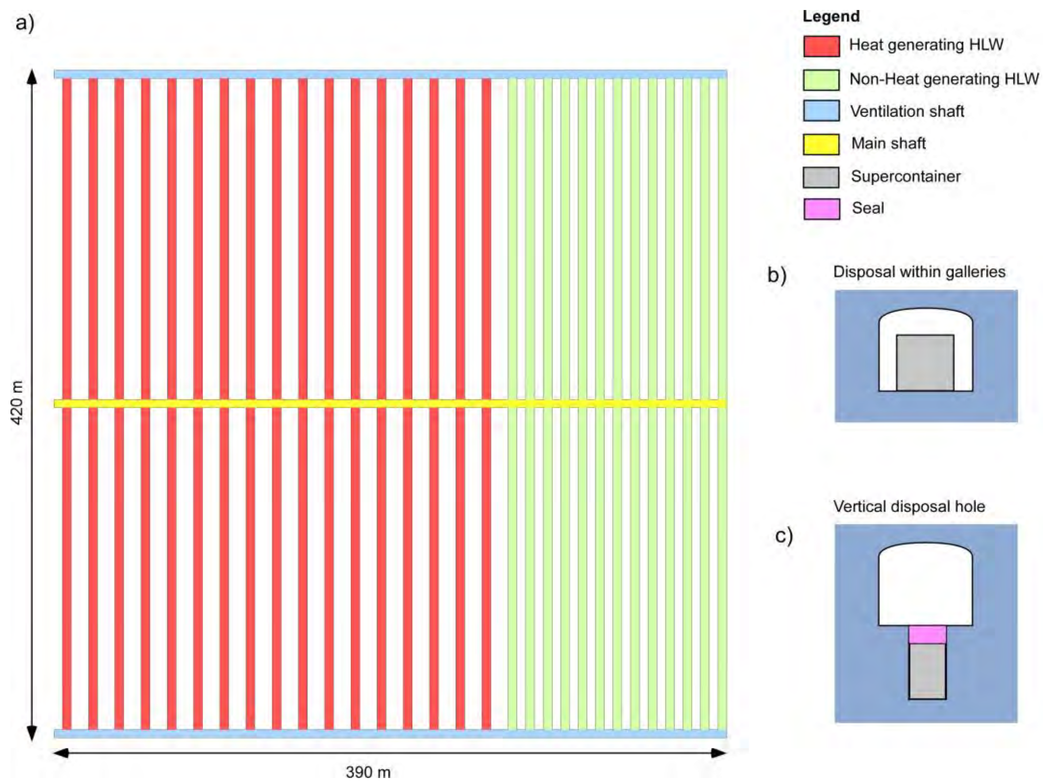


Figure 3-2. The High-Level Waste Lower-Level Section of the Repository.

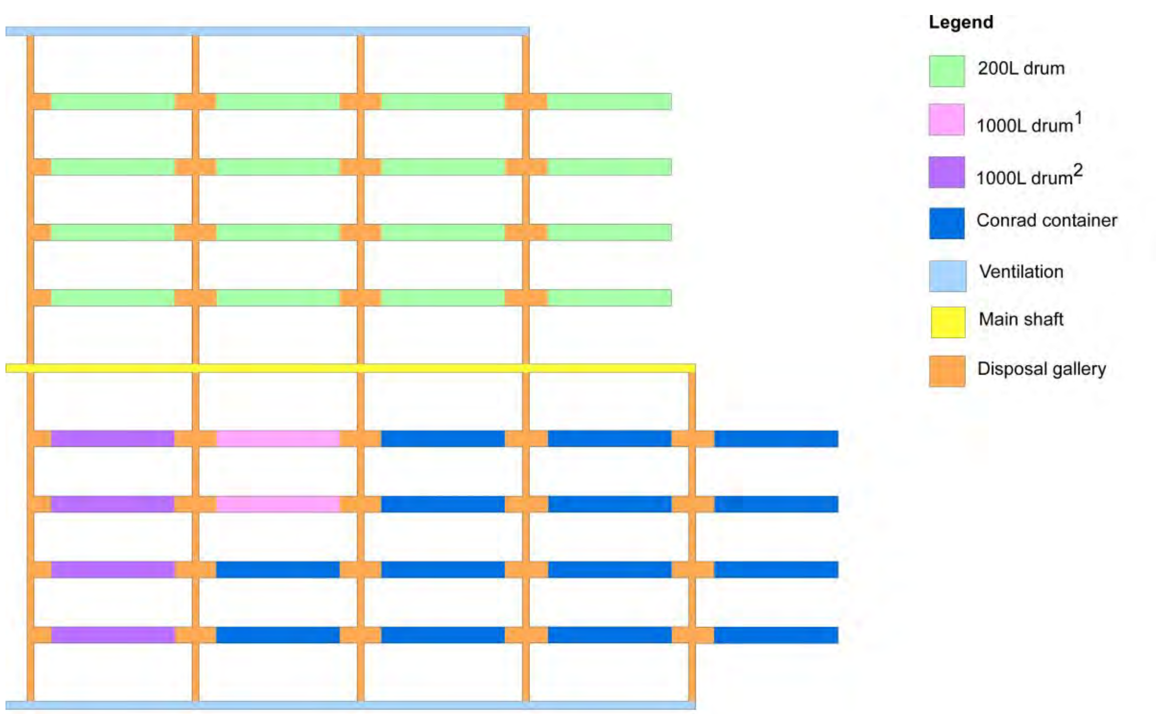


Figure 3-3. The LILW-TENORM Upper-Level Section of the Repository.

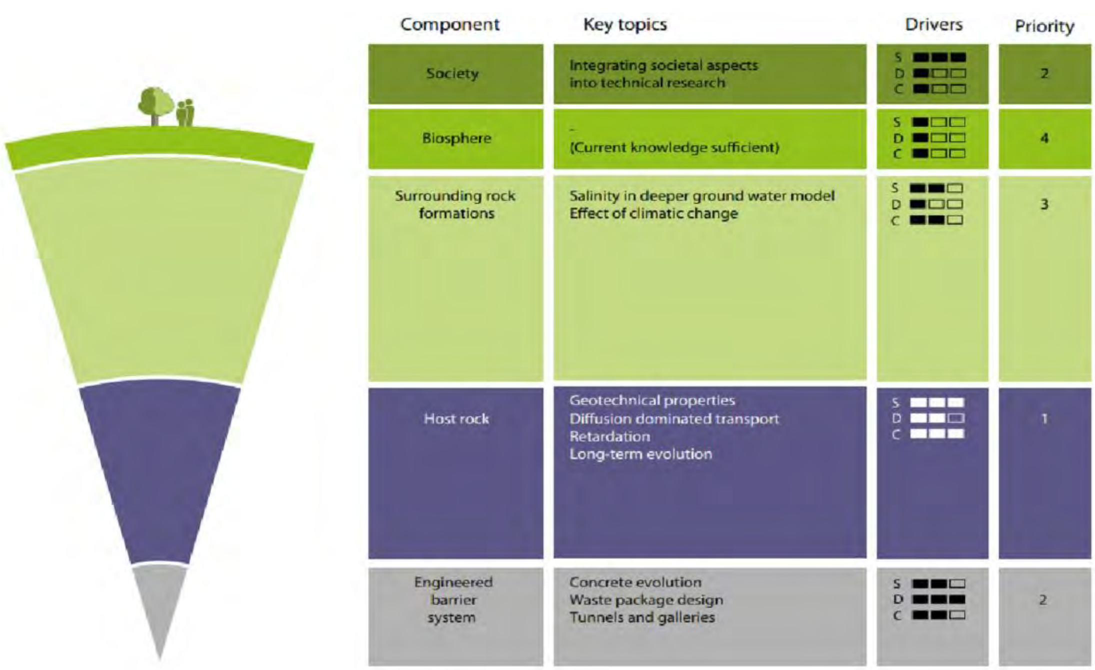


Figure 3-4. Research Focus and Priorities.

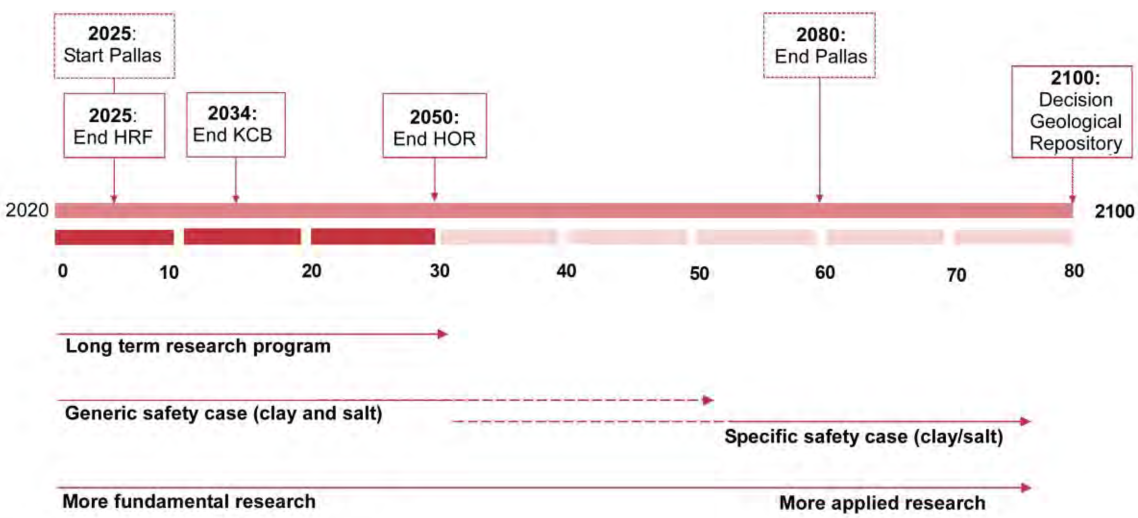


Figure 3-5. Outline of the New Research Program in the Netherlands.

3.3 German Process

3.3.1 Introduction

BGE is a state-owned company that was established in September 2016 following the Act on the Organizational Restructuring in the Field of Radioactive Waste Storage of July 26, 2016. The Repository Site Selection Act (StandAG, 2017) was enacted on July 27, 2013, and defines the site selection procedure with a goal of ensuring the best possible safety measures for storing HLW in Germany over a period of 1 million years. This process is meant to be participatory, transparent, learning, and self-questioning, as well as based on scientific evidence. The selection procedure consists of three phases and should be completed by 2031. After each phase, concluding decisions are to be made by the Bundestag and the Bundesrat (The German federal parliament and upper house of the German political system, respectively).

As shown in Figure 3-6, the responsibilities within the procedure are clearly defined. The BGE is the project developer and implements the site selection procedure. The Federal Office for the Safety of Nuclear Waste Management (BfE) is the legal supervisor and will organize public participation. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) is responsible for the technical and legal supervision of the BfE. The BMU has the overall political responsibility for permanent storage of radioactive material and supervises the BGE in the role of a shareholder. The ministry is supported by several advisory panels, and these panels will review whether or not the site selection process is conducted according to the requirements and criteria of the StandAG. The independent and pluralist National Advisory Board (NBG) accompanies the site selection process in a public service-oriented manner. The NBG consists of six public figures who are appointed by the Bundestag and three citizens who are nominated by a participation procedure. Other stakeholders of the site selection procedure include responsible municipal associations, civic oversight groups, regional authorities, local authorities, and public-interest parties.

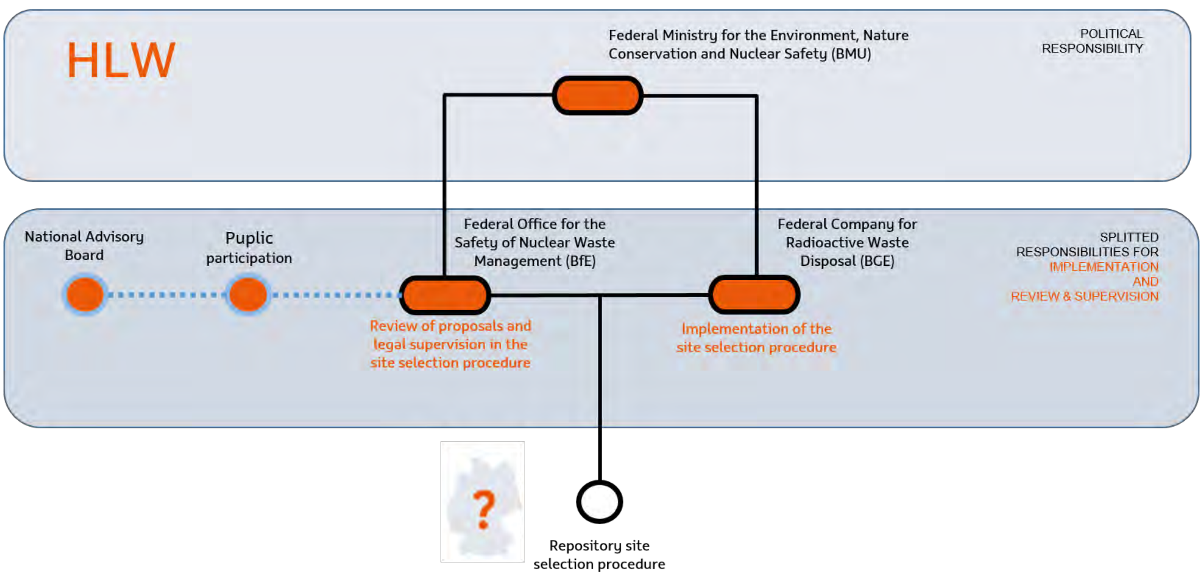


Figure 3-6. Responsibilities in the Site Selection Procedure.

3.3.2 Site Selection Procedure

The site selection procedure consists of three phases and several steps, which will gradually reduce the number of potential sites (see Figure 3-7). Three host-rock types are considered: rock salt, claystone, and crystalline rock. After each phase, the proposals by the BGE are examined by the BfE. On this premise, the BMU informs the Bundestag and the Bundesrat of further steps proposed in each case. The respective phases end with a federal law. The three phases are explained in the following text.

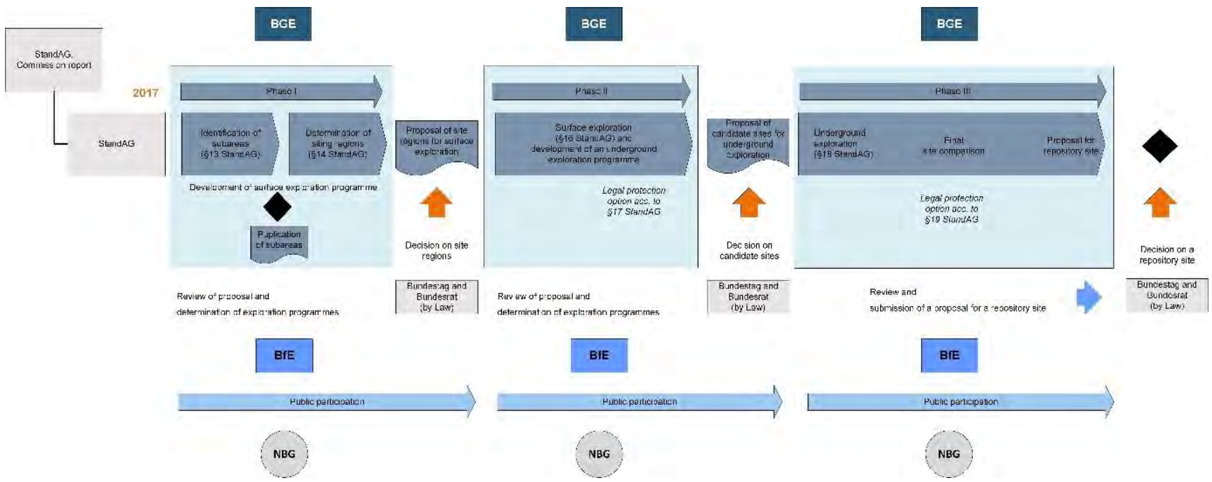


Figure 3-7. Site Selection Procedure in Germany.

Phase 1: Identification of Subareas and Determination of Regions for Surface Exploration

The BGE collects geoscientific data from the federal and regional authorities, processes the data, and applies the exclusion criteria (see Figure 3-8). Regions that fulfill the minimum requirements are then identified. Based on geoscientific assessment criteria, the BGE evaluates the remaining regions with respect to their overall geological suitability.

Exclusion Criteria

- Mining activities or drillholes
- Active fault zones
- Quaternary volcanism exists or volcanic activities are expected
- Local seismic activity is higher than in earthquake zone 1 (DIN EN1998-1/NA 2011-01)
- Large-scale uplift of more than 1 millimeter per year over 1 million years
- Young groundwater occurs in the containment providing rock zone (CRZ) or emplacement area

Minimum Requirements

- Low permeability
- Minimal thickness of 100 meter (exception crystalline rock)
- Top surface of the CRZ has to be at least 300 meter below terrain surface
- Suitable extension in area and heights
- Preservation of barrier effect for 1 million years

Geoscientific Assessment Criteria

- Transport of groundwater
- Configuration of rock complex
- Spatial characterization
- Predictability
- Valuation on favorable rock-mechanicas properties and tendency of creating pathways for fluids
- Further safety-relevant properties (e.g., gas production, temperature compatibility, ability of retention of radionuclides in rocks of the effective containment zone, hydrochemical conditions, and overburden)

Figure 3-8. Exclusion Criteria, Minimum Requirements, and Geoscientific Assessment Criteria.

The BGE determines possible subareas, which will be discussed in a conference convened by the BfE with citizens and community representatives from these areas as well as technical experts. Representative preliminary safety investigations are to be carried out in the regions where potential sites are located. The

BGE develops site recommendations where a surface exploration is to take place and submits these recommendations to the BfE. The Bundestag then selects sites where a surface exploration will occur.

Phase 2: Surface Exploration and Proposal for Underground Exploration

The BGE explores the location and conducts advanced preliminary safety investigations and a socioeconomic potential analysis. The BGE reapplies the legally defined criteria and requirements to determine the sites for underground exploration. Exploratory programs and test criteria are developed for the underground exploration that are verified by the BfE. The Bundestag then selects sites where underground exploration will occur.

Phase 3: Underground Exploration, Site Proposal, and Decision

The BGE explores the sites underground, applies the test criteria set for this survey, and conducts extensive preliminary safety investigations for the operating phase and the phase after closure of a possible repository. The results are then provided to the BfE, which carries out an Environmental Impact Assessment. The BGE reapplies the statutory criteria and requirements to determine the locations and, based on a comparative assessment, develops a location proposal for the repository that includes a technical comparison of at least two locations.

At the end of the site selection procedure and based on the findings, the BfE will develop a proposal for a repository site, which will be forwarded to the BMU. The Bundestag and Bundesrat will develop the bill that defines the repository site.

4 MODELING CHALLENGES

The Modeling Challenges topical session was divided into two areas. The first part of the session focused on modeling geomechanical evolution of salt repositories, and the second part of the session centered on brine- and gas-migration modeling in salt.

4.1 Geomechanical Modeling Challenges

Underground structures in salt do not remain static; they continually evolve until the salt reaches a lithostatic stress distribution. This evolution can impact operational safety and repository design, compact geotechnical barriers, reduce the volume available for gas storage, and help isolate waste from the biosphere. Predicting these effects demands scientifically sound models based on high-quality experimental data. The presentations covered the topics of thermomechanical behavior of intact salt, shearing of bedding interfaces, and crushed-salt reconsolidation. A presentation on micromechanical processes in crushed and intact salt was planned but was ultimately canceled because of an unexpected loss of experimental data.

Dr. Andreas Hampel (Hampel Consulting) provided a status update on the Verbundprojekt: Weiterentwicklung und Qualifizierung der gebirgsmechanischen Modellierung für die HAW-Endlagerung im Steinsalz (WEIMOS) project. The WEIMOS project seeks to improve constitutive models for the deformation, fracture, and healing of intact salt through careful laboratory experiments and benchmarking models against in situ tests. Dr. Hampel began by discussing low-shear-stress creep tests that are currently underway and how important sample conditioning is to laboratory salt testing (see Chapter 7). He then described the WEIMOS' efforts to understand how dilatancy reduction (i.e., microcrack healing) depends on stress state and temperature. The study revealed that previous healing tests produced inconclusive results because of difficulties with precisely measuring the volume change. Future healing tests will be performed on new high-precision test equipment. Dr. Hampel mentioned future plans to study the tensile behavior of predamaged salt and plans for two "Virtual Demonstrator" simulations. These virtual demonstrations of a drift seal and tensile failure around an empty drift will showcase and benchmark new modeling capabilities.

Mr. Steve Sobolik (SNL) followed Dr. Hampel by describing another important laboratory testing regime identified by the WEIMOS project: characterizing and modeling the mechanical behavior of bedding-plane interfaces. RESPEC performed a series of shear tests on salt/polyhalite, salt/anhydrite, and salt/clay interfaces that were extracted from a potash mine near the WIPP site. Surprisingly, the clay seam (i.e., salt/clay interface) cohesion and friction angle were nearly the same as pure salt without any interfaces. The clay seams were not believed to be representative of clay seams from WIPP, so Mr. Sobolik initiated efforts to extract actual WIPP clay seams. Meanwhile, preliminary tests on artificially manufactured clay seams measured a cohesion and friction angle that was roughly one-half that of pure salt.

Mr. Christian Lerch (BGE TEC) reviewed the various thermal, hydraulic, and mechanical constitutive models used for crushed salt. The review was commissioned as part of a project to complete the experimental database and improve existing models, which endeavors to improve predictions of crushed-salt reconsolidation. The talk qualitatively addressed the coupling between thermal, hydrological, and mechanical processes; discussed the important subprocesses within each process; and briefly presented how each model attempts to capture the relevant processes. Mr. Lerch concluded that hydrological and mechanical processes require further attention, especially at consolidation levels close to total compaction representative of intact salt.

Mr. Brett Belzer (RESPEC) presented geomechanical simulations to help design the WIPP westward-expansion main access drifts. A yield-pillar design for the new drifts was motivated by citing the ground-control issues in the 30-plus-year-old access drifts at WIPP. This design concept uses slender, yielding, pillars between the main access drifts to transfer the vertical load to wider abutment pillars. Mr. Belzer described efforts to validate the geomechanical model that he subsequently used to analyze the design concepts. Good agreement was found between the predicted RESPEC salt dilatation factor of safety and the stability observations in existing WIPP access drifts. When applied to the new yield-pillar access drift designs, the model predicted substantially fewer ground-control problems than observed in the existing WIPP access drifts.

Geomechanical modeling is an evolving art. Since Project Salt Vault, geomechanics practitioners have endeavored to predict large-scale behavior associated with nuclear-waste disposal. To undertake such modeling, many contributing elements are needed and their implementation is interrelated. A constitutive model, whether reconsolidating granular salt or solid, natural salt, has multiple physical/mechanical/chemical mechanisms. Sample treatment and pretest conditioning are fundamental to quality laboratory results. Through collaborative efforts, test techniques have been improved and interpretation has become more exacting. Evaluating deformation processes requires precise experimental methods, impartial data analysis, and microscopic observations, if possible. Ultimately, micromechanical deformation processes are responsible for observed behavior. As noted by Mr. Belzer, geometrical ratios of entries and pillars also create mechanical responses by stress redistribution in a creeping medium. The challenges are not new, but the tools for addressing them improve every day to the mutual benefit of these investigations.

4.2 Brine- and Gas-Migration Modeling Challenges

Brine and gas migration are important for their role in radionuclide migration in PA predictions, the enhancement of metal corrosion in a repository, and their impacts on near-field processes in a heat-generating waste repository. The presentations covered the topics of coupled thermal, hydrological, and mechanical (THM) benchmarking; two-phase flow in long-term PA calculations in repository mine workings; single-phase, density-dependent groundwater flow through formations adjacent to a salt formation; and an update on the brine-availability heater test in salt at WIPP.

Dr. Michael Rutenberg (Technische Universität Clausthal [TUC]) gave an introduction to and update on the status of the BenVaSim benchmarking project. This project is a collaboration between TUC, BGR, the Swiss Federal Nuclear Safety Inspectorate, GRS, Lawrence Berkeley National Laboratory (LBNL), and the Swiss Seismological Service. The project compares THM models to each other and to analytical solutions. The first benchmark was a single-phase flow problem, and the second example was a simplified two-phase flow problem. Both test cases illustrated Biot poroelastic coupling. Dr. Rutenberg demonstrated that subtle issues exist with some of the simulators that took significant time to debug and, in general, the benchmarking exercise is a success.

Mr. Guido Bracke (GRS) discussed a long-term PA including a two-phase flow modeling exercise that was conducted in the workings at the Morsleben repository (Endlager für radioaktive Abfälle Morsleben [ERAM]) in Germany. Three models were presented with increasing levels of complexity and realism in their representation of mine geometry. The model results showed the impacts of brine and gas flow, including liquid and gas radionuclides, on the PA of the facility. While the three predictions were different in details related to the magnitude of fluxes through time, they generally gave similar answers and illustrated that some simplification of the flow system is justified.

Dr. Jens Wolf (GRS) showed basin-scale groundwater flow simulations performed using the GRS-developed d^3f variable-density flow model. The numerical model implements a historic basin-scale geological and hydrological model of the region surrounding WIPP. From 14,000 years in the past to 10,000 years into the future, a comparison is being made between d^3f, the previous results from WIPP, and PFLOTRAN. The basin-scale flow problem is a difficult numerical exercise because of the geological and hydrological heterogeneity, large areal extent of the model domain, thin vertical layers in the basin, and movement of the water table during the long simulation period.

Dr. Kris Kuhlman (SNL) provided an update on the brine-availability test in salt, which is an ongoing borehole heater test with brine migration observations at WIPP. The test is a collaboration between SNL, Los Alamos National Laboratory (LANL), LBNL, and the WIPP facility. Two patterns of horizontal boreholes will compare liquid samples, gas samples, and geophysical responses of heated and unheated salt. The boreholes have been drilled and testing will soon be underway. The goal of this project is to better understand the three primary sources of water in evaporite deposits (i.e., intergranular brine, intragranular brine, and hydrous minerals) and how they differentially respond to changes in pressure, temperature, and deformation. Geophysical observations will include electrical resistivity tomography, acoustic emissions, fiber-optic distributed temperature and strain observations, and ultrasonic travel-time tomography. Building on the long history of underground testing in salt, the team intends to rebuild some testing capabilities and participate as a task in the 2020–2023 round of DEvelopment of COupled models and their VALidation against EXperiments (DECOVALEX) model comparison.

The presentations from this session were on a wide range of topics relevant to brine migration through and near salt deposits, but they share the theme that brine migration requires careful consideration. Predicting brine migration in these scenarios is complicated by hydromechanical coupling, two-phase flow, density-dependent flow, and flow through the evolving damaged rock zone. Geochemical effects (beyond simply dissolving and precipitating halite) can also be significant but are often neglected to simplify the situation.

5 NATURAL CLOSURE OF SALT OPENINGS

5.1 Introduction

An inherent advantage of a geological repository in salt is that salt creep will cause openings to close over time and eventually encapsulate the waste. In the far-field of the repository, classic isochoric salt creep occurs without damage, but any damaged salt surrounding excavations will naturally heal over time as stress equilibrium is reestablished. However, this behavior has not been incorporated into the PA for WIPP, which assumes mostly static conditions over the regulatory period of 10,000 years. Large areas of WIPP were also recently abandoned as open rooms without a PCS being installed. Consequently, questions have been raised regarding the evolution of these areas during the assessment period and if PA assumptions should be revisited.

A breakout session titled "Natural Closure of Salt Openings" was held at the 10th US/German Workshop on Salt Repository Research, Design, and Operation. The breakout session included presentations by the following:

1. Mr. Tom Peake (US EPA) outlined the regulatory framework for the importance of understanding natural evolution of openings in salt.
2. Dr. Evan Keffeler and Dr. Frank Hansen (RESPEC) provided examples of the behavior and mechanisms that drive closure and rock damage during the operational period of salt excavations.
3. Dr. Till Popp (IfG) discussed examples of postoperational observations concerning room closure in commercial salt mines and salt reconsolidation.

The presentations are provided in Appendix D, and this chapter briefly summarizes the information and conclusions provided during the breakout session.

5.2 United States Regulatory Perspective

The WIPP PA assumes mostly static conditions over the 10,000-year regulatory period. For example, the PA assumes that rooms left open after facility closure will have a constant permeability that is ten orders of magnitude greater than intact salt for 10,000 years; this assumption was intended to be the upper bound of possible conditions. However, industry analogues and studies of reconsolidating salt backfill indicate that the porosity and permeability of the open rooms will reduce over time and eventually become equal to the native salt that surrounds the facility.

Initial conditions for the PA have changed. WIPP closure has been delayed by decades compared to early projections, and the anticipated open volume at closure has increased. No plans are currently in place for backfilling many of these open areas. Likewise, the long-term closure rates and the physical condition of open areas at the time the facility closes are uncertain. Because of these uncertainties, several questions have been raised relating to the PA; specifically:

1. What are the long-term closure rates and healing potential of open drifts where ground falls have occurred?
2. What initial conditions should be assumed for ground conditions and the role of ground support at the start of the performance period?
3. After the facility's closure, when will the porosity and permeability of open rooms approach intact halite?
4. How much will the open rooms close before gas pressure becomes significant?
5. How should the evolution of the underground be modeled in the PA?

With the increasing amount of abandoned open excavations as compared to the early 1990s, these uncertainties may have a greater impact on the PA.

5.3 Operational Time Frame

5.3.1 Mechanisms

After a conventional excavation is created in salt, two long-term phenomena occur—creep and near-excavation (near-field) damage. Far-field creep deformation usually occurs at constant volume (i.e., isochoric) in response to shear stress; the salt will continue to creep as long as shear stress exists around the excavation. Damage occurs when the shear stress at a given level of confinement exceeds the dilation or brittle (short-term) strength criteria. Near-field damage is manifested as the formation of an excavation damage zone (i.e., damaged rock zone). Within the excavation damage zone, fractures are oriented preferentially along the excavation axis, which creates interconnected porosity, and the permeability consequently increases rapidly with increasing porosity.

Closure (i.e., convergence) of the excavation is a combination of the far-field salt creep and near-field rock damage deformation processes. The creep rates, damage manifestation, and damage accumulation rate depend on the geology, material properties of the rock, stress conditions (depth), and excavation geometry with respect to depth. Convergence rates vary widely in salt mines and are time-dependent. Except for cases of gross instability, rates are greatest immediately after the excavation is created (usually between 0.1 and 1 percent per day) and decay with time. For example, steady-state, roof-to-floor convergence rates at WIPP vary from 50 to 150 mm/year (rates can be greater in areas with poor roof or floor conditions), while the convergence rates in the Morsleben repository are only 1 to 2 mm/year.

Creep deformation is a three-dimensional process, and room convergence occurs in both the horizontal and vertical directions. Deformations measured as excavation convergence are associated with surface subsidence, whereby the volumes of both processes will be equal in the long term. In room and pillar facilities developed in salt, the roof and floor beams shorten laterally and thicken vertically while the pillars shorten vertically and expand laterally. Depending on geology, stress, and mine design (especially in bedded salt formations), pillar expansion can induce large lateral compressive stresses in the immediate roof and floor, which drive roof and floor instability commonly observed and mitigated during operations.

The type of damage that develops in the roof and floor largely depends on the geological setting of the excavation. If the immediate roof or floor comprise massive salt or massive sedimentary interbeds (e.g., dolomite, shale, or anhydrite), the primary manifestation of roof or floor damage is the development of low-angle shear fractures. The low-angle shear fractures will usually propagate until intersecting a plane of weakness, such as a bedding plane or clay seam. If the immediate roof or floor is laminated salt or rock, separations will form at the weak partings, and with continued lateral expansion of the pillars, the thin beams in the immediate roof and/or floor eventually buckle.

Rib damage typically manifests as dilated (cloudy) salt, scale, and rib slabs. Over time, the damaged salt sloughs off the pillars, and the pillars will eventually develop a stable hourglass shape, as shown in Figure 5-1. This hourglass shape is consistent with the damage profile predicted by numerical structural simulations and laboratory analogue tests on uniaxially loaded salt specimens.

5.3.2 Case History

WIPP provides examples of damage types that occur in massive versus laminated salt. The lower (original design) horizon of WIPP is characterized by massive salt in the immediate roof but relatively thin salt overlying polyhalite in the floor. In the lower horizon, roof damage manifests as a low-angle shear fracture that initially develops off one rib and grows until intersecting Clay G, which is present approximately 2 to 3 m above the mine roof. After supplemental ground control is installed, a second low-angle shear fracture develops off the other rib, as depicted in Figure 5-2. In areas where shear fractures became well developed on one rib but supplemental support was not installed, an extensional failure forms above the other rib, which eventually leads to a roof fall. When the floor salt is thin, floor damage usually manifests as delamination along the polyhalite contact, and the thin floor beam eventually buckles up into the room, as shown in Figure 5-3.

Figure 5-1. Hourglass-Shaped Stable Pillar at the Teutschenthal Mine (Photograph courtesy of Dr. Staubert).

Figure 5-2. Low-Angle Shear Fractures Exposed in a Brow Between the Lower and Upper Horizons at the Waste Isolation Pilot Plant.

In the upper horizon where the roof was mined to Clay G, the immediate roof is salt with thin anhydrite laminations approximately every 0.5 m. After the room is mined, the roof salt delaminates along the anhydrite stringers, as shown in Figure 5-4. With continued horizontal room convergence, the thin salt beams buckle down into the room. When the floor salt is massive, low-angle shear fractures develop off one or both ribs, as shown in Figure 5-5. The shear fractures grow until they intersect a clay seam or lithological contact (e.g., with polyhalite). At WIPP, visible rib damage typically extends up to 1 m into the pillars. Rib damage manifests as scale, pillar sloughing (shown in Figure 5-6), and salt dilation.

Figure 5-3. Buckling of Thin Floor Salt at the Waste Isolation Pilot Plant.

Figure 5-4. Delamination of Roof Salt Along an Anhydrite Stringer at the Waste Isolation Pilot Plant.

5.4 Postoperational Time Frame

5.4.1 Mechanisms

Industry experience provides a basis for understanding the evolution of openings in salt after an area has been abandoned. After ground-control activities have been suspended, the roof conditions will deteriorate and the roof will eventually fall. The timing, progression, severity, and geometry of the roof falls depends on the mine design, in situ stress, and geology. The floor will expand and potentially buckle into the

Figure 5-5. Low-Angle Shear Fracture in the Massive Floor Salt at the Waste Isolation Pilot Plant.

Figure 5-6. Pillar Sloughing at the Waste Isolation Pilot Plant.

room, but again, the timing, progression, and geometry of floor failure will depend on the mine design, in situ stress, and geology. Similarly, scale will continue to form on the ribs and fall into the room. The ground falls and floor heaves tend to be episodic. A ground fall will typically be followed by a period of quasi-stability. During this period, stresses redistribute further into the surrounding rock, which may cause further damage; if the damage is severe enough, another ground fall may occur. An example of a room filled with roof debris and floor heave at a commercial North American salt mine is shown in Figure 5-7.

Figure 5-7. Example of a Room Filled by Roof Fall Debris and Floor Heave in a Commercial Salt Mine in North America (Room Was Mined 35 Feet [10.7 Meters] Wide).

The failed material that accumulates in the room has bulked significantly compared to intact halite and will have substantial porosity and permeability. After sufficient room closure, the blocks of broken salt and any interbedded rock will break down into smaller pieces. Salt-reconsolidation processes will then begin to dominate material behavior within the excavation. The reconsolidating rubble will also apply a back stress to the excavation surfaces, which will continually reduce the shear stresses around the excavation, thereby reducing the volumetric closure rate of the room for periods up to thousands of years, depending on the local conditions. This back stress also promotes healing within the damaged rock zone.

As back stress develops, salt-reconsolidation processes dominate, which have been extensively studied as part of the salt backfill closure system concept. Initially, blocks of salt debris will break down via brittle fracture process, the blocks will reorient, and porosity will reduce. As grain-to-grain contact increases, pressure solution-redeposition occurs along with crystal-plastic deformation. These processes isolate pore spaces, which results in substantially reduced permeability even with corresponding small reductions in porosity (Figure 5-8). Industry examples of backfilled or fully converged rooms in salt and potash mines show that the salt or salt backfill will encapsulate any nonsalt debris within the room (i.e., pieces of nonsalt interbeds, cabling, or rock bolts). Eventually, the rubble in the room and the damaged rock zone will have reconsolidated to the point of becoming effectively impermeable.

While the general phenomenon of the natural evolution of openings in salt is understood, the timing currently cannot be predicted with much confidence. The time to major evolutionary milestones of an unbackfilled opening in salt undoubtedly depends on the mine design, in situ stress, and geology.

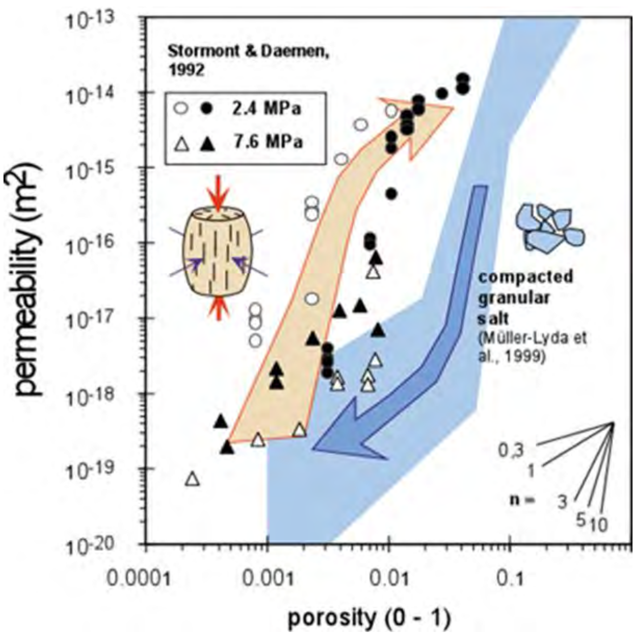


Figure 5-8. Relationship Between Permeability and Porosity for Reconsolidating Compacted Granular-Salt Fill (Stormont and Daemen, 1992; Müller-Lyda et al., 1992).

5.4.2 Case History

The Teutschenthal salt and potash mine in Saxony-Anhalt, Germany, provides unique case examples of the postoperational evolution of open rooms. The mine operated from 1908 to 1982 and several access drifts and mining chambers (stopes) were recently remined. An access drift was originally mined in October 1962 through potash salt that contained carnallite. This drift was one of the primary ventilation drifts though the early 1980s. The drift was abandoned in the 1990s because of a rock burst that occurred in 1996 in the adjacent underdimensioned mining field, but this drift was not backfilled when abandoned. In 2017, the drift was remined using a road header. As shown in Figure 5-9, the drift had completely closed, and electrical wires that were abandoned in the drift had become encapsulated by the reconsolidated salt (described as self-backfill here) that consisted mainly of carnallite. The usual convergence rates in the mine are less than 1 percent per year; however, acceleration of the convergence-driven reconsolidation of the self-backfill material was enhanced by the increased humidity in the ventilation air.

The reconsolidated salt was sufficiently hard that a miner was required to remove the material. In fact, laboratory strength tests performed on the reconsolidated salt showed that it had the same strength as native intact carnallitic salt. The permeability of the formerly brecciated rock material was also restored to less than 10^{-19} m^2 as determined by laboratory tests.

Mining chambers were also exposed during remining in 2017, and one of the chambers is shown in Figure 5-10. The mining chambers had up to 30 percent of the original volumes remaining, and the remainder of the original volume was filled with partially to fully reconsolidated potash salt.

Figure 5-9. Remining of a Main Access Drift at the Teutschenthal Mine.

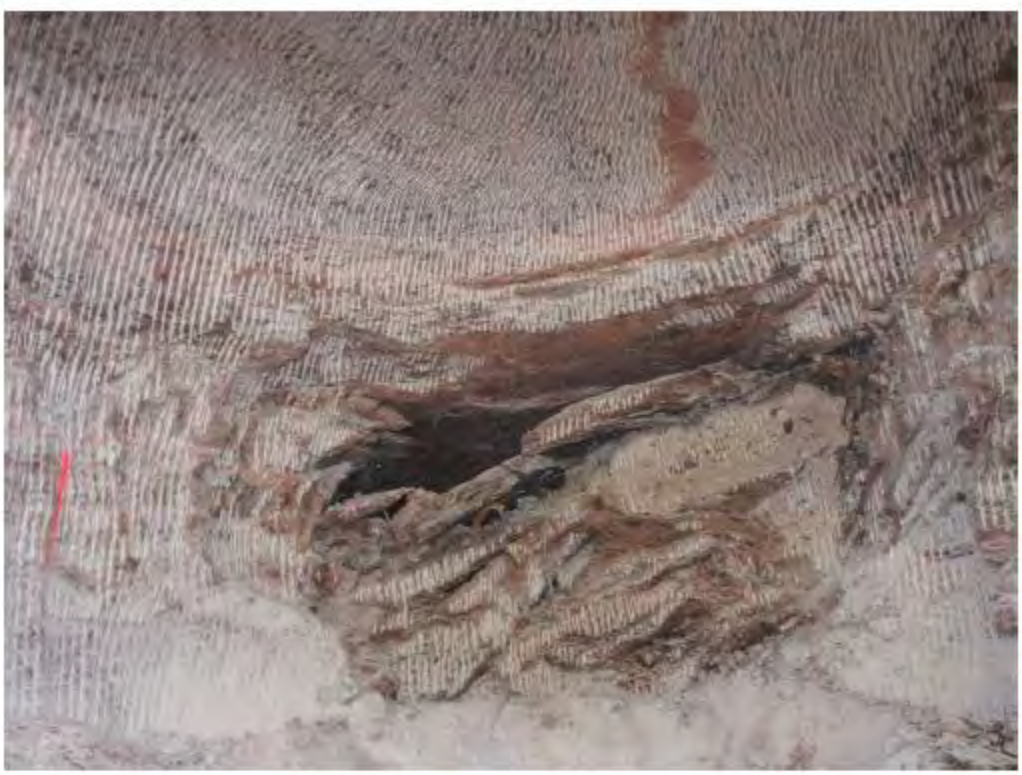


Figure 5-10. Mining Chamber Exposed During Remining at the Teutschenthal Mine.

5.5 Summary

While the PA for WIPP assumes mostly static conditions for the regulatory period, current knowledge of salt mechanics indicates that open rooms will close over time and damaged salt surrounding the excavations will heal. Examples from the Teutschenthal Mine indicate that under certain conditions, unfilled rooms can fully close and reconsolidate within decades if humidity is available.

Other examples of completely closed rooms, such as recorded in the BAMBUS work (Bechthold et al., 2004), were discussed in the breakout session. Evolution of the unbackfilled WIPP underground will involve substantial volume reduction and porosity decrease. The WIPP site is also statutorily obligated to 100 years of institutional control after closure, so natural closure will ensue without the possibility of introducing fluids by human intrusion. The extensive Geotechnical Annual Reports provide decades of geomechanical data and document closure rates that will bring roof and floor into contact within a few decades for the fastest closing rooms in the facility and within a century for the slowest closing rooms. Thereafter, granular-salt reconsolidation will follow. WIPP native salt has sufficient moisture from hydrous minerals, grain-boundary brine, and fluid inclusions to facilitate fluid-assisted pressure solution/redeposition reconsolidation processes. Any nonsalt debris within the rooms will eventually be encapsulated by the salt and sealed off. On a local scale and perhaps on a global scale, reconsolidation will advance toward native conditions and leave little porosity for future brine being introduced by human intrusion. The breakout session concludes that revisiting the WIPP PA in a formal setting is warranted to more accurately represent future states of the underground.

6 ENGINEERED BARRIER SYSTEMS

Backfilling and sealing of salt repositories has been a topic of interest for US/German collaborators for many years. Crushed-salt backfill made of granular mine-run salt (i.e., not crushed or sorted beyond that accomplished by the mining process) has been investigated for decades because of its heat-transfer properties, its capability to stabilize mining openings, and its great potential to reestablish the natural rock-salt barrier by reconsolidation in the long term. Thus, crushed salt contributes to operational and long-term safety. Three presentations regarding stabilization and barrier function were provided by the technical staff of the Technical Bergakademie Freiberg (TUBAF), the Nuclear Waste Partnership (NWP), and GRS. The German salt repository design assumes that, until the crushed salt is reconsolidated sufficiently to assume its barrier function, additional plugging and sealing measures are necessary to prevent brine intrusion from the overburden into the repository. At the 2018 US/German workshop in Hannover, Germany, an overview was given on existing sealing structures made of MgO concrete. Additional experiences that evaluated further variations of MgO-based materials and their applications were presented by BGE and IfG. Recent findings on the thermodynamical stability of MgO-based construction materials were added by TUBAF. Practical experience gained constructing a bitumen seal were addressed by BGE. Finally, an integrated project to develop backfill materials for the range of geological environments and waste types considered in the UK was introduced by the RWM.

6.1 Crushed-Salt Backfill Optimization and Application

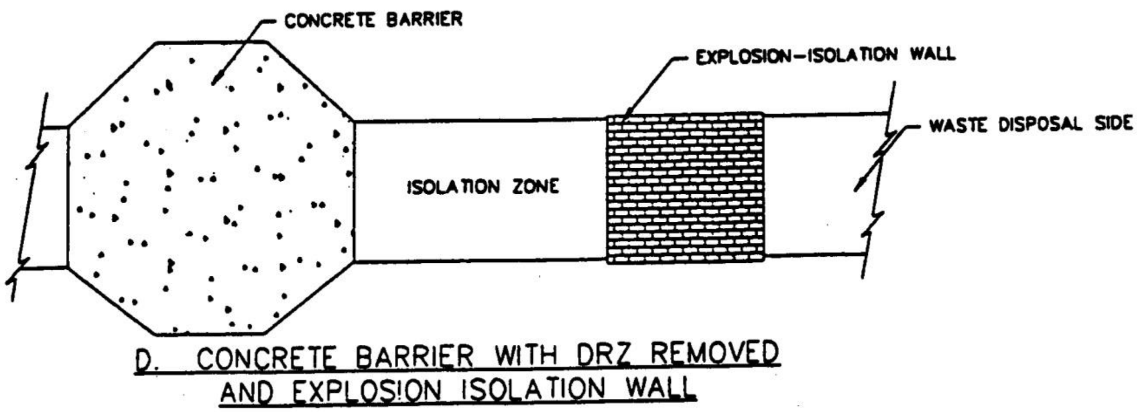
Further development of crushed-salt backfill focuses on its optimization with respect to its special application. The goal of a project (called Gefügestabilisierter Salzgrusversatz [GESAV]) is to optimize crushed salt by a binder in such a way that

- It shows an early load-bearing capacity.
- The end product consists of natural salt minerals.

On this basis, a salt binder was developed comprising bassanite, kieserite, arcanite and $MgCl_2$-H_2O brine. This salt binder generates polyhalite minerals, which build bridges between the crushed-salt grains creating a stabilized matrix by virtue of polyhalite's long-term stability. The GESAV material contains 85 percent crushed salt and 15 percent salt binder. This material is currently being tested at an industrial-scale at the Sondershausen Mine. The emplacement technology was first successfully tested, verifying the mixing procedure of the crushed salt and the binder as well as different backfilling techniques. The behavior of the emplaced backfill is monitored by measuring devices to record time-dependent settlement, pressure increase, and permeability. Polyhalite content has increased with time during the test.

Experience was provided from WIPP, which is the only operated GDF for radioactive waste in salt. The waste is emplaced in large panels, and entries to the panel area were to be closed after the panels were filled. When the facility was licensed, four design options (A to D) of panel closure systems (PCS) were available. At that time, Option D, which is illustrated in Figure 6-1, was selected by the US EPA. The PCS was designed to contribute to operational safety with an anticipated service life of 35 years.

The operational criteria indicate that the PCS design shall limit migration and flow of volatile organic compounds through the disturbed rock zone. The PCS shall sustain pressure and temperature from a hypothetical gas explosion and address most severe ground conditions. Occasional maintenance as opposed to routine maintenance is permitted.



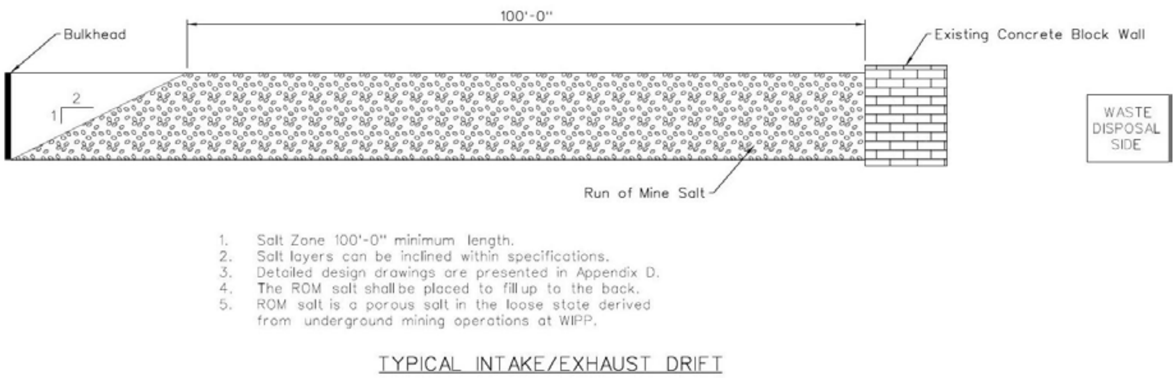


Figure 6-1. Panel Closure Option D (Top) and Run-of-Mine Panel Closure System After Review (Bottom).

For construction, conventional mining practices should be applied, considering available underground services. Thermal cracking of concrete components must also be considered. The estimated intrinsic permeability and conductance as well as the estimated costs play an important role in evaluating the design alternatives.

After design review, the list of alternatives includes three basic options: monoliths of various material, block wall variants, and backfills. Combinations of the basic options gave rise to a fourth option. The concrete barrier was omitted and replaced by crushed-salt backfill after the design review. One variant of the US EPA-approved PCS after review is given in Figure 6-1. The US EPA agreed that this structure provided equal design performance. Construction is straightforward and expected to have reduced operational impact and cost less. These modifications rely on improved knowledge of crushed-salt behavior covering the operational period.

Considering the long-term behavior of crushed salt, natural analogues, and research projects, confidence is provided that the natural salt barrier may be reestablished in less than 1,000 years at a compaction state below 1 percent porosity. The Kompaktion von Salzgrus für den sicheren Einschluss (KOMPASS) project was established to reduce uncertainties in predicting crushed-salt reconsolidation and create the prerequisite for enhancing the safety case for a repository in rock salt. The project focuses on completing the experimental database; improving the process of understanding; and enhancing and calibrating models to reliably predict crushed-salt reconsolidation, especially in low-porosity ranges that is decisive for barrier function.

The porosity range below 5 percent is of special interest in assessing long-term safety because diffusive transport in pores of crushed salt may act as the most relevant transport process and becomes relevant after long periods if pore water is present. So far, the diffusion coefficient of free water has been applied in the long-term safety assessment. To support this result experimentally, the Diffusion in Kompaktierten Salzgrus (DIKOSA) project includes the pore diffusion coefficient for crushed salt having porosities of 4 percent ($k = 1 \times 10^{-16}$ m²) and 2 percent ($k = 3 \times 10^{-17}$ m²). As a result, the diffusion coefficient through granular salt was not estimated to be significantly different from the diffusion coefficient in free water. The low porosity and the slow diffusion process do not lead to notable radiological consequences. Safe containment of radioactive waste is guaranteed by a combination of constructed seals in the short-term and crushed salt compacted to low porosities less than 5 percent.

6.2 Plugging and Sealing

Because crushed-salt compaction takes time, additional shaft and drift seals are included in the design to avoid brine inflow from the overburden during the initial period after repository closure. Salt-mining experience has shown that salt concrete and Sorel concrete, clay/bentonite, and asphalt/bitumen materials provide effective seals in many applications. Progress made in several ongoing sealing projects in the Asse II Mine, the Teutschenthal Mine, and the Morsleben repository is described in the following text.

Construction materials with MgO as a binding agent and $MgCl_2$ solution as a mixing liquid have been playing an important role since 2007 in stabilizing the Asse II Mine openings and sealing of drifts, shafts, and boreholes as well as cracks and fissures. Because of the different opening sizes and technical equipment used, different material compositions have been developed to form a group of construction materials that are compatible with each other. The basic binder components combine 3 $Mg(OH)_2 \times 1$ $MgCl_2 \times 8$ H_2O and 5 $Mg(OH)_2 \times 1$ $MgCl_2 \times 8$ H_2O during the setting process that forms the so-called long-term stable 3-1-8-phase and the meta-stable 5-1-8 phase (Sorel phases). The meta-stable 5-1-8 phase transforms itself into the stable 3-1-8 phase over the long term.

By changing the percent by weight of the components and adding several aggregates in size and quantity to the binder, the following four recipes are currently used in routine operation:

- Mainly Sorel concrete A1 is used as construction material for flow barriers and as backfilling material. The aggregate is salt grit with a maximum grain size of 4 mm.
- Sorel concrete A0 is used to bind up to 18 percent NaCl brine.
- IM-Asse-1 is used for filling wide gaps and boreholes. A higher amount of $MgCl_2$ solution is added with a fine-grained salt aggregate with a maximum grain size of 0.3 mm.
- MFBBa-17/3/30 is used to inject cracks and fissures. Brucite is added to this mixture as a slow-reacting binding agent along with barite powder as a very fine-grained aggregate with a grain size of 5 µm.

These Sorel materials were developed both above ground and in an underground laboratory on the 490–750-m-level in the Asse II Mine to account for the specific mine climate.

One of the important principles in all of the development phases was to upscale the research procedure step by step from small-scale (3–5 liters), to medium laboratory-scale (ca. 30–40 liters), to pilot-scale (3-5 m^3), and eventually industrial-scale (> 800 m^3). The scale changes take into account the conditions of in situ production and test the technical equipment of every application. This procedure minimizes mistakes caused by scaling factors. All steps were accompanied by a strict quality control program. The production workflow for salt concrete is illustrated in Figure 6-2. Sampling points for quality control are marked with red bullets in the figure.

Sorel material has been successfully used within the scope of the emergency measures carried out at the Asse II Mine. Currently, approximately 350,000 m^3 of Sorel material have been placed in routine operation.

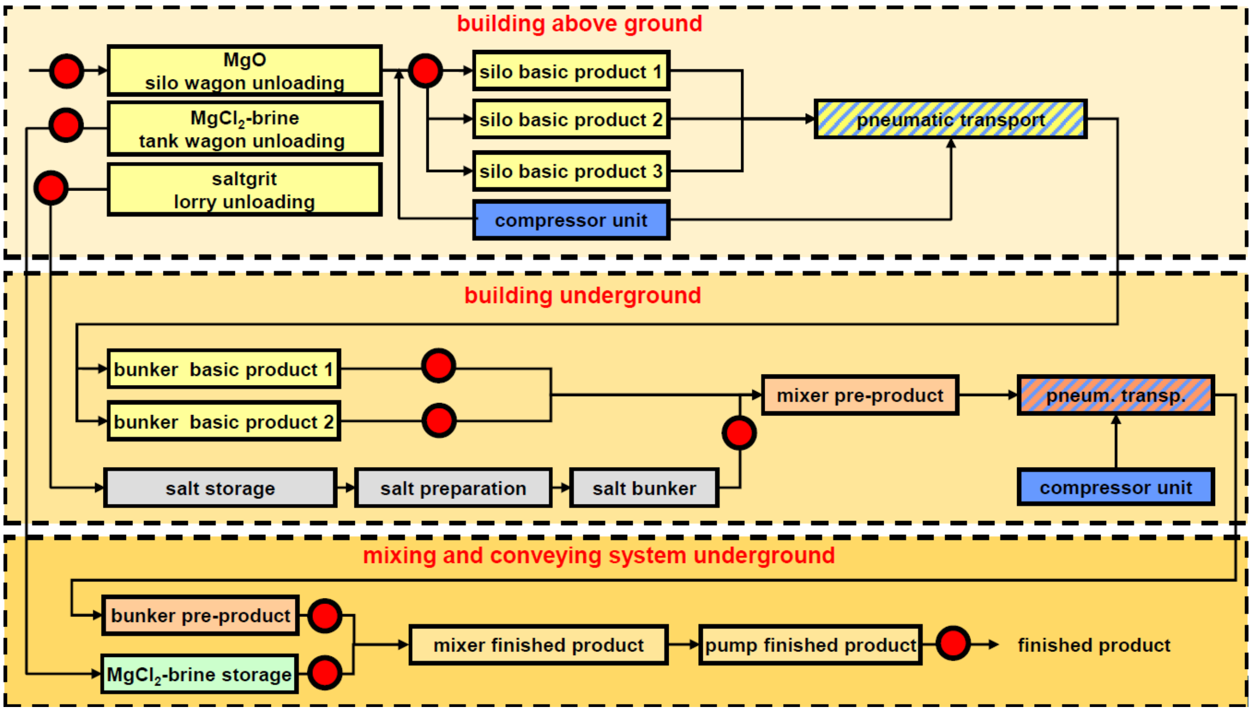


Figure 6-2. Production Workflow for Salt Concrete and Sampling Points for Quality Control (Red Bullets).

In addition to the A1 and A0 concretes, mixtures of MgO-based materials were developed to match site-specific requirements of the Teutschenthal Mine and the Morsleben repository. Gravel, sand, anhydrite powder, micro-silica, and quartz powder are used for aggregates in the DBM2, C3, and D4 mixtures. All concrete types are cast in place; the D4 mixture can be applied as a shotcrete as well. The technical feasibility of a shotcrete seal was demonstrated in a pilot test (called GV2) in the Teutschenthal Mine. The shotcrete is applied if a temperature reduction during the setting process is considered important, such as a salt environment that contains minerals with a high amount of crystalline water. The shotcrete was initially assumed to show construction joints that led to an elevated permeability. After applying brine pressure on the pilot seal GV2 in the Teutschenthal Mine, experimental results showed that the construction joints did not play an important role. This result is explained by the 5-1-8 Sorel phase generated by the D4 mixture during the setting process, which transforms to the 3-1-8 Sorel phase in the case of brine intrusion leading to self-healing. The D4 mixture forms the 5-1-8 Sorel phase during the setting process; whereas, DBM2 and C3 mixtures generate mainly 3-1-8 Sorel phases.

A further important result of the investigations of the MgO-SEAL project in the Teutschenthal Mine was extending the thermodynamical stability field of the 3-1-8 Sorel phase to 0.5 mol Mg^{2+}/kg H_2O content in NaCl-saturated brine at 25 °C. The 3-1-8 Sorel phase remains stable at lower $MgCl_2$ contents in NaCl-saturated brine and covers a larger range of brine-intrusion scenarios. Consequently, the range of MgO materials applications was extended significantly.

Comprehensive knowledge on MgO-based construction materials is available considering its industrial handling, mechanical and hydraulic material properties, and long-term stability. Different mixtures are available that constitute a toolbox for different applications.

A sealing concept using gravel and asphalt and/or bitumen will be applied in the Morsleben repository to seal one ventilation shaft that connects several horizontal drifts. To demonstrate that this seal can be constructed with the quality assumed in the safety assessments, several tests have been conducted. In 2015, a large-scale in situ test was conducted to evaluate the construction process. The main goal of the test was to demonstrate the technical feasibility of constructing a plug made of gravel and bitumen under the logistic constraints underground while meeting occupational health and safety requirements concerning working with about 190 °C hot bitumen in a vertical excavation. The influence of the hot bitumen on the surrounding rock salt and the pressure resulting from the bitumen filling the pores between the grains of the gravel was also measured.

The test was conducted in a ventilation shaft with a nearly square base area of approximately 12 m^2. Photographs of these operations are shown in Figure 6-3. After constructing an abutment made of gravel and several filter layers, a sealing element approximately 6 m high was built. The last filter layer was equipped with pressure and temperature sensors, and additional temperature sensors were installed on the rock-salt surface. The sealing element was constructed in steps. First, a layer of approximately 0.5 m of gravel was poured into the shaft and compacted. This layer was then covered with hot bitumen. After a certain amount of cooling time, the next layer of gravel was poured. This process was repeated several times with cooling waiting times ranging from approximately 12 hours to 3 days.

Figure 6-3. Pilot Test in the Morsleben Repository – Emplacement of Gravel and Bitumen.

All quality requirements were met, and all occupational health and safety measures were implemented successfully. The material properties were verified by sample testing and the construction process was monitored by quality measures. The quality of the filling was assessed from the measured pressure and by calculating the remaining pore volume between gravel grains and bitumen based on the masses of the materials used and the previously measured volume of the excavation. The calculations showed a remaining pore content of approximately 1.5 percent, which is below the target value of 3 percent that is typically applied in water engineering. The pressure measurements showed that bitumen acts like a liquid. This pilot test showed that this type of vertical seal can be built as intended.

6.3 Roadmap to Design

An integrated project was initiated in the UK to develop backfill for a wide range of waste types and several geological environments. Lower-strength sedimentary rocks (e.g., clay) and higher-strength rocks (e.g., granite) are considered as potentially suitable host-rock types. Backfill immediately surrounds the waste packages in design concepts. Mass backfill is used to fill the GDF accessways. The objective of the first phase of this project is based on the following outcomes:

- A fully integrated and justified roadmap for delivering technically feasible and scientifically underpinned backfill materials that meet the long-term safety requirements.
- A justified business case for the next phase of technical work that links key decisions and interfaces within the geological disposal technical program.

Implementation issues will be addressed in Phase 2 of the project.

6.4 Summary

Salt repository performance requires effective closure and sealing measures to conserve the naturally dry environment of a salt repository and avoid radionuclide release. Projects related to crushed-salt backfill have begun recently to increase knowledge and investigate measures to optimize crushed-salt backfill properties with respect to its function. A general project regarding backfill was presented to develop a roadmap for identifying backfill materials for different waste types and geological environments.

Additional seals are required to cover the time period until the salt barrier is established. Progress was made in developing a suite of MgO-based materials that serve as a toolbox for different applications. Note that additional knowledge was gained on the thermodynamic stability of the 3-1-8 Sorel phase that increases the robustness of MgO-based materials against a wider range of brine-intrusion scenarios. The technical feasibility under in situ conditions was demonstrated for a vertical gravel/bitumen seal.

7 LABORATORY SALT TEST SAMPLE CONDITIONING

7.1 Introduction

The goal of this breakout session was to identify and discuss the influences of sample conditioning on the mechanical behavior of salt and provide a summary of standard procedures and best practices. Experimentalists who test salt have continually improved techniques to ensure that inadvertent influences do not compromise mechanical test results. Undesired influences can result from handling and storage, shipping, sample preparation, test procedures, characterization, consolidation, and more. Sample size, precision of machining, end effects, environmental control, mineralogical characterization, test protocol, and a host of other considerations can influence responses to stimuli.

The breakout session titled "Test Sample Conditioning" was led by Mr. Stuart Buchholz (RESPEC) on May 29, 2019, at the 10th US German Workshop on Salt Repository Research, Design, and Operation. The breakout session included presentations by the following individuals:

- Mr. Stuart Buchholz (RESPEC) highlighted a research project (DeVries, 2010; Brosnahan and DeVries, 2011) that evaluated the influence of preconditioning time on the dilation strength of Avery Island salt.
- Mr. Jake Hladysz (RESPEC) presented a brief overview of RESPEC's procedures for core handling, storage, shipping, and consolidation.
- Dr. Uwe Düsterloh (TUC) discussed standard procedures for sample preparation and the influence of sample conditioning on the mechanical behavior of salt.
- Dr. Till Popp (IfG) addressed the possibility that laboratory tests are representative of in situ properties. Besides scale (size) effects, Dr. Popp also discussed the timescale and loading conditions for low-stress creep tests.

The presentations are provided in Appendix D, and the following sections summarize the information provided during the breakout session as well as additional standard procedures that were provided by RESPEC, IfG, TUC, and BGR to supplement the breakout.

7.2 Sample Collection, Packaging, and Shipping

Techniques used for sample collection depend on the project type. This section addresses a few of these methods for both underground and surface coring projects.

7.2.1 Sample Collection

Several techniques are available for retrieving core in an underground mine. The collected core size can range from 50 mm in diameter up to tens of centimeters. The core can be extracted by drilling or by retrieving large blocks from the mine pillars or floor. The example discussed here uses a concrete coring rig with a diamond-bit core barrel that is 300 mm in diameter and 560 mm in length, as shown in Figure 7-1. An extension was added to allow drilling a second core deeper into the sidewall. Figure 7-2 shows an example where core was extracted from the mine floor. In both cases, the core was released after being drilled by either using pry bars or inflatable flat jacks. The free core was extracted from the hole by using either a thin steel-wire noose or nylon strap.

Core collected from the surface is generally obtained by using a conventional coring rig with or without fluid in the borehole. Conventional coring rigs can retrieve core that range from 27 mm in diameter up to approximately 140 mm in diameter. For salt testing purposes, RESPEC typically requests 101.6-mm-diameter cores retrieved in aluminum sleeves. The aluminum sleeves help preserve core quality and reduce mechanical breakage while coring or when laying down the sleeves to be processed.

Figure 7-1. Large-Diameter Core Extracted From the Sidewall of a Mine.

Figure 7-2. Large-Diameter Core Extracted From the Floor of a Mine.

7.2.2 Core Packaging

For large-diameter core extracted in the field, RESPEC typically wraps the cores in plastic wrap and several layers of bubble wrap. The cores are loaded into a wooden crate that is tightly packed, and each core is separated by heavy foam material. Examples of boxed cores are illustrated in Figures 7-3 and 7-4. Figure 7-4 also shows the large-diameter core fit into tight-fitting cardboard tubes with wooden caps to secure the core during transport.

If the large-diameter cores are to be placed in long-term storage, RESPEC extracts the cores from the original packing containers. After photographing and describing, the cores are wrapped in aluminum foil and sealed with a microcrystalline wax, as shown in Figure 7-5.

Figure 7-3. Boxed Core Samples Ready for Shipping.

Figure 7-4. Large-Diameter Core Packaged for Transport.

Figure 7-5. Large-Diameter Core Prepared for Long-Term Storage.

Small-diameter core taken from the surface is usually obtained in much higher volumes and the shipping and packaging techniques may vary greatly. When the core is collected in aluminum tubes, the tubes are usually sawn into predefined lengths. The ends of the tubes are sealed with wax or a rubber cap is taped or hose-clamped to each end. The aluminum tubes can be placed into wooden boxes where they are tightly packed with foam material. Many coring service providers also have plastic or aluminum core vaults where each tube is secured into position without touching another. An example of an aluminum core vault is shown in Figure 7-6.

Figure 7-6. Core Vault Packed With Aluminum-Sleeved Salt Core.

Upon arrival at RESPEC's laboratory, the aluminum-sleeved core is cut and placed in cardboard boxes. In instances where hydrous evaporites (i.e., carnallite, tachyhydrite, and bischofite) are present, the cores are wrapped in plastic bags to protect them from humidity and core degradation, as illustrated in Figure 7-7. BGR and TUC use a slightly different approach to protect the cores after arrival. Upon arrival at the BGR laboratory, the core is stored in an air-conditioned room at a temperature of approximately 22 °C and relative humidity less than 40 percent and not sealed in plastic bags. TUC applies a storage container to protect claystone samples from aging.

Figure 7-7. Core Packaged in Plastic Bags and Boxed for Protection From the Environment.

In some instances, the core may be cut in the field, boxed, and shipped on wooden pallets. This method will be most prone to damage during shipping. Another shipping method is wrapping the core in bubble wrap and placing the core in capped polyvinyl chloride (PVC) tubes before being shipped on a pallet. This method reasonably precludes damage during shipping; however, the core cannot easily be viewed, and the footprint is quite large compared to boxing (if the core is to be stored long term).

7.2.3 Core Shipping

Core shipped via land should be transported on an air-ride trailer to minimize damage. In cases where the temperatures are below freezing, a temperature-controlled reefer truck is recommended. A proper Chain-of-Custody form should be used each time the core is shipped from one location to another.

7.3 Specimen Preparation

Specimen preparation will vary, depending on the size and shape of the original core (i.e., small- or large-diameter cylinders, blocks, or chunks). For large-diameter cores or blocks, the sample will need to be cut to size to fit into a mill or other fixture used for subcoring. RESPEC typically uses band saws with either diamond or carbide blades to reduce the sample size. BGR and TUC use similar methods for coring large blocks. Other options may include a chain saw or a concrete coring rig with the appropriate bit size.

Once the core is shaped to a manageable size, a vertical, variable-speed mill is used by RESPEC to subcore the samples to nominally 101.6 mm in diameter. A thin-kerf diamond coring bit is used and Bright-Cut NHG metal working fluid is used as a lubricant to prevent evaporite materials from dissolving. The subcored sample is then sawed to length, and the ends are finished in a lathe to produce a right-circular cylinder. The same, or similar, process is used by BGR and TUC to finish specimens within tolerance.

For smaller-diameter core (i.e., typically 101.6 mm in diameter), the specimens are prepared by initially sawing a length of rock from the field core. The ends and the diameter are then finished in a lathe using carbide tooling to produce a right-circular cylinder that maintains the largest diameter possible. Typically, the test specimens are constructed with a minimum length-to-diameter ratio of 2:1. The finished samples are then weighed, and a bulk density is calculated by using the finished dimensions to determine volume. Depending on the project, ultrasonic compression and shear-wave velocities are determined and photographs taken using both reflected and transmitted light. At BGR, an additional photograph is taken using a high-resolution core scanner. The standard practices for preparing rock-core test specimens and verifying conformance to dimensional and shape tolerances are described in ASTM International Procedure D4543.

7.4 Preconsolidation Chambers

At RESPEC, salt specimens are preconsolidated in hydrostatic pressure vessels (see Figure 7-8) at 20 megapascal (MPa), room temperature, and for 10 to 14 days, depending on the project. Consolidation vessels are made of 0.75-inch-thick 1025 steel and are long enough (610 mm) to fit two 203-mm-long salt specimens. Salt specimens are prepared to finished pretest standards before being placed in consolidation vessels. The finished samples are placed in double-neoprene jackets with aircraft-lock wire to secure the jackets to the end platens. Specimens that have a rough outside surface are treated with silicone kitchen-and-bath sealant to prevent the jacket from being punctured. The jacketed samples are then placed inside the vessels, which are filled with silicone oil. The jackets and platens protect the samples from the silicone oil, which is used to apply the hydrostatic pressure. The platens are vented to the outside of the vessel so that all of the air can escape, and the vented platens aid in identifying a leaky jacket once the system is pressurized. After consolidation is complete, the samples are refinished one last time before testing.

At BGR, salt cores are wrapped in Teflon foil (0.1 mm) to minimize friction effects and prevent the jacket from being punctured during preconsolidation and testing. The specimens are then placed in either one or two elastomer jackets (e.g., Viton). A single jacket is used if the sample has relatively smooth surfaces and the tests involve only small sample deformation; two jackets are used otherwise. Hose clamps are used to secure the jackets to the end platens. Teflon foil is also placed across both ends of the sample (Teflon foil is perforated if hydraulic testing is involved) to minimize friction between the sample and the platens. This method efficiently reduces areas with lower shear stress at the ends of the specimen and results in a less heterogeneous stress field inside the sample. Minimizing friction also significantly reduces barrel-shaped deformation.

Figure 7-8. Sample Preparation and Preconsolidation Chambers.

At BGR, preconsolidation is performed in the test rig. The pressure and the termination criterion (e.g., a given preconsolidation time, or the undershooting of a given consolidation rate) depends on the project. Preconsolidation in the test rig is conducive to obtaining a complete data record of the consolidation process and preventing any unnecessary unloading or other disturbance between preconsolidation and subsequent testing. Although preconsolidation in the test rig is preferred, preconsolidation chambers can be used in cases of uniaxial tests where hydrostatic loading in the test rig is impossible.

7.5 Sample Conditioning

Under undisturbed in situ conditions, salt is believed to be free of microfractures. However, core retrieval involves stress relief that may result in microfractures forming. Packing, shipping, unpacking, and specimen preparation can induce further microfracturing. To mitigate induced damage, test specimens are typically “healed” in preconsolidation chambers, as noted previously. In the breakout session, various observations regarding preconsolidation techniques were discussed, with the fundamental understanding that conditioning helps reduce unknown variability if subjected to a sufficiently long period of appropriate temperature and pressure conditions.

7.5.1 Research Study Overview

Mr. Stuart Buchholz (RESPEC) highlighted a research project (DeVries, 2010; Brosnahan and DeVries, 2011) that was conducted to evaluate the influence of preconditioning time on the dilation strength of a domal salt. For this study, 27 constant mean stress (CMS) tests were performed to investigate the impact of preconditioning durations. The salt specimens were subjected to a hydrostatic stress of 20 MPa at room temperature for 1, 5, 10, 20, and 40 days before testing. The test results from these preconditioned specimens were compared with tests performed on specimens that were not preconditioned and are shown in Figure 7-9.

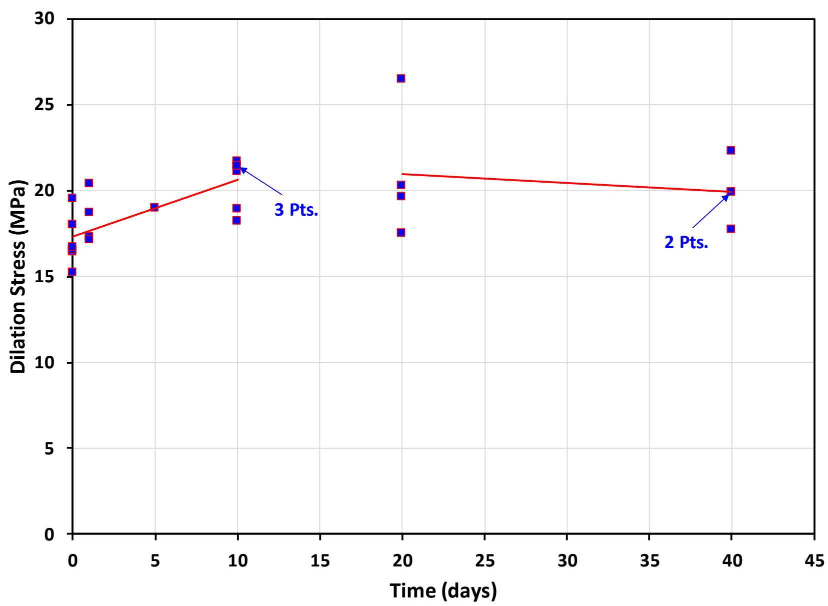


Figure 7-9. Dilation Stress Versus Preconditioning Time.

Although the number of tests performed limits the statistical significance of the results, the data suggest that the propensity for salt to dilate is lower for specimens that are preconditioned compared to those that are not preconditioned. The specimens that were preconditioned for 20 or 40 days also began to dilate at roughly the same stress levels as the specimens that were preconditioned for 10 days. The specimens that are preconditioned for 10 days exhibited nominally a 12 percent greater dilation limit than those preconditioned for 1 day and 21 percent greater than tests performed on specimens that were not preconditioned. However, specimens that were preconditioned for 20 or 40 days produced roughly the same dilation stress as those preconditioned for only 10 days. This information clearly shows the effects of conditioning and a practical duration.

7.5.2 Pore Pressure Considerations

To ensure that the material behavior determined in the laboratory experiments sufficiently represents that of the in situ rock, the drill cores must be appropriately protected against aging effects from the time of extraction until rock-mechanics experiments begin in the laboratory. Sensitive core material (predominately clay and claystone) is generally protected against drying out or moisture uptake from the ambient air by sealing it in a plastic bag and storing under climatically suitable ambient conditions.

Rocks that are also subject to pore-water pressure exhibit a change in their mechanical characteristics that increases with the storage time (structural weakening), despite storage in an environmentally controlled room and protection against drying out or moisture uptake. The cause for this change is shown in Figure 7-10. Subsequent to extracting core material from the rock mass, the pore-water pressure in the pore space of the rock is still effective because of the low hydraulic conductivity. Both the mechanical rock-mass stress and the hydraulic pressure that were active at the extraction location are reduced to the atmospheric pressure level during the coring process.

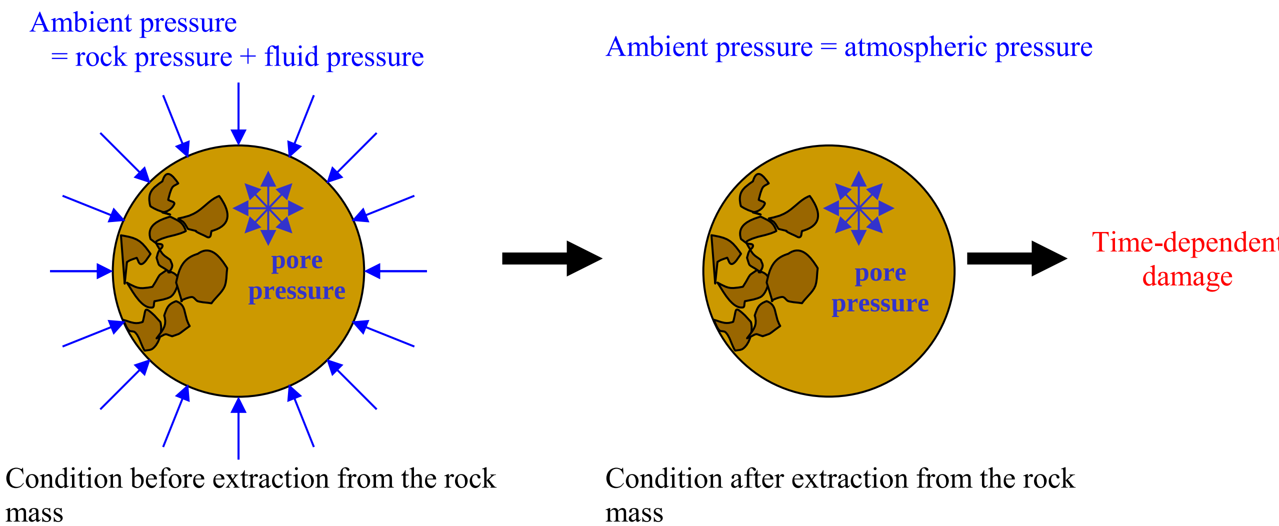


Figure 7-10. Schematic Representation of the Pore-Water Pressure Effect After Extraction.

The result is increasing, tangentially oriented, tensile stresses originate within the rock structure in the direction of the sample surface. With increasing storage time, the internal pore pressure may lead to microcracking and affect mechanical and hydraulic properties.

The laboratory test results generally show a high influence on conserving the original quality of claystone samples to interim storage conditions (immediately after extracting core material). For the case where the plastic bags are used to seal the specimens during interim storage, the following occurs:

- An increase in the shear strength of the rock (increase of the effective stress because of the reduced pore-water pressure or desaturation [suction]).
- An increase in damage and weakening of the rock microstructure resulting from the actual pressure difference (e.g., the difference between the internal pore-water pressure and the ambient pressure that has now been reduced to the atmospheric pressure).
- An increase in damage of the rock microstructure by further desaturation, which leads to contraction cracks (e.g., shrinkage and enlarged suction) forming.

A successfully demonstrated method for avoiding the aging effects previously outlined is the interim storage of the drill cores in special, sample-storage containers (i.e., pressure cells) directly after their extraction. The storage container shown in Figure 7-11 protects the sample against drying or wetting and allows setting and maintaining isostatic stress corresponding to the extraction location, which preserves a certain pore pressure.

The storage container consists of a circular pressure cylinder, the top and bottom of which are closed pressure-tight with cover plates.

After extracting the drill core from the rock mass, segments of defined length are prepared, sealed in coated film, and encased with a rubber jacket. Pressure plates are then positioned, one on the top and the other on the bottom of the rock core. The pressure plates are locked to the rubber jacket with metal clamps or a tensioning wire to give a firm and force-closed connection between the rubber jacket and the pressure plates. This step is followed by installing the jacketed rock core in the storage container to which the bottom cover plate has been fitted (Figure 7-11). The bottom pressure plate makes positive connection to the bottom cover plate. The top cover plate is attached, which centers the sample in the storage container. Isotropic pressure loading is completed by filling the annular space between the sample jacket and the inner wall of the storage container with hydraulic oil. Bores in the top and bottom pressure plates ensure that the hydraulic oil can also penetrate throughout the area between the bottom and top cover plates and the top pressure plate.

Figure 7-11. Photographic View of the Storage Container (Patented).

Filling the storage container is complete when hydraulic oil emerges from the vent hole in the top cover plate (avoidance of air bubbles in the pressure space). Following filling and venting, the pressure in the storage container is brought to the preferred value via a hydraulic pump. The membrane reservoir and pressure relief valve in the hydraulic circuit ensure that the predetermined pressure is held constant over the storage time and is largely independent of temperature fluctuations. An important feature of the sample storage outlined previously is that the hydraulic pressure is universally distributed because the pressure acts both radially and axially on the sample. Figure 7-12 gives an impression of the installation sequence.

7.5.3 Unloading Effects

As already demonstrated, reconsolidating a salt specimen is a necessary step before triaxial strength testing to obtain realistic values. However, the effect of reconsolidation is partially canceled during unloading. IfG always performs a short-term loading phase of the salt specimens in a triaxial cell. The first step is to load the specimen to a stress level that corresponds to the recovery depth. The efficiency of the preloading is documented by the volumetric strain change, as shown in Figure 7-13. As illustrated in Figure 7-13, the pore opening occurs with the pure elastic unloading. This effect is obviously greater for increasingly larger and faster unloading cycles. This reopening effect is usually neglected but can be seen in the first part of the loading phase via additional compaction. In low-deviatoric stress creep tests, measured axial strain may include recompacting the dilated pore space, which falsely increases the apparent strain rates.

Figure 7-12. Installation of a Rock Sample Into a Storage Container.

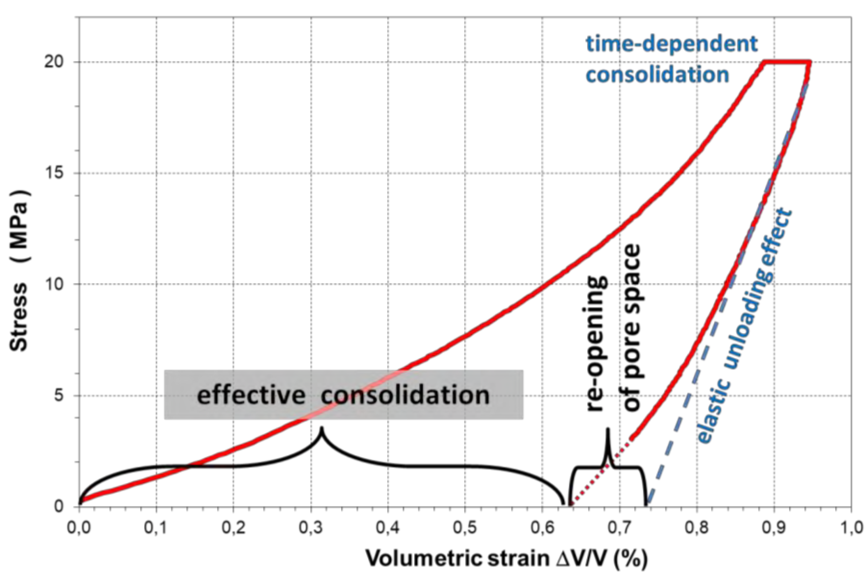


Figure 7-13. Loading and Unloading Cycle During Preconsolidation: Waste Isolation Pilot Plant Rock Salt Specimen 613/106-7/TC3 20MPa.

7.6 Other Discussions and Questions

Other discussions and questions brought to attention during the breakout session included the following:

- If preconsolidation is performed in chambers where the pressure is released before loading into the test rig (as opposed to preconsolidating in the test rig and immediate testing), does it matter that the salt will relax slightly, as shown in Figure 7-13? This topic may deserve further elaboration in continued US/German workshops.
- As asked by Dr. Popp, sample size may be of importance because mechanical properties are characterized by scale effects, mainly because weakness planes or impurities are arranged in different layers. What sample size is required to represent the material properties according to lithological variations?
- Did packaging create differences attributed to argillaceous and clean WIPP salt?
- According to Mellegard and Pfeifle (1993), horizontally oriented, 0.4-m-diameter specimen stock was dry (air) cored from the ribs of several of the test rooms at WIPP. The argillaceous salt was sealed after drilling to preserve the natural moisture content of the clays. The clean salt was not sealed because no significant amounts of clay minerals were (visually) present. Mineralogy was not performed nor were discussions held on how the attribution of clean and argillaceous was determined; however, when so-called clean and argillaceous salt was later delivered to German laboratories for WEIMOS testing, no discernible difference was noted in the mechanical response. Therefore, differences in sample treatment may have given rise to artificial differences in mechanical results.
- Humidity in salt samples can occur at grain boundaries or as intracrystalline fluid inclusions. In short-term strength tests, the potential for pore-fluid pressure effects may be neglected. However, the role and efficiency of the different types of humidity inside salt on the long-term creep behavior is largely unknown. Especially in a low-deviatoric stress regime, humidity-assisted deformation processes are probably more important. An experimental approach focusing on this topic has not been undertaken.
- The internal microstructure of salt samples will generally recover at elevated temperatures. Changes to the substructure needs to be kept in mind as part of sample conditioning.
- One of the current challenging questions of the US/German workshop concerns creep processes at low-deviatoric stress. Because of the extraordinary precision required of these experiments, it is imperative that extraneous effects of sample conditioning be mitigated. To ensure that the starting sample conditions are dependably free of laboratory externalities, IfG ran the experiment diagrammed in Figure 7-14 on several specimens. During test TCC34, initial isostatic consolidation at 20 MPa was conducted for a total of 133 days, first at room temperature, and then at 120 °C (see Figure 7-14). The isostatic conditions, particularly at 120 °C, surely annealed the substructure to a certain degree. The goal of this preconditioning procedure was to obtain a more-or-less dilatancy-free initial state for specimens at the beginning of creep tests with small deviatoric stresses. For these tests, a damage-free initial state is of special importance. However, this test still leaves questions such as: (1) why was the strain changing over such a long time (i.e., was it continually removing initial damage)? and (2) why was the transient response so great at the beginning of both temperature phases in the consolidation?

7.7 Summary

Test sample quality can be affected by several factors, including sample collection, shipping, storage, sample preparation, consolidation, and more. As discussed in this chapter, each laboratory uses slightly different methods to achieve quality test specimens. Regardless of the exact procedures, the ultimate goal is to produce samples where pressurization or annealing practices are employed to heal unintended damage from external influences.

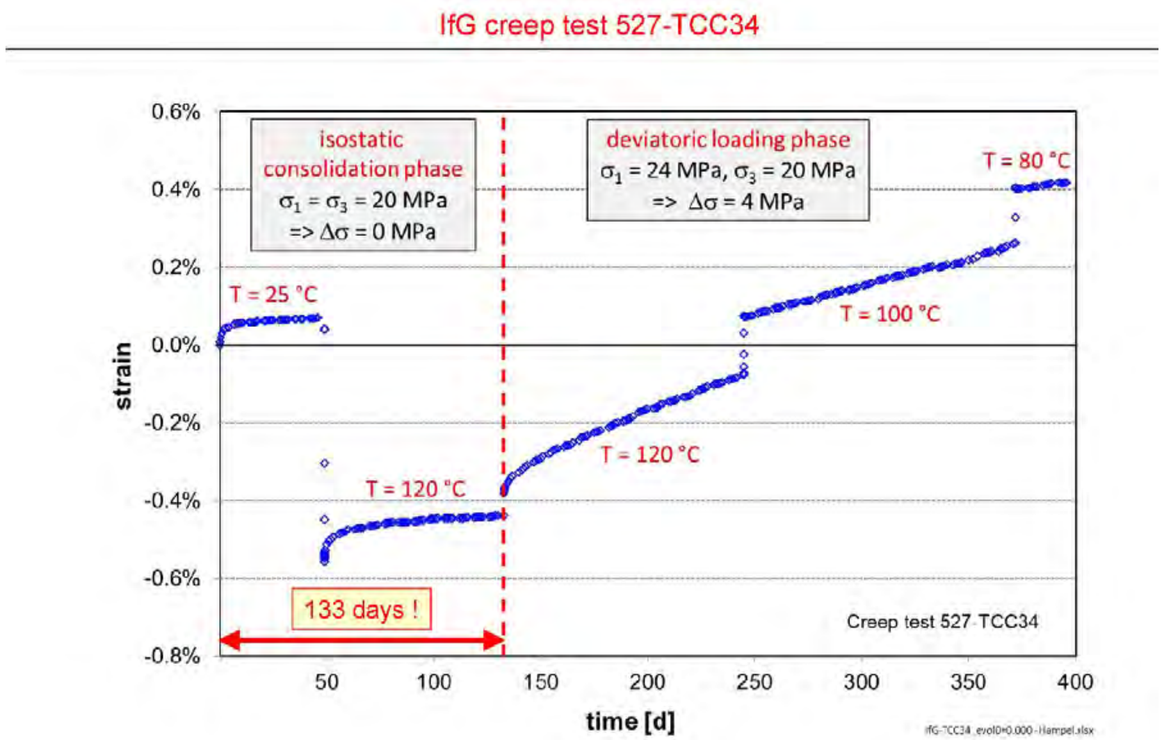


Figure 7-14. Strain Versus Time for Isostatic Consolidation and Creep Test.

Under undisturbed in situ conditions, salt is believed to be free of microfractures. To mitigate induced damage, the test samples are typically “healed” in hydrostatic pressure vessels for a predetermined time, pressure, and temperature. Research has shown that preconditioning will reduce the unknown variability of test results. One example showed that specimens preconditioned for 10 days were, on average, approximately 12 percent stronger than those preconditioned for 1 day and 21 percent greater than tests performed on specimens that were not preconditioned.

Sample conditioning is a relatively new research area. Experimental results discussed in this session clearly showed the importance of sample conditioning to improve the quality of test results. Research and joint collaboration will continue well into the future to better understand the healing processes of salt and best practices for conditioning test samples.

8 TECHNICAL BARRIERS AND OPERATIONAL SAFETY

8.1 Overview

As some European waste-management organizations are close to constructing or commencing operations for HLW and spent nuclear fuel (SNF) repository, operational safety has become an issue of public interest. For the last few years, especially since the serious operational events at WIPP, operational safety has been a focus for US/German collaboration. Theoretical considerations of how to transfer the methodology of FEPs from the long-term safety assessments of a repository to evaluate operational safety were presented at the 9th US/German workshop. Experience gained and lessons learned from the fire accident and a radiological event at the WIPP site in 2014 were presented in earlier workshops. This year, the lessons learned were highlighted again but with a forward focus for the site. A presentation from the International Atomic Energy Agency (IAEA) highlighted ideas and consequences for disposing surplus plutonium at WIPP.

Germany restarted a site selection process for an HLW and SNF repository. The Site Selection Act as of 2017 stipulates considering three potential host rocks (i.e., salt, claystone, and crystalline rock). Significant RD&D has been performed for more than 40 years and centered around design, construction, operation and closure of a repository in salt (domal and flat-bedded salt formations). Rigorous RD&D played a role in designing suitable waste containers as well. A prototype of a shielded container (POLLUX®) was designed and fabricated by the German Nuclear Industry in the 1980s. In Germany, similar advancement for a repository in claystone and crystalline rock are still missing; however, Finland and Sweden have very mature designs for crystalline repositories. Because the technical barriers of a repository, particularly the waste packages, are becoming more scrutinized in public debate and, therefore, more important than in the past for operational safety considerations, BMWi launched an RD&D project to systematically derive design requirements for waste packages for all three host rocks that are to be considered in Germany. The approach and early results of a RD&D project titled KoBrA (requirements and concepts for disposal containers for heat-generating radioactive waste and spent fuel in salt, clay and crystalline rock) were presented. For comparison purposes only and without any link to the US national waste-management program, ideas to derive design requirements for HLW and SNF containers were also presented.

8.2 Operational Safety

The lessons learned regarding operational safety at WIPP were presented by the NWP (operator and manager of WIPP). Following the fire event (i.e., underground fire involving a salt haul truck) on February 5, 2014, and the radiological event (i.e., an exothermic reaction involving the mixture of the organic materials and nitrate salts inside a drum) on February 14, 2014, a series of investigations were performed in tandem to the remediation activities at the site. Details of both events were discussed and the remediation measures described in previous workshops. Methods to prevent future safety failures and the consequences for future site operation were explained in the 10th US/German workshop. One of the main lessons learned was realizing that different safety cultures exist at WIPP that juxtaposed nuclear versus mining philosophy. Consequently, safety-training measures for the staff (including mine operation) were launched. Personnel were trained to recognize critical safety deficiencies and instructed to take appropriate actions. Beyond these measures, the expectations and capabilities of the facility shift manager to manage all aspects of an emergency or abnormal event were defined. The radiological event revealed that the national transuranic waste program was not robust enough to identify incompatible waste. Together, these operational safety events evidenced process improvements that, if implemented, improve repository system robustness for the future. Overall, these key elements underpin a safety culture, procedural and technical baselines, succession planning, and contractor assurance.

The National Academy of Sciences panel, which comprises 15 senior professionals, evaluated excess plutonium disposal at WIPP, and a summary of its findings was presented. The committee was to evaluate the general viability of the US DOE's conceptual plans for disposing surplus plutonium at WIPP to support US commitments under the Plutonium Management and Disposition Agreement (PMDA) and identify actions that could be taken by the US DOE and other entities. The PMDA, which was signed by the US and the Russian Federation in 2000 and amended in 2010, commits both countries to disposing 34 metric tons of surplus plutonium by incorporating plutonium into mixed oxide (MOX) fuel followed by irradiation. The panel evaluated ideas and concepts of the US DOE, accounted for WIPP's current capacity, and provided the following conclusions and recommendations:

- The remaining statutory capacity as defined in the WIPP Land Withdrawal Act and New Mexico Environment Department permit at WIPP should be treated as a valuable and limited resource by the US DOE.
- The US DOE should assess prospects for successfully amending the existing legal agreements to allow diluting and packaging 34 metric tons of surplus plutonium at the Savannah River Site and its disposal in WIPP.
- If the dilute and dispose option becomes the program of record, the National Academy of Sciences panel strongly suggests that the US DOE consider empowering an independent technical review organization to provide oversight. This function is similar to that of the Environmental Evaluation Group during the licensing process for WIPP.
- In addition to and separate from the independent review organization representing the state of New Mexico, periodic classified reviews by a team of independent technical experts for Congress should be required until classified aspects of the dilute and dispose plan, including the safety and security plans, are completed and implemented.

The summary of the evaluation will be available in a final report in the summer of 2019.

8.3 Technical Barriers

As of the summer of 2017, StandAG stipulates a new procedure for siting a final HLW and SNF repository. The stipulation requires that all three potential host-rock formations (i.e., salt, clay, and crystalline rock) in Germany have to be considered. A safety concept for such a repository (depending on the type of host rock) relies on waste containment only by natural barriers (i.e., host rock and overburden), natural and geotechnical barriers (i.e., drift and shaft seals), or technical barriers (i.e., containers). These containers must provide safety functions of containment, shielding, subcriticality, decay heat dissipation, operability, and retrievability during handling and disposal and include a contingency for retrievability. Subsequently, containers have to provide these safety functions depending on the geological boundary conditions. Because only a single prototype container (POLLUX®) is available for a salt repository, Germany launched the RD&D project called KoBrA, which is a common undertaking of Bundesanstalt für Materialforschung und-prüfung (BAM) and BGE TEC. BGE TEC provided an overview of the project and results achieved thus far.

KoBrA's main objective is to systematically derive requirements for HLW and SNF containers and develop generic container concepts. Existing legislation and technical guidelines will be considered as well as international experience. The main container safety functions must be considered during the repository lifetime from operation to closure or, if required, during a retrieval period before final closure. The KoBrA project will eventually provide a set of design criteria and suggestions for generic container concepts. Parallel to the survey of the international state-of-the-art waste container design criteria, a methodological approach was developed to systematically derive container design criteria, as shown in

Figure 8-1. This approach comprises a stepwise derivation of requirements. Beginning with the general regulatory requirements and a chronological breakdown of requirements over the repository lifetime, generic significant container/package functions will be derived. The possible impacts on the package will also be considered. In a next step, package functions and possible impacts will be analyzed for generic repository systems in the three host rocks (e.g., drift disposal in domal salt). The last step comprises a quantification of package functions and impacts; thus, quantified design requirements will be achieved. The complexity of the process of deriving requirements according to this approach was illustrated by a few examples. The project's goal is to achieve sufficiently precise criteria to directly derive package concepts. By the end of 2019, the project results will be summarized and compiled in a report.

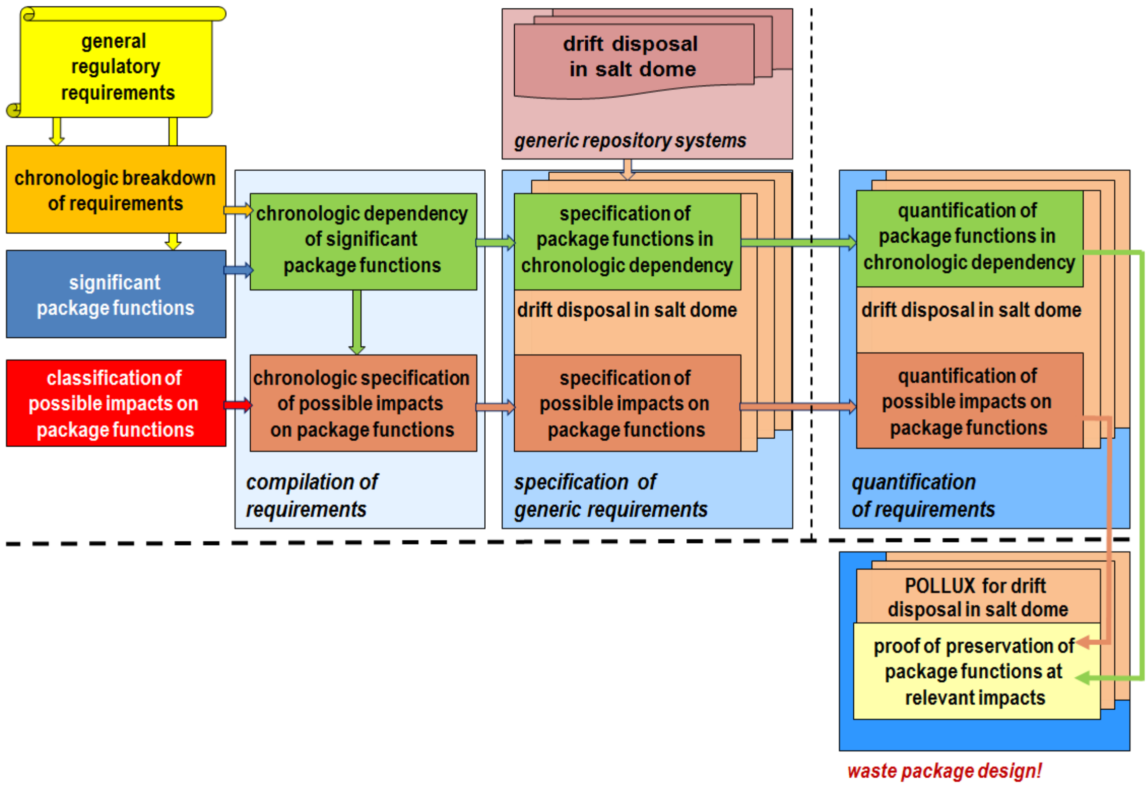


Figure 8-1. KoBrA Approach to Derive Waste-Package Design Requirements.

For comparison purposes only and without any link to the US national waste-management program, ideas to derive waste-package requirements and design approaches in the US were presented by SNL. The procedure to derive requirements is, in principle, similar to the approach explained by the BGE TEC. However, the approach is more related to a system-level, iterative, risk-informed process, which means that system performance objectives, site characterization, and trial concepts have to be considered from the very beginning of the package design approach. This approach includes screening regulatory requirements and developing package functions over the repository lifetime. An example was given for a license application design study for a canister and a disposal overpack for Yucca Mountain. According to the performance specification of the canister, functional analysis and requirements allocation were performed. Adequate materials were selected for package components according to the expected environment conditions and the lifetime of the package functions. Another example of investigations for an SNF container was presented. From 1995 to 2019, a few standardized, multimedia canister studies were performed in the US for safely and feasibly storing, transporting, and disposing commercial spent fuels. These studies include a multipurpose canister concept (1995) as well as a transport-aging-disposal canister (2019). The technical readiness level for each specification was evaluated for each of the waste containers considered. These investigations comprise three categories. Category A states that an engineering solution is evident or evidence exists in the international literature. Category B states that developments are technically feasible for the generic environment but require further study. Category C states that demonstrating feasibility for the generic environment requires resolving significant technical challenges. Criticality analyses were performed to exclude criticality during the operational period of the repository and after repository closure. In summary, extensive experience related to waste-package design is available in the US. However, if SNF will be disposed, then additional RD&D efforts are needed.

9 CONCLUDING REMARKS AND OUTLOOK

The contents of this report record activities of the 10th US/German Workshop on Salt Repository Research, Design, and Operation. This is the first year for UK participation, and they made significant contributions to this workshop and the subsequent Salt Club meeting of the NEA. Major technical areas of discussion are identified in the agenda (see Appendix A). Individual chapters written by subject-matter experts summarize presented material as well as verbal exchanges. All available presentations are assembled in Appendix D and provide a rich resource for salt repositories.

The breakout session paradigm was exceptional this year. Natural closure of salt openings was discussed at length because the topic is pertinent to contemporary deliberations of the WIPP compliance certification. Information from this workshop may be useful when the current representation of WIPP evolution is reviewed. A chapter on salt laboratory sample conditioning is sufficiently comprehensive that it warrants consideration for external publication in a reputable rock-mechanics journal. The combination of multiple testing laboratory experiences illustrated various conditioning effects, thereby establishing standard procedures that lead to better experimental results. This achievement exemplifies one of the main purposes for the workshops.

As the 10th workshop ended, commitments were made for the 11th meeting, which will be held in Braunschweig, Germany. Details of the 2020 workshop will be determined by the Steering Committee, but the venue has been arranged at the Steigenberger Parkhotel. Participants generally agreed that 2½ days would accommodate the workshop agenda more comfortably. Commencing at approximately noon on Monday, May 11, 2020, technical elements will run through Wednesday May 13, 2020. A geological field trip through the Harz Mountains is planned for Thursday, May 14, 2020. The NEA Salt Club meeting is tentatively slated for Friday May 15, 2020.

Suggested topics for the next gathering include ongoing RD&D projects involving engineered barrier systems and materials/backfill associated with that research. Geomechanics modeling will showcase analyses applying new laboratory testing data that are continually acquired by the laboratory partnerships. Design and engineering practices will be discussed, including use of modeling benchmarks. Actinide and brine chemistry activities are expected to be summarized along with ancillary special topics. Breakout sessions have not been identified at this time, but as is the usual practice, agenda topics and participant interests develop throughout the year. This routine generates a workshop that comprises contemporary and mutually beneficial content.

If I have seen further, it is by standing on the shoulders of Giants.

(Isaac Newton; 1675)

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Appendix A:

Agenda

Agenda as of May 14, 2019

10th US/German Workshop on Salt Repository Research, Design, and Operation

May 28th through 30th 2019

Venue: South Dakota School of Mines and Technology Campus, Rapid City (SD), USA

May 28 – Tuesday

Day 1	08:30-08:40	**Kick off** and organizational details	W. Bollingerfehr, BGE TEC M. Bühler, KIT-PTKA S. Dunagan, SNL
	08:40-08:50	Welcome	L. Roberts, SDSM&T
	08:50-09:00	Welcome remarks	T. Gunter, DOE
	09:00-09:10	Welcome remarks	H. Wirth, BMWi
	09:10-09:20	Welcome remarks	K. DeVries, RESPEC
	09:20-10:05	Invited lecture ‘10 years US/D Workshops’	F. Hansen
	10:05-10:20	IAEA presentation (short update)	A. Orrell, IAEA
	10:20-10:50	**Coffee Break** and **Group Photo**	
	HLW/SF Repository: National Programs and Site Selection Processes (chair: T. Gunter, DOE)		
	10:50-11:15	Repository site selection for radioactive waste in Germany – procedure	J. Rienäcker-Burschill, BGE
	11:15-11:40	Comparing the safety of different repository systems with only one yard stick	J. Mönig, GRS
	11:40:12:05	The Dutch national program: Towards a safety case in rock salt	J. Bartol, COVRA
	12:05-12:30	The UK’s site selection program	A. Shelton, RWM

10th US/German Workshop on Salt Repository Research, Design, and Operation

Day 1

12:30-13:30	**Lunch Break**	
	Topical Session: Modelling Challenges (chair: B. Reedlunn, SNL)	
13:30-13:50	Selected modelling challenges in R&D project WEIMOS	A. Hampel, Hampel Cons. S. Sobolik, SNL
13:50-14:10	Micromechanical Investigations in R&D projects WEIMOS and KOMPASS	M. Mills, SNL
14:10-14:30	Realistic modelling in R&D project KOMPASS – generic and/or specific	C. Lerch, BGE TEC
14:30-14:50	Modelling WIPP expansion	B. Belzer, RESPEC
	Breakout Session: Natural Closure of Salt Openings (chair: E. Keffeler, RESPEC)	
14:50-15:50	• *Purpose: Open discussion and examples of natural closure of mined salt openings.* • *Goal: To capture a range of possible conditions that can arise naturally over time or develop as a result of engineering measures such as back filling or sealing.*	3 - 5 short contributions selected by the chair person.
15:50-16:20	**Coffee Break**	
	Topical Session: Modelling Challenges cont'd (chair: Kris Kuhlman, SNL)	
16:20-16:40	R&D project BenVaSim Introduction to a Benchmarking of TH^2M Simulators and First Results	M. Rutenberg, TUC
16:40-17:00	Two-phase fluid flow calculations for a repository in a used mine in rock salt	G. Bracke, GRS
17:00-17:20	Basin-Scale Density-Dependent Groundwater Flow	J. Wolf, GRS
17:20-17:40	DOE-NE WIPP heater tests update	K. Kuhlman, SNL
19:00	**Workshop Dinner (Whole Hog Dinner at RESPEC)**	

May 29 – Wednesday

Day 2			
	Topical Session: Engineered Barrier Systems – Sealing Systems / Backfill (chair: M. Bühler, KIT-PTKA)		
	08:30-08:50	Fitting of magnesia cement for building of geotechnical constructions and injection grout	T. Meyer, BGE TEC
	08:50-09:10	Experiences from an In-Situ Test Site for a Sealing Element in Shafts and Vertical Excavations in Rock Salt	T. Schröpfer, BGE
	09:10-09:30	Planning of the WIPP barriers	R. Carrasco, NWP
	09:30-10:00	The KOMPASS project - Crushed salt behavior – why it has become so important	J. Wolf, GRS O. Czaikowski, GRS
	10:00-10:30	MgO shotcrete for engineered barrier systems in salt formations - in situ tests with inflow of $MgCl_2$ bearing solution (R&D project MgO-SEAL)	D. Freyer, TU BA Freiberg T. Popp, IfG GmbH
	10:30-10:50	**Coffee Break**	
	10:50-11:10	In situ testing of a new long-term stable backfill material for HAW repositories in saline formations: Backfill methods, in situ measurement system and backfill behavior (R&D project GESAV II)	S. Pötzsch, TU BA Freiberg
	11:10-11:30	Potential Backfill Materials in the UK	A. Shelton, RWM
	Breakout Session: Test Sample Conditioning (chair: S. Buchholz)		
	11:30-12:30	• *Purpose: To identify and discuss influences of sample conditioning on mechanical behavior.* • *Goal: To summarize standard procedures and best practices. Perhaps issue a joint standards resolution on behalf of the Salt Club.*	3 - 5 short contributions selected by the chair person.
	12:30-13:30	**Lunch Break**	

Penultimate Agenda as of May 14, 2019

10th US/German Workshop on Salt Repository Research, Design, and Operation

Day 2

Special Topics (chair: W. Bollingerfehr, BGE TEC)		
13:30-13:50	Research activities in stratiformal rock salt in Germany	J. Lippmann-Pipke, BGR
13:50-14:10	CO_2 production rates from organic waste in saline solutions a) Relevance in the context of Schachtanlage Asse II	M. Altmaier, KIT-INE
14:10-14:30	CO_2 production rates from organic waste in saline solutions b) Modelling approach and quantification	L. Wissmeier, CSD / J. Mönig, GRS
14:30-14:50	Simulations of a Heated Borehole Experiment at WIPP: Early Results	P. Stauffer, LANL
14:50-15:20	**Coffee Break**	
Technical Barriers & Operational Safety (chair: S. Dunagan, SNL)		
15:20-15:40	How to correctly derive requirements for waste packages designed for SF and HLW – The R&D project KoBrA	W. Bollingerfehr, BGE TEC
15:40-16:00	Waste Package Requirements and Design Approaches in the US	E. Hardin, SNL
16:00-16:20	Summary of the National Academy of Sciences panel covering WIPP	A. Orrell, IAEA
16:20-16:40	Operational Safety: WIPP - lessons learned	R. Carrasco, NWP
16:40-17:00	Wrap up and outlook	W. Bollingerfehr, BGE TEC M. Bühler, KIT-PTKA S. Dunagan, SNL
May 30 – Thursday		
Field Trip		
09:00-15:00	Geology of the Black Hills	RESPEC

Day 3

Penultimate Agenda as of May 14, 2019

10th US/German Workshop on Salt Repository Research, Design, and Operation

Organized by:	• Sandia National Laboratories • Project Management Agency Karlsruhe (PTKA), Karlsruhe Institute of Technology (KIT) • BGE TECHNOLOGY GmbH, Peine
Locally assisted by:	• RESPEC • South Dakota School of Mines and Technology
Registration:	https://foundation.sdsmt.edu/salt-workshop
Costs:	$250 (payment with registration) This will include catering for light breakfast, lunch, and breaks for 2 days. Field trip expenses and supper on May 28th are also included.
Venue:	South Dakota School of Mines and Technology Campus 501 E. Saint Joseph St., Rapid City
Program committee:	W. Bollingerfehr (BGE TEC), S. Dunagan (SNL), M. Bühler (KIT-PTKA)
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Appendix B:

List of Participants and Observers From the 10th Workshop

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41	Bühler, Michael	KIT
42	Bollingerfehr, Wilhelm	BGE TECHNOLOGY
43	Gunter, Tim	DOE
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Appendix C:

Abstracts

Update on the UK Geological Disposal Facility Siting Process

Dr Amy Shelton, Senior Research Manager

Radioactive Waste Management

Nuclear technology has been a part of our lives in the UK for over 60 years and is used in power generation, industry, medicine and defence. Today, nuclear energy provides almost a fifth of the UK's electricity. These activities have created radioactive waste which we need to manage safely. Radioactive Waste Management (RWM), a subsidiary of the Nuclear Decommissioning Authority (NDA), is responsible for implementing Government policy on the management of High Activity Waste through geological disposal.

Geological disposal is one of the UK's largest ever environmental protection projects, which will provide a safe and secure long-term solution for the disposal of higher activity radioactive waste. This presentation provides an overview of the process to identify suitable sites and engage and work with communities in the development of this major infrastructure project.

KOMPASS - Compaction of granular salt for the save enclosure: WP3 Modeling

C. Lerch
10. US/German Workshop on
Salt Repository Research, Design and Operation,
Rapid City, USA
May 28-29, 2019

ABSTRACT

The KOMPASS project is a joint project of six organizations from the US and Germany in which the behavior of granular salt is investigated with regard to its limits with respect to proofs in a repository for radioactive waste.

The concept of the containment providing rock zone CRZ /BMU 2010/ leaded to a change in the verification procedure and in the requirements for individual components of the repository. In particular, backfill material of the open cavities has become much more importance if this material has to replace the technical barriers function in the long term. The evidence to be applied for this condition corresponds to that of the geological barrier - the proof of minor release. This proof presupposes, on the one hand, that transport through the backfill material can be described. A realistic determination of the permeable behavior of the granular salt is necessary among other things. On the other hand a potentially present fluid does not lead to a damage of the achieved condition in the backfill. The first proof is preferably located on the hydraulic side while the second is primarily the determination of the stress state in the misalignment and thus primarily a mechanical evaluation.

The consideration of the behavior from backfill under the conditions of a repository for heat-generating waste is essentially a THMC-coupled process. The major part of the chemical process class is seen in the area of dissolution and recrystallization; this behavior is initially assigned to the hydro-mechanical behavior.

The thermal behavior is the most advanced process between all the other processes, sub-processes and coupling processes with respect to the verification procedure. Models exist which map the expected processes and the measured behavior well.

The hydraulic behavior can also be well described in a wide range of the behavior of a granular material. In the area of low residual porosities, however, the experimentally determined data show behavior that cannot be clearly identified at this point in time. Dilatant rock salt shows a hydraulic behavior, which is not only described by the state of loosening. Although there are fundamental differences in the pore structure between a highly compacted crushed salt and a damaged rock salt, the above-mentioned aspects show that further efforts are required both on the experimental and on the model analytical side in order to successfully pass a verification procedure.

The hydraulic behavior of the granular material can only fill its central position in the verification concept if, in addition to the hydraulic behavior mentioned above, the mechanical behavior of this material is well described. This mechanical behavior consists of a number of different sub-processes. Experimental investigations and physical models enable the determination and characterization of these sub-processes including the state and field variables influencing them. In addition to global aspects, the characterization of the sub-processes describes specific behavior.

It should be noted that humidity is an essential field variable of mechanical behavior of crushed salt. The presence of moisture is a necessary prerequisite for individual sub-processes, and with sufficient moisture content, this sub-process becomes a decisive deformation process. The transition between the dry and a sufficiently humid state can take place in a very small interval of moisture.

If the constitutive models currently used within the joint project are considered, there are individual constitutive laws as well as some variants of the CWIPP model. This reference to CWIPP is due to the early project status and is primarily caused by the calculation program used. Whether and to what extent individual sub-processes are taken into account in the respective constitutive laws depends on the stage of development of the respective constitutive model, but also on the previous intended use. There are many differences between the partial constitutive models of the project partners. For example, dislocation creep is described by three summands in the case of the constitutive model Callahan et al. while in the other cases only one is used. A further example is the stress dependence, which in the case of Callahan et al. in addition to the first stress invariant and second invariant of the stress deviator, as in the other models, contains the Lode angle as the third invariant of the stress tensor. Or: Volumetric and deviatory creep rates are described together within one differential equation for some models, and by separate differential equations in others. Thus, the differences between the constitutive models become obvious at the equation level, but they can already be seen in a more dense form from the extent of the field and state variables taken into account. A few remarks:

The compaction process is over a long distance a process that is determined by the interaction between the salt grain particles. The degree of compaction achieved is described by the porosity. However, only two material models contain the possibility of treating different grain structures with the same porosity.

At least in Germany, the application purpose is predominantly limited to the area of dry crushed salt. If a material model with only one viscous deformation mechanism is used in a simulation, the simulation of a wetted condition is represented by a modified second parameter set and not, as required, by a corresponding partial constitutive law.

In a first step of the project, a suitable parameter basis for the respective constitutive model will be established on the basis of an essentially isotropic five-stage compaction test for dry crushed salt. The comparison with a standard parameter set also allows to estimate special features in the experimental test or in the standard parameter set. On the basis of the found parameter basis, the extent to which the individual constitutive laws reflect the characteristics in the partial constitutive models is compared. So, the further development of the constitutive models can take place on this basis and in interaction with the other work packages in this joint project.

/1/ BMU: Sicherheitsanforderungen an die Endlagerung wärmeentwickelnder radioaktiver Abfälle. Stand: 30. September 2010. Berlin: BMU, 2010. (https://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/sicherheitsanforderungen_endlagerung_bf.pdf)

Brett E. Belzer, RESPEC

MODELING THE WIPP EXPANSION

Abstract: The existing waste panels at the Waste Isolation Pilot Plant (WIPP) will soon be filled and an expansion to the west for additional waste panels is planned. To expand, a new set of mains must be mined to connect the new waste panels to the existing and planned infrastructure. The new mains will need an operational life of at least 30 years and should be more functional with reduced ground-control maintenance requirements than the current mains. The design process was divided into three tasks: 1) preconceptual design using the Van Sambeek salt-pillar equations, 2) validation of computer modeling approach and development of stability metrics, 3) detailed geomechanical modeling to develop conceptual designs toward a final design. Empirical evidence along with a new modeling approach to predicting the behavior of excavations over the next 30 to 50 years were used in the design process. The focus of this study was to provide a mains design capable of providing better ground-conditions and less operational maintenance compared to the current mains design. At the end of this study, a new mains system was recommended that is expected to substantially reduce stresses that cause low angle shear fractures to form and distress the ground control system thus extending the time to first major ground control rehab and reducing long term maintenance efforts.

Basin-Scale Density-Dependent Groundwater Flow

Kristopher L. Kuhlman (SNL), Jens Wolf and Anke Schneider (GRS)

The first three-dimensional transient basin-scale groundwater flow model of the overburden of the Waste Isolation Pilot Plant (WIPP) was created by SNL in the 1990s (Corbet & Knupp, 1996). The model was covering an area of about 8,700 km² and consisting of 10 flat bedded layers, describing the hydrogeologic units above the Salado salt formation, the Rustler Formation and the Dewey Lake Formation. The numerical grid was consisting of only 18,000 hexahedrons. At that time, it was not possible to regard the influence of density effects on the flow regime.
Currently, SNL and GRS are recreating the old model using their modern numerical flow and solute transport codes, PFLOTRAN (SNL) and d^3f++ (GRS). The models will be set-up including density-driven flow and with finer numerical grids. Finally, a comparison of the results is planned.
Preliminary results will be presented and a roadmap for the next works and developments will be given.

Modyfing magnesia cement for preparing geotechnical constructions and injection grout

Thomas Meyer, Nina Müller-Hoeppe, Lieselotte v. Borstel, Joachim Engelhardt
(BGE TECHNOLOGY GmbH)
Antje Carstensen, Lutz Teichmann, Matthias Heydorn, Marcus Tresper
(BGE GmbH)
10th US/German Workshop "Salt Repository Research, Design, and Operation"
May 28th / 29th, 2019 / Rapid City

ABSTRACT

Since 2007, construction materials with MgO as binding agent and $MgCl_2$-solution as mixing liquid have been playing an important role in the stabilization of mine openings and the sealing of drifts, shafts, and boreholes as well as of cracks and fissures in the Asse II Mine, Germany. Due to the different sizes of the openings and the technical equipment applied, different material compositions have been developed. The basic binder components combine to 3 $Mg(OH)_2$ x 1 $MgCl_2$ x 8 H_2O in the long-term, the so-called long-term stable 3-1-8-phase (Sorel phase). By adding several aggregates in size and quantity to the binder, four recipes are currently used in routine operation.

- Mainly Sorel concrete A1 is used as construction material for flow barriers and as backfilling material. Its aggregate is salt grit with a maximum grain size of 4 mm.
- Sorel concrete A0 is used to bind up to 18% NaCl-brine.
- For filling wide gaps and boreholes, IM-Asse-1 is used. It contains a higher amount of $MgCl_2$-solution and a fine-grained salt aggregate with a maximum grain size of 0.3 mm.
- MFBBa-17/3/30 is used to inject cracks and fissures. To this mixture, brucite is added as slow reacting binding agent and barite powder as very fine grained aggregate with a grain size of 5 µm.

The development of these Sorel materials was carried out both above ground and in an underground laboratory on the 490/750-m-level in the Asse mine to take into account the specific mine climate. An above ground laboratory is available to investigate and control all components of the Sorel materials, e.g. by carrying out mineralogy analyses using X-ray diffraction and grain size measurements with a laser granulometer. Special medium-scale investigations underground were used to test the suitability of the mixtures with respect to their individual applications and to gain experience for setting up and establishing the quality assurance program for the underground conditions. For example, the following medium-scale tests were performed:

- expansion tests in casks equipped with strain gauges
- penetration measurements in glass casks
- column tests with and without pressure

One of the important principles in all development phases was to upscale the research procedure step by step from small-scale (3 – 5 l) to medium lab scale (ca. 30 – 40 l) to pilot scale (3 – 5 m^3) and eventually industrial scale (> 800 m^3). All steps were accompanied by a strict quality control program. This procedure minimizes mistakes caused by scaling factors.

In parallel to the development process, repeated discussions with the mechanical engineers were necessary to find the best way to produce the Sorel materials that are best suited for the in-situ conditions.

Within the scope of the emergency measures carried out at the Asse mine, the successful use of Sorel material has been demonstrated. Up to now, approx. 350.000 m^3 of Sorel material have been placed in routine operation.

Experiences From An In Situ Test Site For A Sealing Element In Shafts And Vertical Excavations In Rock Salt

Jan Bauer, Monika Kreienmeyer, Beatrix Stielow, Thomas Schröpfer, Jürgen Wollrath
10. US/German Workshop on Salt Repository Research, Design and Operation,
Rapid City, US America
May 28-29, 2019

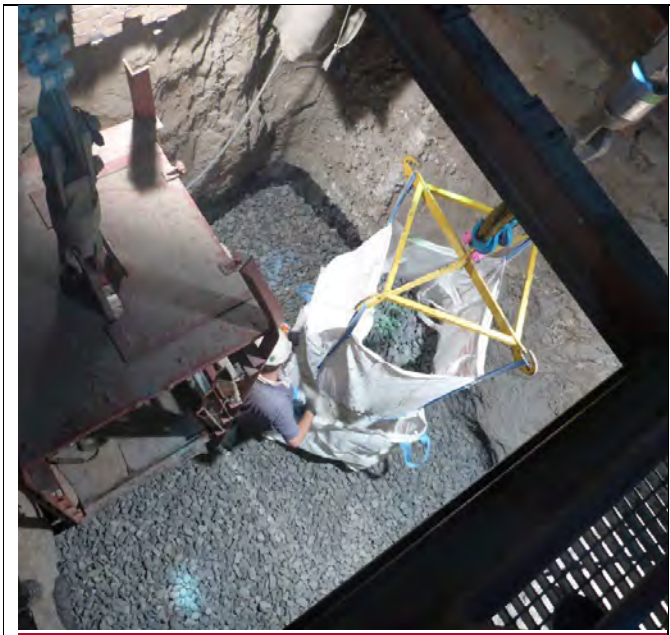
ABSTRACT

The repository for radioactive waste at Morsleben (ERAM) in Germany contains low-level and intermediate-level waste with a volume of about 37.000 m³, which is disposed of in different locations of the mine. Currently, the repository is under licensing for closure. The closure concept includes extensive backfilling of cavities and drifts and sealing of the two shafts. In addition to this, several horizontal and one vertical sealing element are to be built to separate the emplacement areas from the other mine areas. All these sealing structures are to prevent both brine inflow into the mine and release of radionuclides into the biosphere.

The shafts will be sealed with a combination of sealing elements consisting of gravel, asphalt, bitumen, and clay. The sealing concept using gravel and asphalt and/or bitumen will be used to seal one ventilation shaft that connects several horizontal drifts. In order to demonstrate that these sealing elements can be constructed with the quality assumed in the safety assessments, several tests have been carried out. In 2015, a large-scale in-situ test was carried out to simulate the construction of the future sealing elements /1/.

Taking into account the concept and the requirements for the future sealing elements, a test location was chosen at the ERAM. The main goal was to show the technical feasibility of constructing a plug made of gravel and asphalt under the logistic constraints underground while meeting occupational health and safety requirements concerning working with about 190°C hot asphalt in a vertical excavation. Additionally, the influence of the hot asphalt on the surrounding rock salt and the pressure resulting from the asphalt filling the pores between the grains of the gravel were measured.

The test was carried in a ventilation shaft with a nearly square base area of about 12 m^2. After construction of an abutment made of gravel and several filter layers, a sealing element with a total height of approx. 6 m was built. The last filter layer was equipped with pressure and temperature sensors. Additional temperature sensors were installed on the rock salt surface. Construction of the sealing element consisted of the following steps: A layer of about 0.5 m of gravel was poured into the shaft and compacted. This layer was then covered with hot asphalt. After a certain cooling time, the next layer of gravel was poured. This process was repeated several times with waiting times for cooling ranging from approx. 12 hours to three days.

All quality requirements were met, and all occupational health and safety measures were implemented successfully. The material properties were checked by sample testing and the construction process was monitored by quality measures. The quality of the filling was assessed from the measured pressure and by calculating the remaining pore volume between gravel grains and asphalt based on the masses of the materials used and the previously measured volume of the excavation. The calculations showed a remaining pore content of about 1.5%, which is below the target value of 3% typically applied in water engineering /2/. The pressure measurements show that the asphalt acts like a liquid. Extensive testing has shown that the vertical sealing elements can be built as assumed /3/.

/1/ TU Bergakademie Freiberg (2013): Durchführung eines Großversuchs über Tage zur Optimierung der Einbringtechnologie bei der Herstellung der Widerlager-Dichtelemente aus Bitumen und Schotter (BiSETO), 20.06.2013

/2/ DVWK-Merkblätter zur Wasserwirtschaft (1992): "Asphaltabdichtungen für Talsperren und Speicherbecken".- Heft 22,

/3/ Stielow, B.; Wollrath, J.; Ranft, M.; Kreienmeyer, M.; Schröpfer, Th.; Bauer, J.: Experiences From An In Situ Test Site For A Sealing Element In Shafts And Vertical Excavations In Rock Salt, DOPAS 2016, International Topical Seminar on Plugging and Sealing, Turku, Finland, May 25-27 2016

Stefan Pötzsch, TU Frieberg

In-Situ Testing of a new Long-Term Stable Backfill Material for HAW-Repositories in Saline Formations

In the R&D project GESAV II, technologies for the backfilling with matrix-stabilized crushed rock salt are investigated for suitability and further developed. In the foregoing project GESAV I, a long-term stable backfill material for the refilling of HAW repositories in saline formations was developed on a laboratory scale. The special feature of this material is that the long-term stability of the binder is based on the formation of polyhalite.

The aim of the current project is to raise the Technology Readiness Level from 4 to 7. For this purpose, an underground test site stand was designed and set up in the "Glückauf" salt mine in Sondershausen.

In the in situ tests, backfill technology on a scale of 1:1 is used. So far, three test locations have been backfilled with the following technology: Pneumatic stowing, slinger fill and push fill with subsequent vibratory compaction. The three backfill bodies created in this ways are monitored by measuring technology and then sampled for laboratory tests.

The following objectives have so far been achieved in the GESAV II project:

- Proof of a maximum settlement of 0.28 %

- In-situ detection of the long-term stable binder polyhalite

- Development of a moisture-based monitoring concept

- Continuous adaptation and improvement of the offset technology

- Development of a sampling concept

Integrated project to develop backfill materials for the range of geological environments and waste types.

Dr Amy Shelton, Senior Research Manager

Radioactive Waste Management

The material chosen as backfill in a geological disposal facility will fulfil a number of safety functions as part of a multi-barrier disposal concept. The required safety functions, and their relative importance over time, will vary depending on the disposal concept adopted. The requirements placed on the backfill will be both site-specific and concept-specific. As the siting process develops, it will be necessary to progressively expand RWM's knowledge base on backfill properties, to ensure that backfill options are feasible, cost-effective, and practicable to emplace, and to build confidence that they can be delivered with robust and achievable QA standards. It will also be important to ensure that the scientific and technical levels of maturity concerning backfilling are sufficient at each stage of the siting process to ensure the GDF programme can be delivered with confidence.

RWM have recently established an integrated project working in collaboration with supply chain colleagues to coordinate the development of essential scientific, technological and engineering activities to enable the development of backfill technology as part of a future Geological Disposal Facility. This presentation will provide an overview of the project aims and objectives and the approach taken to developing a programme Roadmap to deliver suitable backfill materials from conceptual stage, through to industrialisation for the range of geological environments considered as part of the UK siting process.

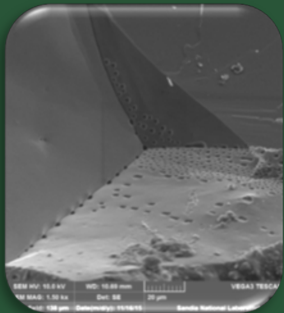
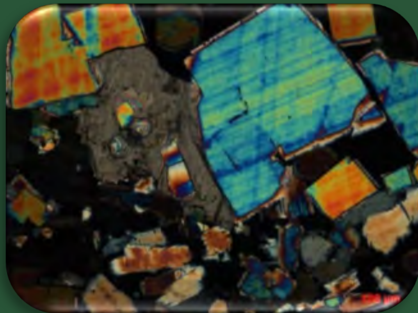
P. Stauffer, LANL

<u>Simulations of a Heated Borehole Experiment at WIPP: Early Results</u>

We report results from a shakedown test in a sub-horizontal borehole in the underground at WIPP that includes a 10.2 cm diameter borehole equipped with a heater surrounded with smaller diameter boreholes instrumented with thermocouples. The central borehole contains an inflatable packer, heater, and constantly flowing nitrogen gas circulation system. In the heated borehole, nitrogen gas circulation outflows to a desiccant container where water mass is measured daily during the experiment to quantify vapor removal. Thermocouples in the nearby boreholes allow us to determine the efficiency of several heater arrangements.

Appendix D:

Presentations

10th US/German Workshop on Salt Repository Research, Design, and Operation

Sandia National Laboratories

BGE TEC
BGE TECHNOLOGY GmbH

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

RESPEC

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

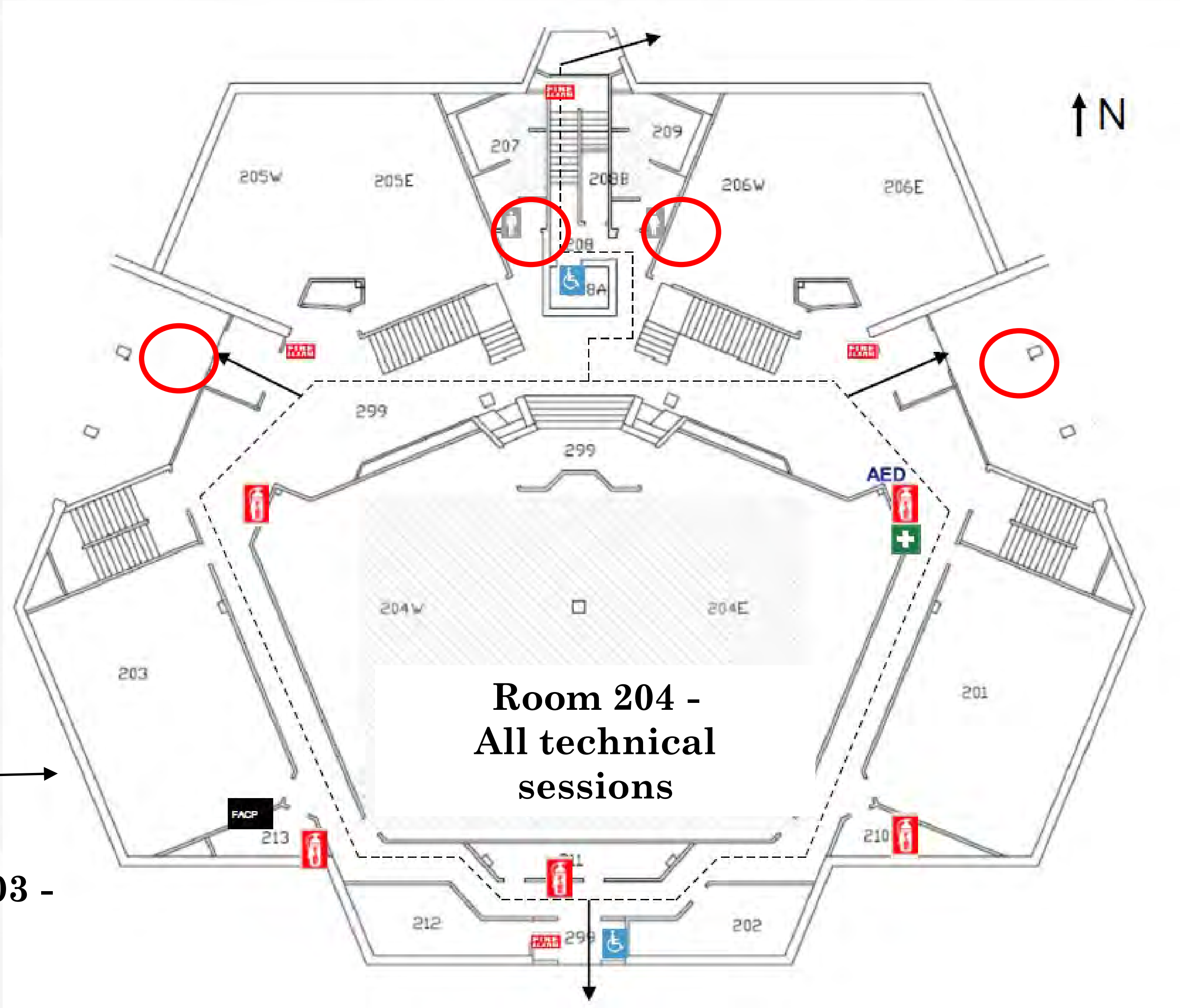
Lance A. Roberts
South Dakota School of Mines and Technology

Rapid City, SD, United States
May 28-30, 2019

WELCOME to the SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY!!

If you think the weather is bad today, check out last week….

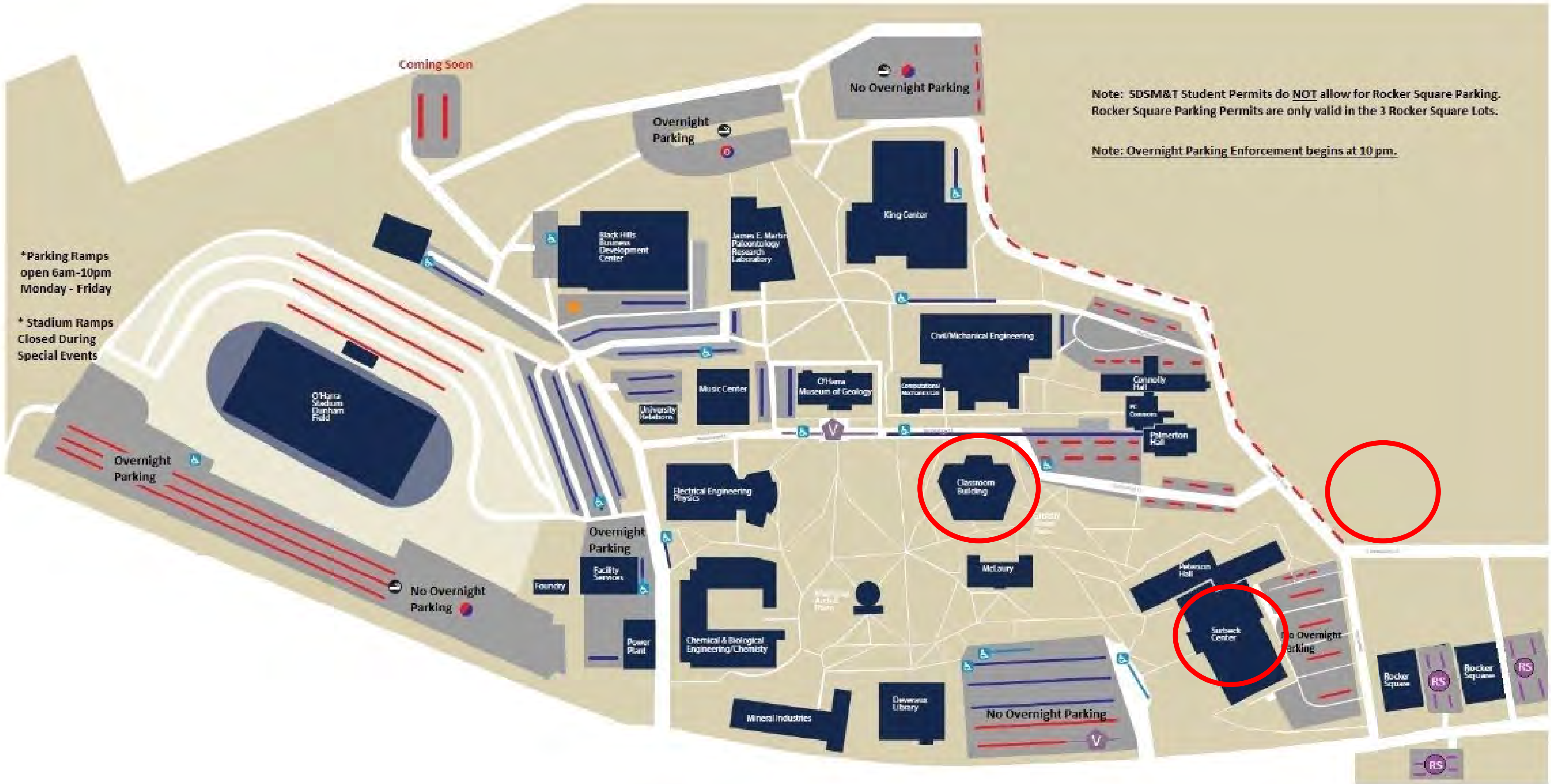
Classroom Building



Room 204 - All technical sessions

Room 203 - Breaks

South Dakota School of Mines



SD Mines is a tobacco-free campus! Smoking must be done at locations off-campus.

We hope you enjoy your time here!

My contact information:

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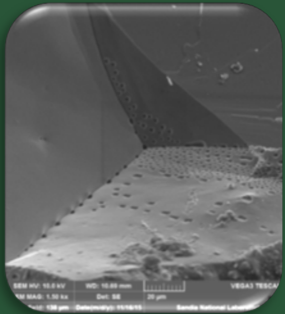
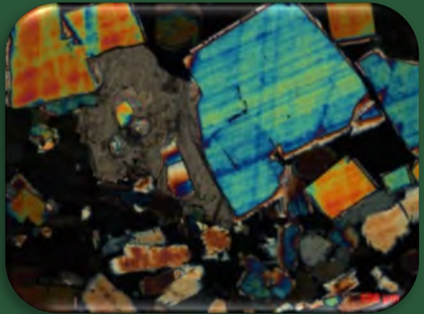
Phone: (605) 394-1973

Ten-Year Review of US/German Collaboration in Salt Repository Research

Sandia National Laboratories

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BGE TECHNOLOGY GmbH

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

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SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

Frank Hansen, PhD, PE
RESPEC

Rapid City, SD, United States
May 28-30, 2019

2010 — CLINTON, MS

1. Features, events, and processes
2. Natural analogues
3. Safety case
4. Materials, including reconsolidating salt and concretes
5. Seal systems
6. Operational safety
7. Laboratory testing
8. Constitutive modeling – Joint Project and WEIMOS
9. Salt Club outreach
10. Knowledge preservation

2011 — PEINE, GERMANY

1. Features, events, and processes
2. Natural analogues
3. Safety case
4. Materials, including reconsolidating salt and concretes
5. Seal systems
6. Operational safety
7. Laboratory testing
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10. Knowledge preservation

2012 — ALBUQUERQUE, NM

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7. Laboratory testing
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9. Salt Club outreach
10. Knowledge preservation

2013 — BERLIN, GERMANY

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

1. Features, events, and processes
2. Natural analogues
3. Safety case
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2014 — SANTA FE, NM

1. Features, events, and processes
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7. Laboratory setting
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2015 — DRESDEN, GERMANY

1. Features, events, and processes
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2016 — WASHINGTON, DC

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

1. Features, events, and processes
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2017 — COVRA

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

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10. Knowledge preservation

2018 — BGR HANOVER, GER.

1. Features, events, and processes
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3. Safety case
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6. Operational safety
7. Laboratory setting
8. Constitutive modeling – Joint Project and WEIMOS
9. Salt Club outreach
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2019 — RESPEC/SDSMT

1. Features, events, and processes
2. Natural analogues
3. Safety case
4. Materials, including reconsolidating salt and concretes
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7. Laboratory testing
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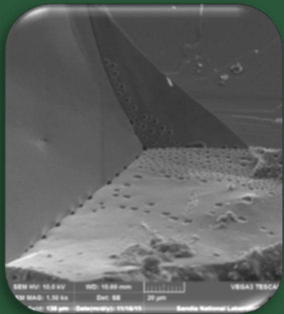
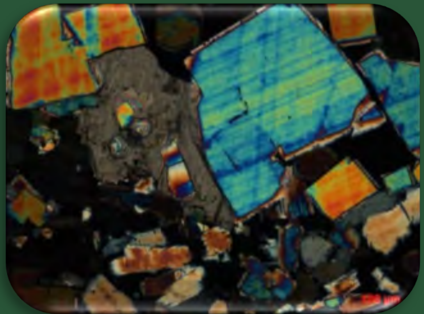
10. Knowledge preservation





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Federal Ministry for Economic Affairs and Energy

Julia Rienäcker-Burschil
BGE mbH – Bundesgesellschaft für Endlagerung mbH

Rapid City, SD, United States
May 28-30, 2019

Outline

- Re-start of the site selection procedure in Germany
- What is the BGE?
- Repository for high-level radioactive waste
- The site selection procedure
- Outlook and challenges

Re-start of the site selection procedure in Germany

2011

After Fukushima the Federal Government decides to develop a new geological criteria-based procedure with the energy concept of June 6, 2011.

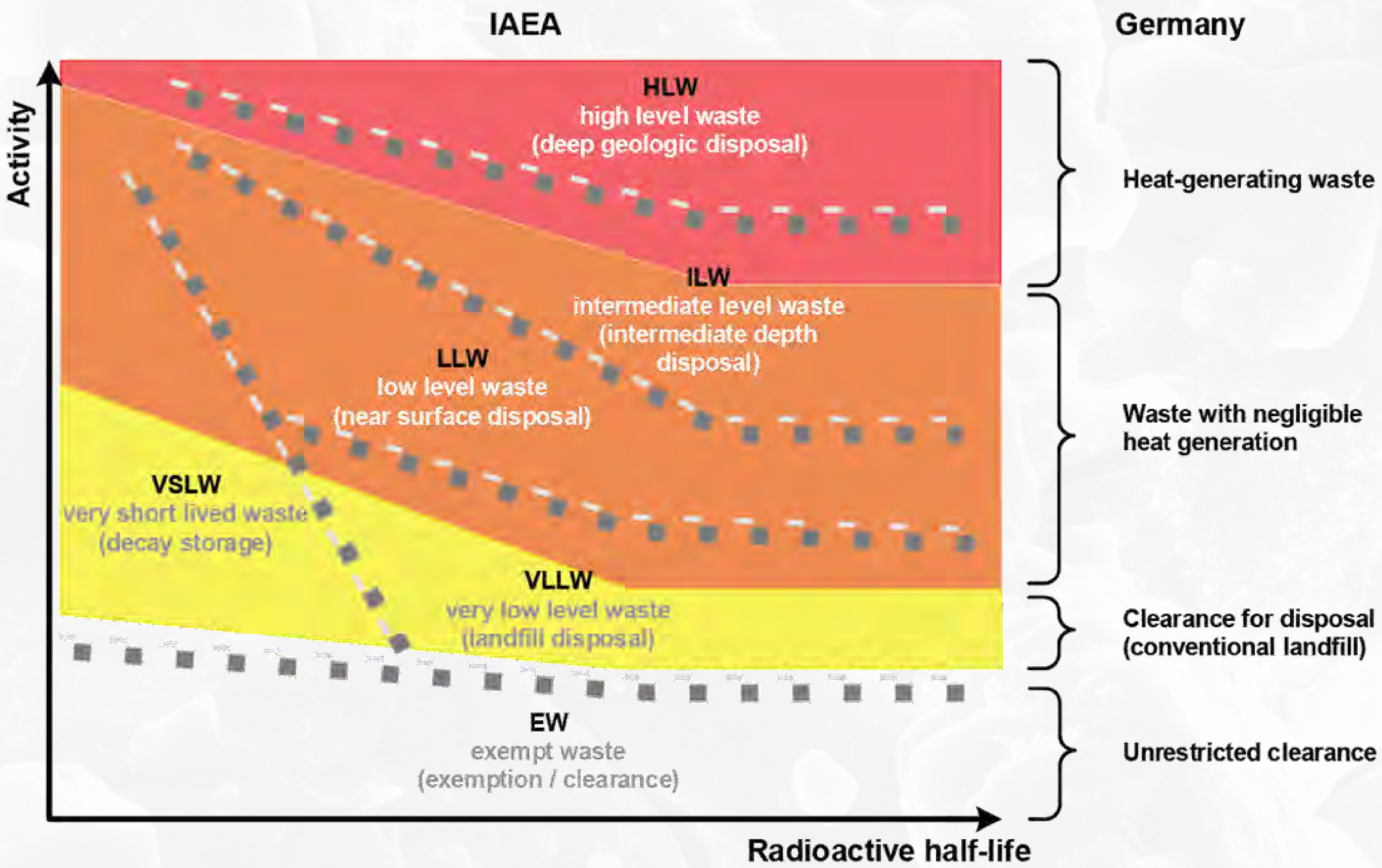
2013 - 2017

New regulation of the repository search and responsibilities.

The *StandAG* (Repository Site Selection Act) comes into force. The aim is to find the best possible site for a repository for high-level radioactive waste.

The operational tasks of site selection, completion of Konrad repository, closure of the Morsleben repository, and retrieval of radioactive waste from the Asse II mine are to be bundled in a state-owned company, the Bundesgesellschaft für Endlagerung mbH (BGE, Federal Company for Radioactive Waste Disposal).

Classification scheme for radioactive waste

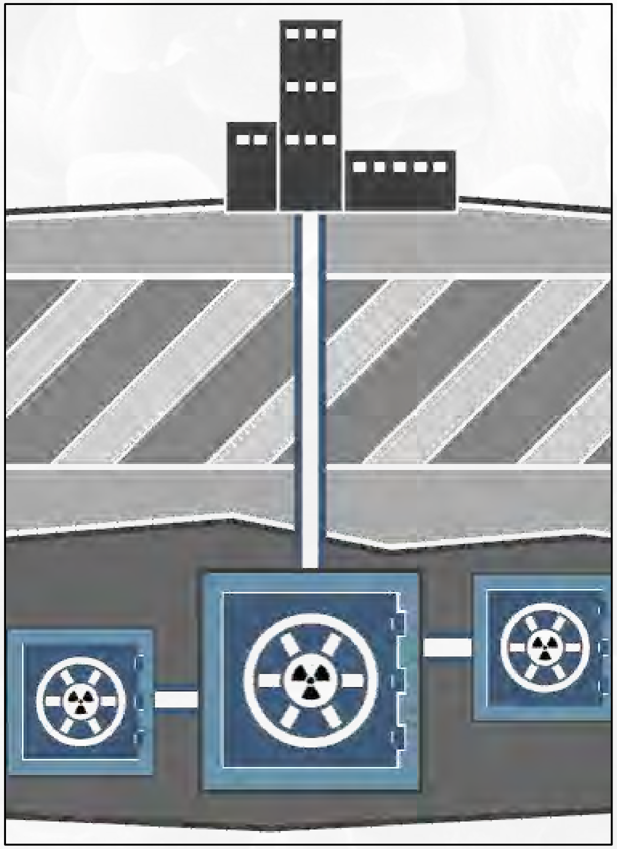


What is the BGE?

- Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
  - Federal Company for Radioactive Waste Disposal (BGE mbH)
    - Asse II mine
    - Repository Morsleben
    - Repository Konrad
    - Product Control
    - Site selection

- Established in 2016
- Around 1,900 employees
- Management Board:
  - Stefan Studt (chair), Beate Kallenbach-Herbert, Steffen Kanitz, Dr. Thomas Lautsch

Repository for radioactive waste



- Location within the Federal Republic of Germany
- Deep geological storage
- Best possible safety for a range of 1 million years
- Retrievability during operating phase
- Retrieval for 500 years after closure of the mine
- Science-based and transparent selection procedure
- Self-questioning process and learning organization

The site selection procedure

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

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

Publication of sub-areas
III. Quarter 2020

Site determination
2031

Phase I

Identification of sub-areas
(§ 13 StandAG)

Determination of regions
(§ 14 StandAG)

Phase II

Surface exploration
(§ 16 StandAG)

Phase III

Underground exploration
(§ 18 StandAG)

Application of:

1. Exclusion criteria
2. Minimum requirements
3. Geological weighting criteria

Realization of the site selection procedure

§ 13 Identification of sub-areas
Starting point: blank map of Germany

Data basis:
Available geoscientific data from federal and regional authorities out of all federal states

1. Application of exclusion criteria

2. Application of minimum requirements

3. Application of geological weighing criteria

Determination of regions with favorable geological conditions

BGE publishes interim report „site regions“

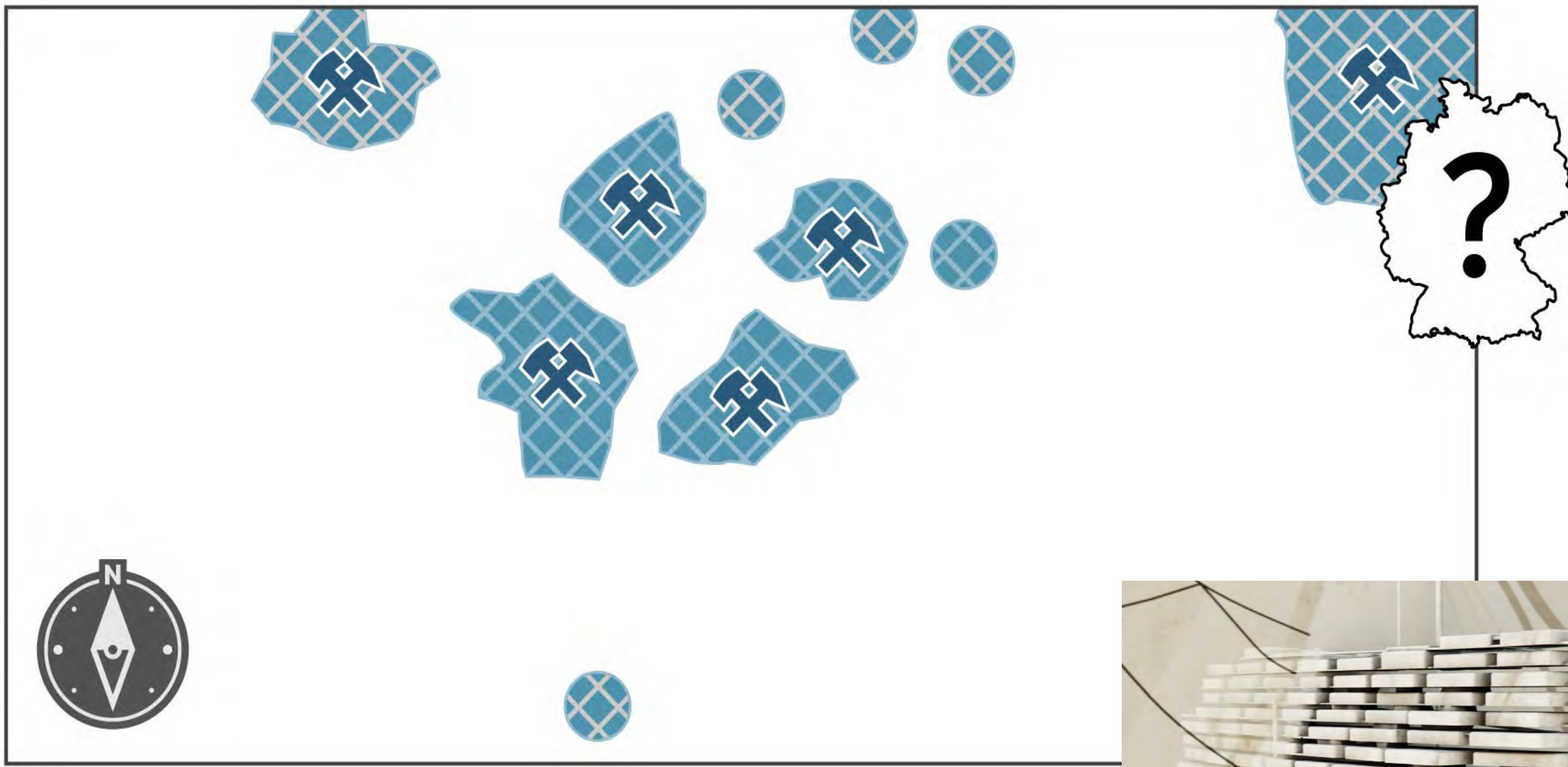
Exclusion Criteria

Exclusion criteria

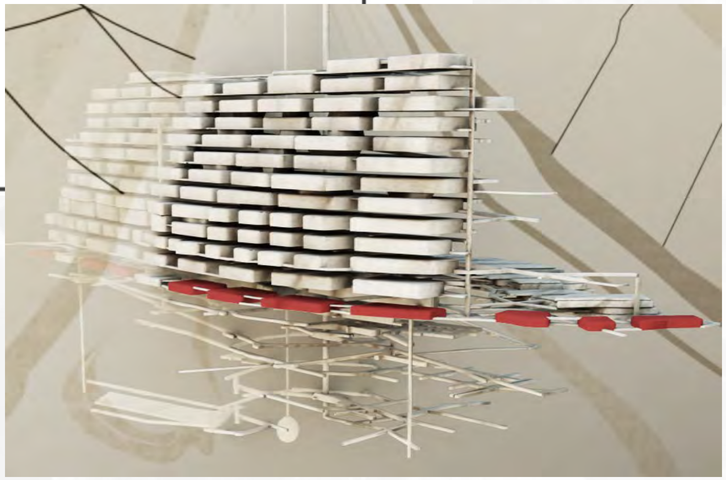
An area is not suitable, if at least one exclusion criteria is met:

- mining activities or drill holes
- active fault zone
- quaternary volcanism exists or volcanic activities are expectable
- local seismic activity is higher than in earthquake zone 1 (DIN EN1998-1/NA 2011-01)
- Large-scale uplift of more than 1mm/year over 1 mio. years
- young groundwater occurs in the effective containment zone or emplacement area

Application of criteria mining activity

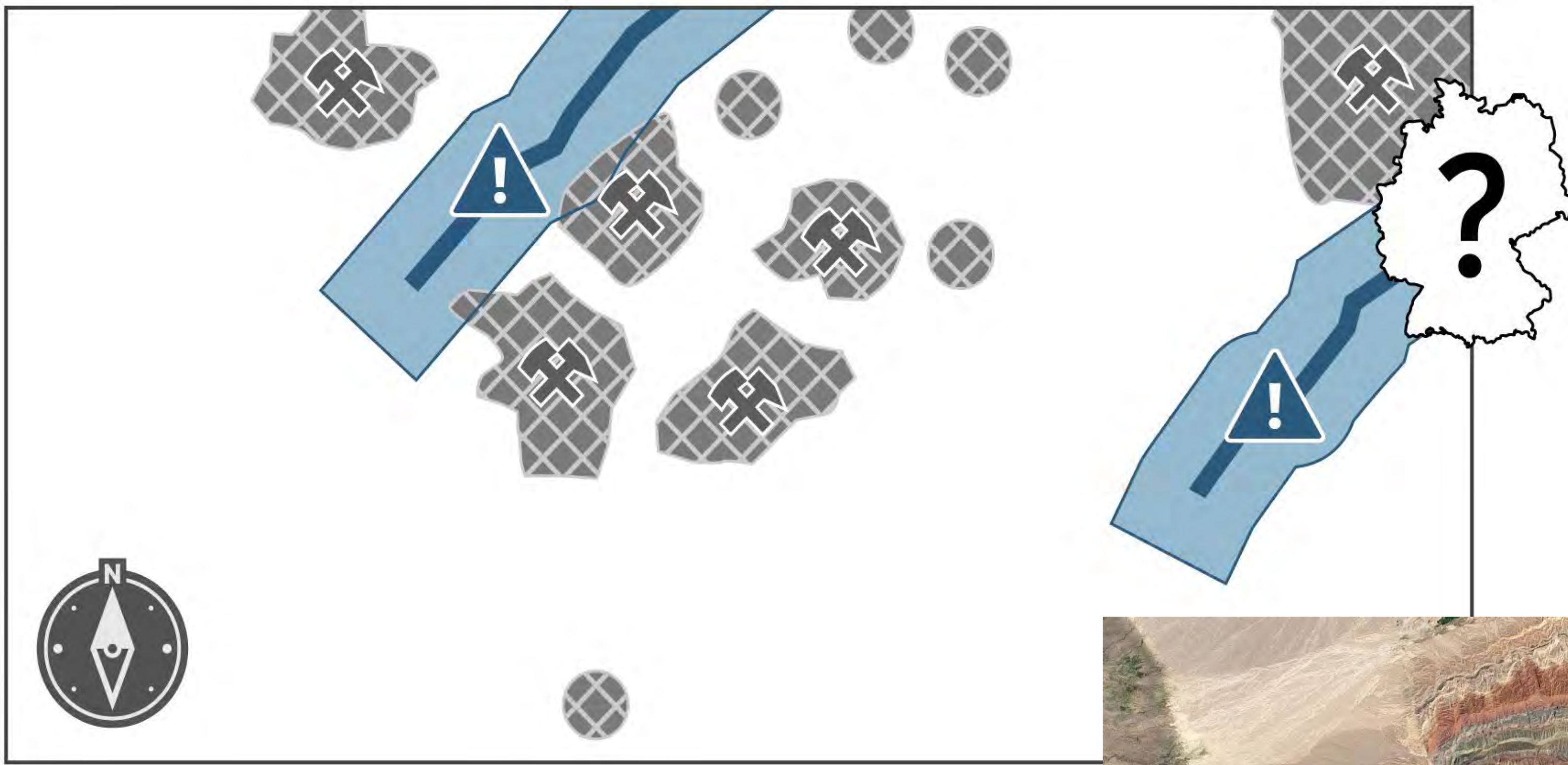


Mining activities and boreholes



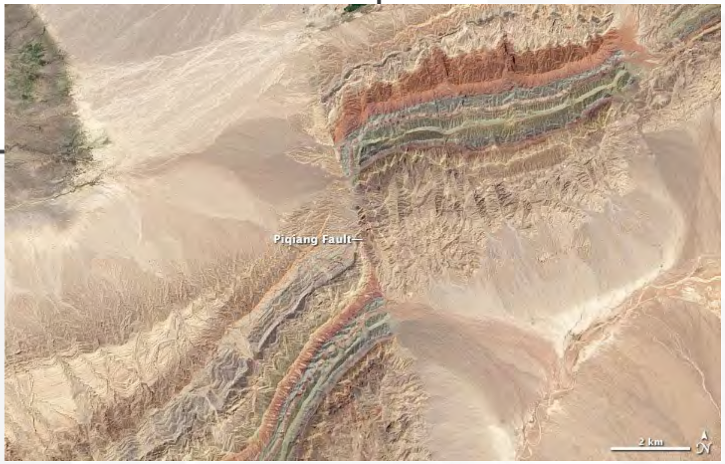
Exemplary: mine shaft Asse II, Remlingen

Application of criteria active fault zones



Mining activities and boreholes

Active fault zones



Exemplary: Piqiang Fault, China (Quelle: NASA)

Application of criteria volcanic activity

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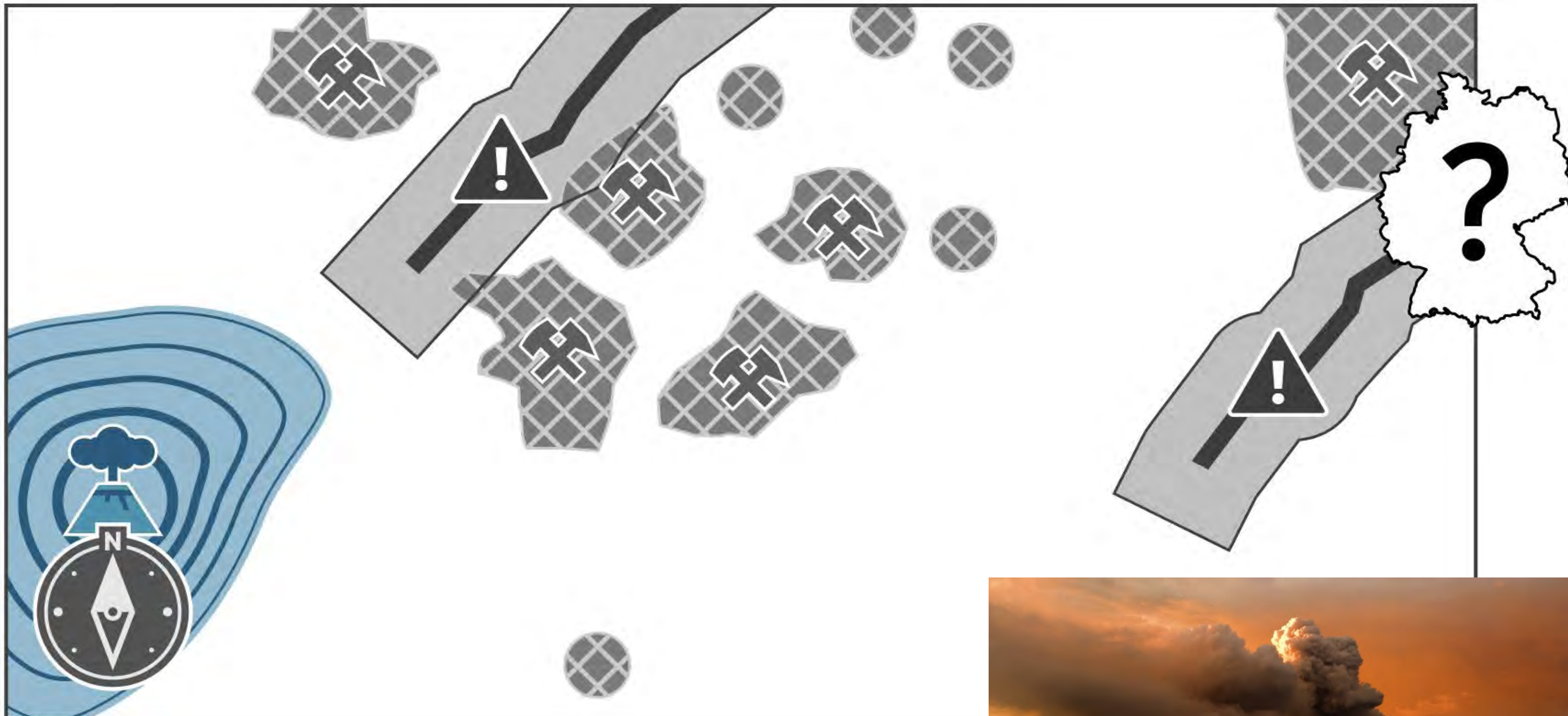
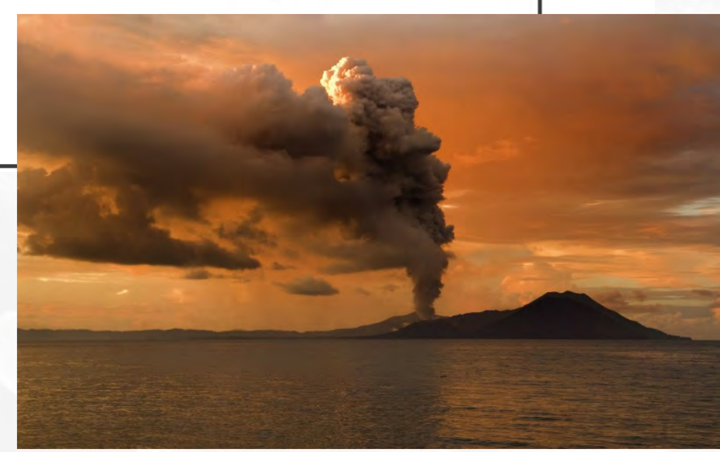
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation



Mining activities and boreholes

Active fault zones

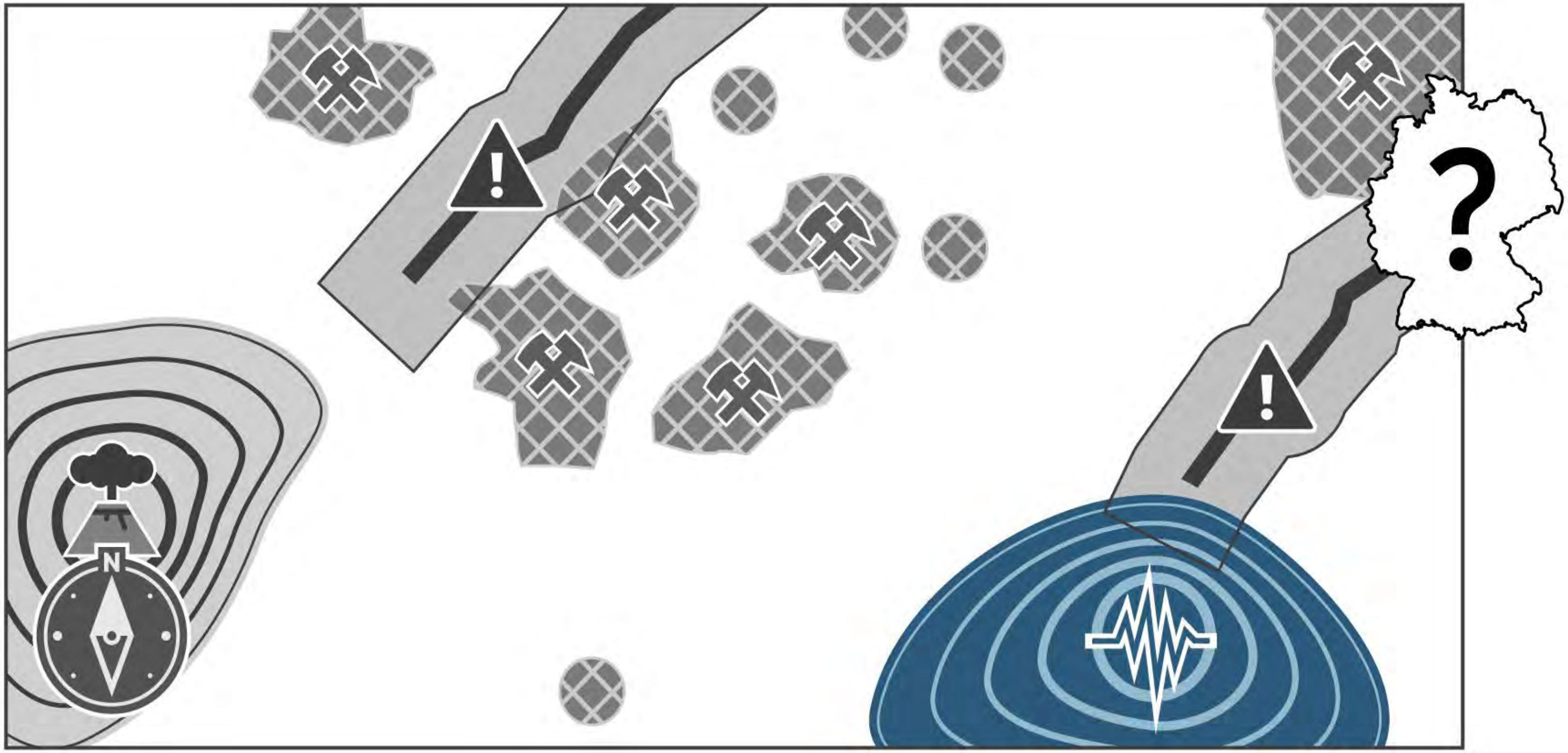
Volcanic activity



Exemplary: Tavurvur Volcano in Papua New Guinea nearby the city of Rabaul.
Quelle: Taro Taylor edit by Richard Bartz - originally posted to Flickr as End Of Days, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=6113476

Application of criteria seismic activity

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

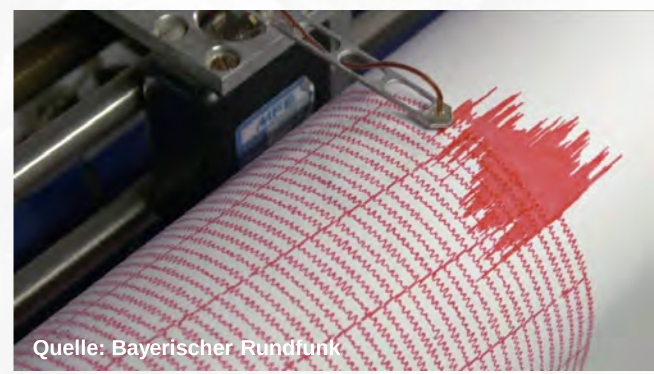


Mining activities and boreholes

Active fault zones

Volcanic activity

Seismic activity



Application of criteria large-scale uplift

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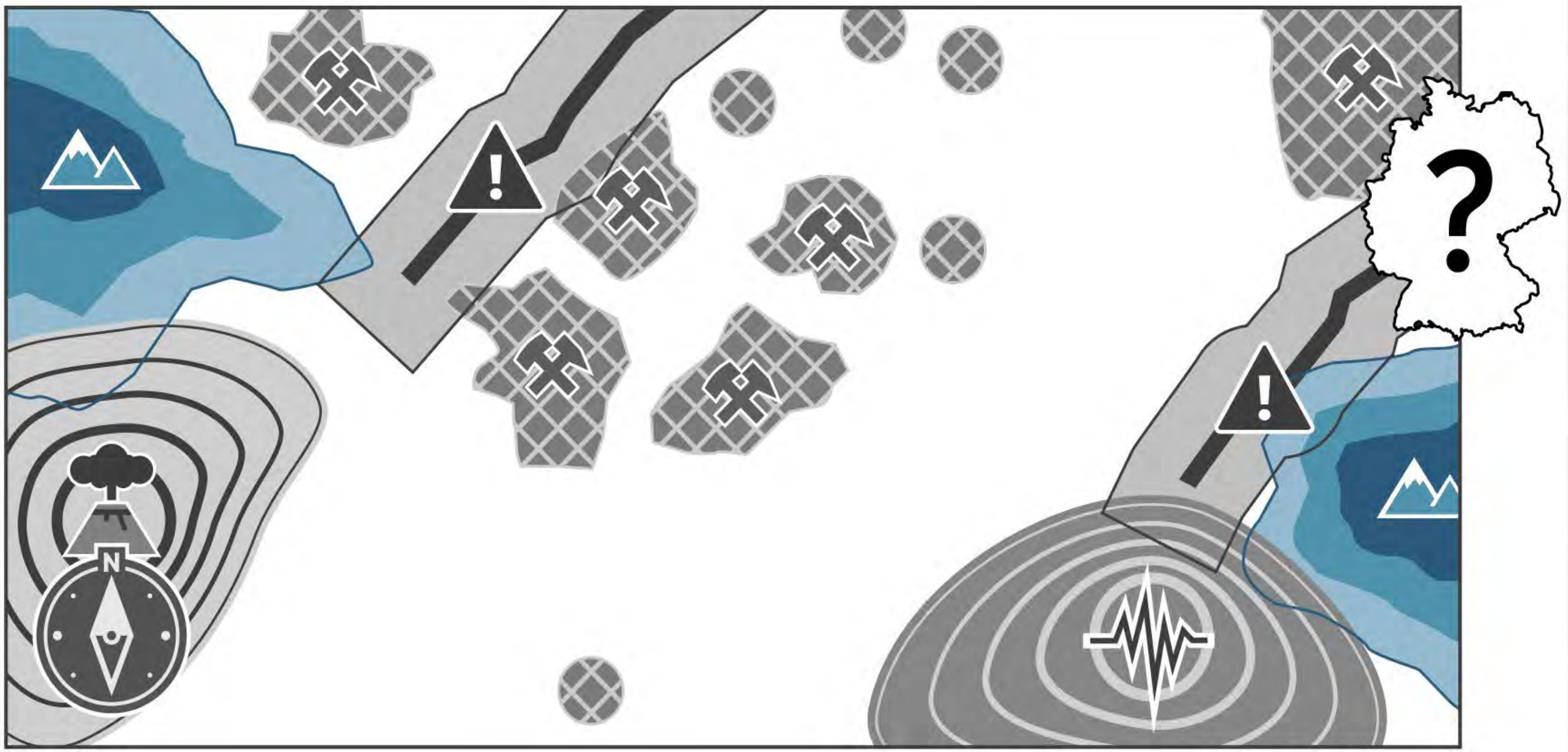
US/GERMAN WORKSHOP
Salt Repository Research, Design, & Operation



Mining activities and boreholes

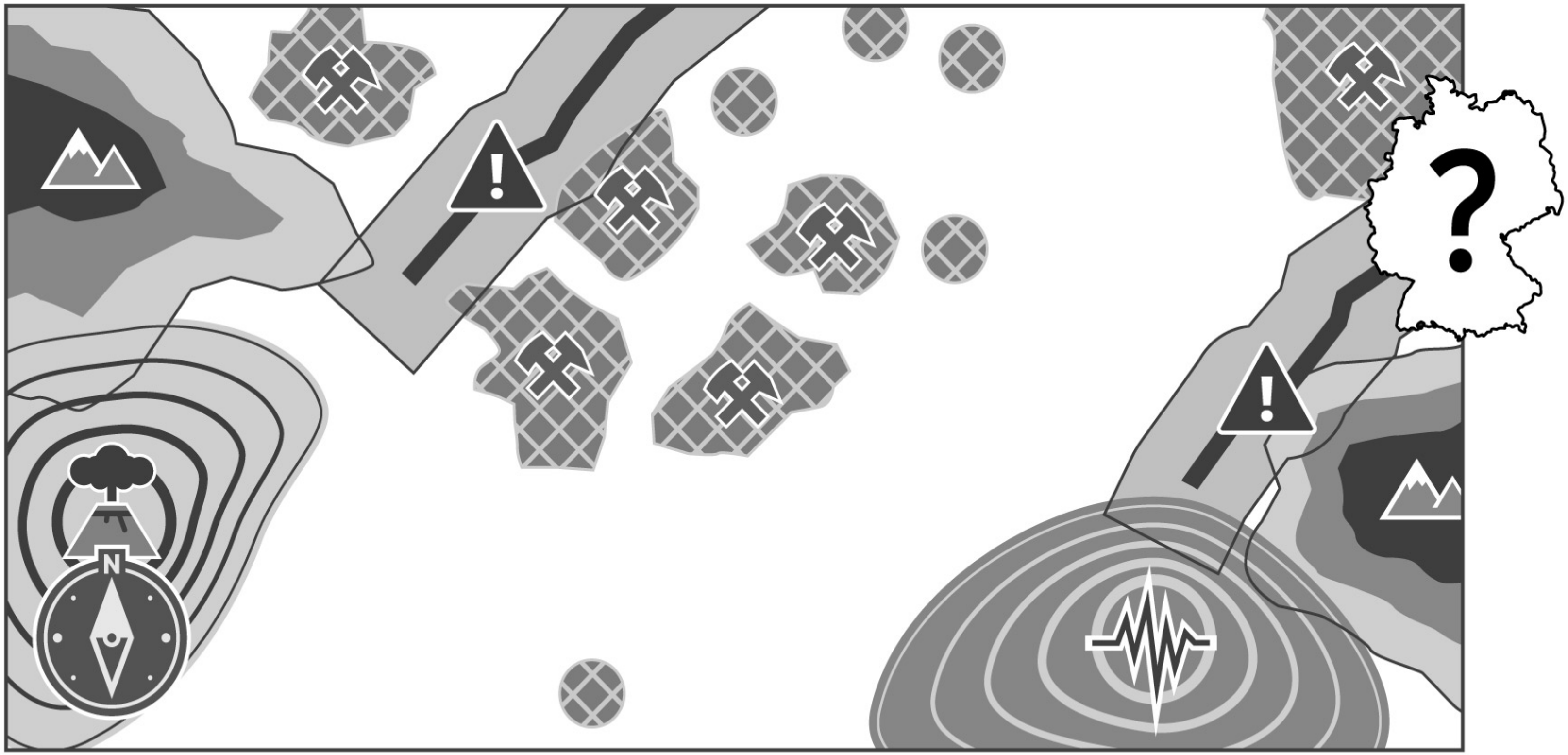
Active fault zones

Volcanic activity

Seismic activity

Uplift

Application of all exclusion criteria



Mining activities and boreholes

Active fault zones

Volcanic activity

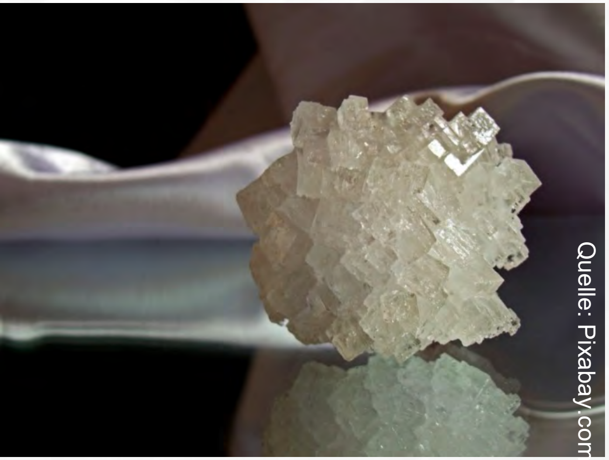
Seismic activity

Uplift

Minimum Requirements

Host rock types

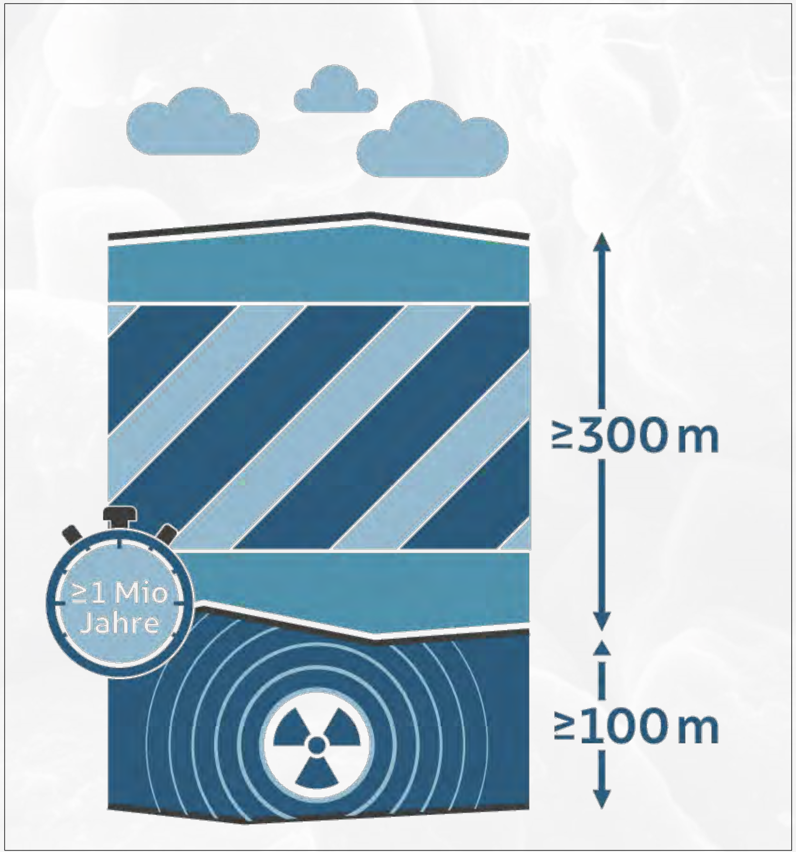
Rock salt



Claystone

Crystalline rock

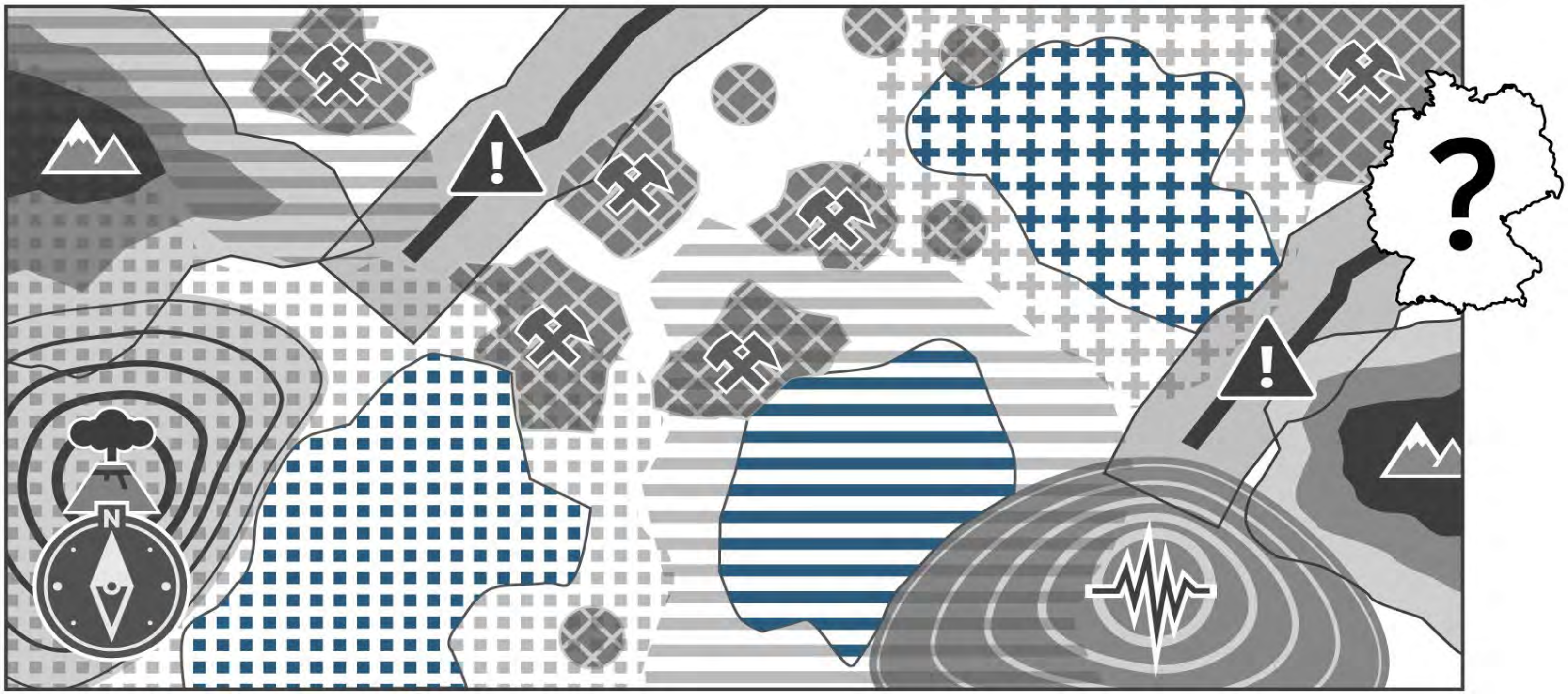
Minimum requirements[1]



- **Low permeability**
- **Minimal thickness of 100 meter** (exception crystalline rock)
- Top surface of effective containment zone (ECZ) has to be at least **300 meter below terrain surface**
- **Suitable extension** in area and heights
- **Preservation of barrier effect for 1 million years**

[1]special requirements apply for rock salt in steep deposit and crystalline rock

Application of exclusion criteria and minimum requirements concluded



Mining activities and boreholes

Active fault zones

Volcanic activity

Seismic activity

Uplift

Host rocks

Site regions with minimum Requirements fulfilled

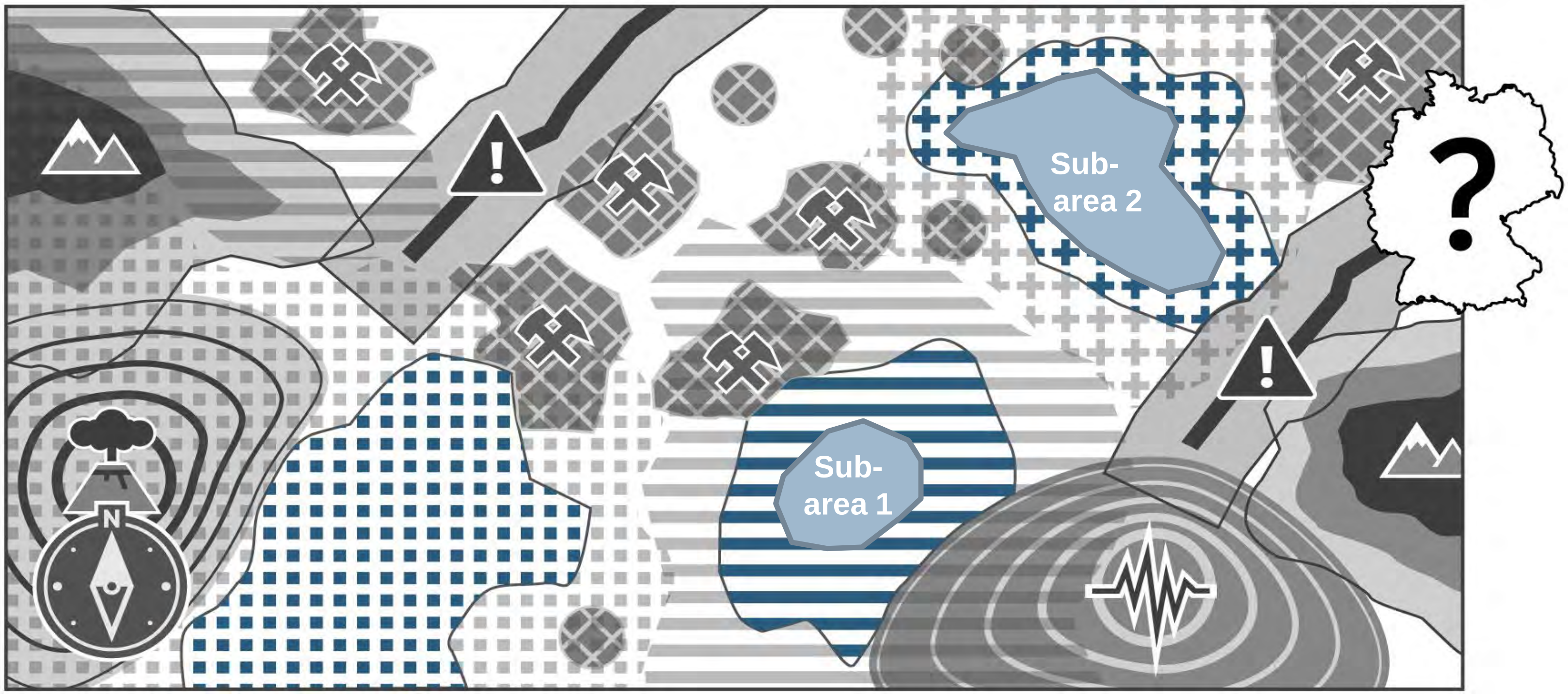
Geoscientific Weighting Criteria

Geoscientific weighting criteria

Achievable quality of containment and expected robustness of the evidences:

- Transport of **groundwater**
- **Configuration** of rock complex
- Spatial **characterization**
- **Predictability**
- Valuation on favorable rock-mechanical properties and tendency of creating **pathways for fluids**
- Further safety-relevant properties (e.g. **gas production, temperature compatibility, ability of retention of radionuclides** in rocks of the effective containment zone, **hydrochemical conditions** and **overburden**)

Application Geoscientific weighting criteria



Mining activities and boreholes

Active fault zones

Volcanic activity

Seismic activity

Uplift

Host rocks

Site regions with minimum Requirements fulfilled

Outlook and challenges

- Heterogeneous database
- Big data → 350 GB, 100 different data types
- Third-party rights of data – legal situation (Geologiedatengesetz)
- Poorly explored regions / Regions with only few data/information

Thank you!

Contact

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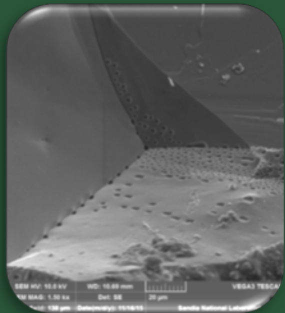
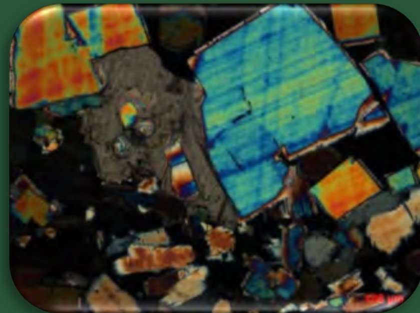



Comparing the Safety of Different Repository Systems with Only One Yardstick

Jörg Mönig
GRS, Geological Disposal Division

Rapid City, SD, United States
May 28-30, 2019

German Site Selection Act (2017)

- Site Selection Procedure
  - White map as starting point
  - to identify the site with the best possible safety over the period of 1 Mio. years for the disposal of German HLW
  - Participatory, science-based, transparent, self-questioning and learning process
  - Comparative procedure in three phases based on criteria
  - Rock salt, claystone and crystalline rock shall be considered as host rock

Site Selection Procedure

- German Site Selection Act (2017)

phase 1		phase 2	phase 3
Identification of subareas (§13)	**Identification of siting regions for surface exploration (§14)**	**Surface exploration and proposal for underground exploration (§16)**	**Underground exploration and site proposal (§18)**

- Application of **exclusion criteria** (§ 22) and **minimum requirements** (§ 23)
- Application of **geoscientific weighing criteria** (§ 24)
  - Representative preliminary safety analyses
    - Advanced preliminary safety analyses
      - Comprehensive preliminary safety analyses

11 Geoscientific weighing criteria

Achievable quality of containment & robustness of evidence

- transportation of radioactive substances by groundwater movement in the CRZ
- configuration of the rock bodies
- ability for spatial characterization
- the long-term stability of favorable conditions

Preservation of isolation performance

- favorable rock-mechanical properties
- tendency to form fluid flow paths

Other safety-relevant properties

- gas formation
- temperature tolerance
- retention capacity in the CRZ
- hydrochemical conditions
- protection of CRZ by the overburden

Geoscientific Weighing Criterion

Geoscientific weighing criterion

Assessment relevant property of the criterion

Assessment parameter or indicator for the criterion

Assessment group

Geoscien. Weighing Criterion 1

- Criterion for assessing the transportation of radioactive substances by groundwater movement in the CRZ

Assessment relevant property of the criterion	Assessment parameter and/or indicator for the criterion	Assessment group		
		favorable	**relatively favorable**	**less favorable**
Groundwater flow	Apparent flow velocity [mm/a]	< 0,1	0,1 – 1	> 1
Available groundwater	Characteristic rock permeability of the rock type [m/s]	$< 10^{-12}$	$10^{-12} – 10^{-10}$	$> 10^{-10}$
Diffusion velocity	Diffusion coefficient [m^2/s]	$< 10^{-11}$	$10^{-11} – 10^{-10}$	$> 10^{-10}$
Diffusion velocity in claystone	Absolute porosity	< 20%	20% - 40%	> 40%
	Degree of consolidation	claystone	Indurated clay	Semi-indurated clay

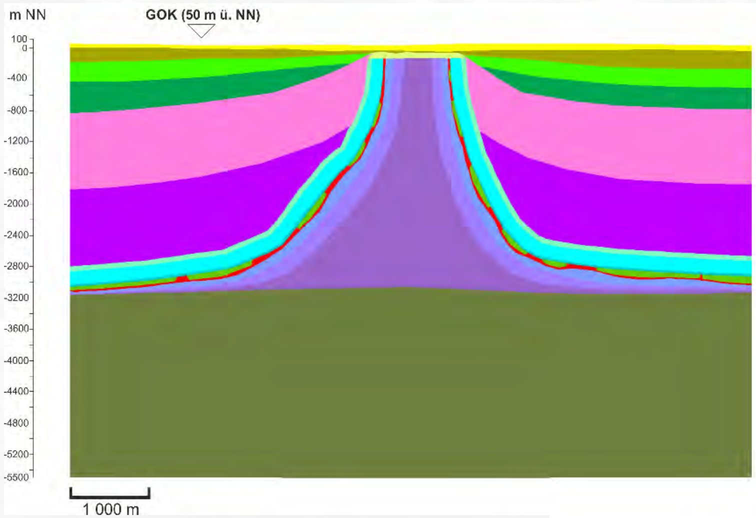
The Yardstick

- Based on geoscientific weighing criteria, it shall be assessed in each ecase whether there is a favorable overall geological situation in an area. The **favorable overall geological situation** results after a safety-oriented weighing of the results for all weighing criteria. The criteria listed in (3) to (5) serve as assessment criteria.

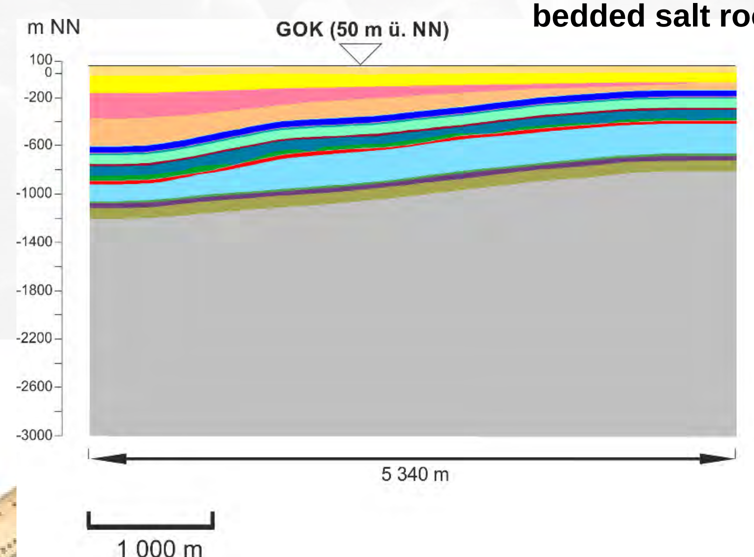
- The implementer shall identify favorable siting regions on the basis of the results from (*representative/advanced/comprehensive*) preliminary safety analyses applying again the geoscientific weighing criteria.

One Yardstick Must Fit All

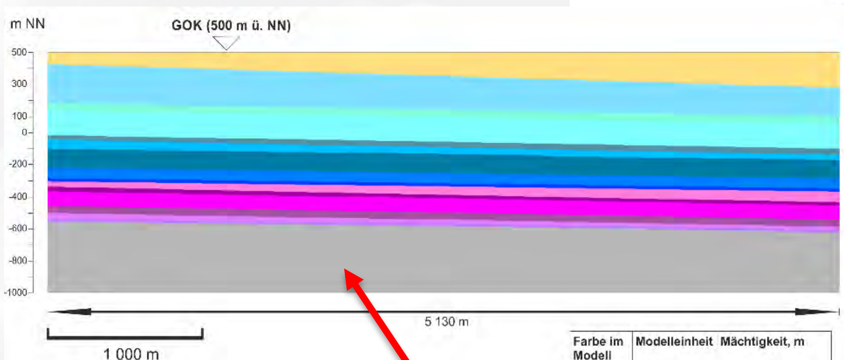
domal salt rock



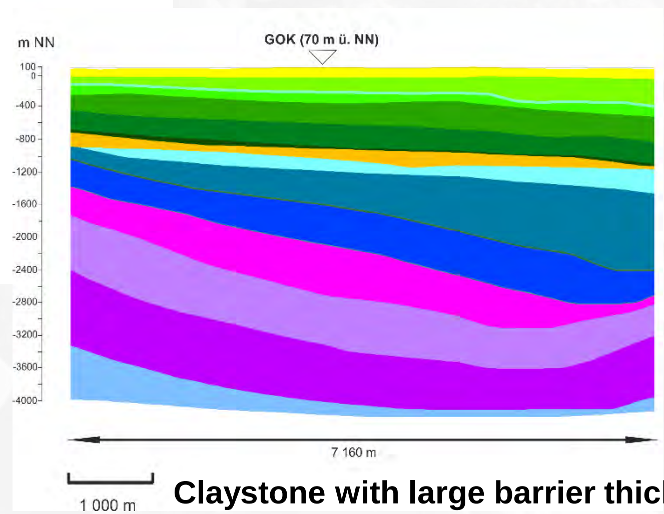
bedded salt rock



Claystone with lower barrier thickness



If bottom layer is crystalline rock, rock strata (salt rock, clay stone) overlying repository area provide CRZ



Claystone with large barrier thickness

Objectives RESUS Project (1)

- Assessment of the significance of the geoscientifc weighing criteria for the safety statement
- Compilation of basic information for performing preliminary safety analyses for repository systems in all possible host rocks (8 systems in RESUS with T_{max} = 100 degree C, 2 with 150 degee C)
  - Typical geological characteristics for the host rock
  - Amount and types of radioactive waste
  - Safety concept
  - Technical repository concept
  - Elements of safety demonstration
- Model calculations regarding for the significance assessment
  - Integrity of geological/geotechnical barriers
  - Radionuclide transport

R&D project funded by

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Objectives RESUS Project (2)

- Recommendations concerning the application of the yardstick
  - Aggregation of individual indicator results to obtain a statement for the criterion
  - Aggregation of assessments for each criterion to obtain a statement for the repository system considered

Challenges

- Three criteria have the assessment group „unfavorable “ instead of „less favorable “ (criteria 3, 4, 11)
- some criteria have only TWO assessments groups
- some criteria provide only qualitative desciptions for the assessment
  - partially even without assessment groups

Geoinformation-based Assessm.

Crit.	Indicator	S1 bedded salt	S2 domal salt
1	**assessment of transportation of radioactive substances by groundwater movement in the CRZ**		
1.1	Apparent flow velocity	favorable no groundwater flow	favorable no groundwater flow
1.2	Characteristic rock permeability of the rock type	favorable virtually impermeabel	favorable virtually impermeabel
1.3	Diffusion coefficient	favorable low due to porosity < 0,1 %	favorable low due to porosity < 0,1 %
1.4a	Absolute porosity	Not applicable (only for repos. in claystone)	
1.4b	Degree of consolidation	Not applicable (only for repos. In claystone)	

Geoinformation-based Assessm.

Crit.	Indicator	S1 bedded salt	S2 domal salt
2	**Configuration of the rock bodies**		
2.1	**Assessment relevant property of the criterion: Barrier effectiveness**		
2.1a	Barrier thickness	relatively favorable shaft profile 113 m in model	favorable shaft profile 444 m in model
2.1b	Degree of enclosure of emplacement zone by CRZ	favorable complete enclose	favorable complete enclose
2.1	**Assessment of property barrier effectiveness**	**favorable**	**favorable**
Rule	The property „barrier effectiveness“ of the criterion can only be „favorable“ if indicator 2.1b is favorable		

Geoinformation-based Assessm.

Repository System	S1 bedded salt	S2 domal salt	T1 claystone with higher thickness	T2 claystone with lower thickness
Achievable quality of containment & robustness of evidence				
criterion 1	favorable	favorable	favorable	favorable
criterion 2	favorable	favorable	favorable	rel. favorable
criterion 3	favorable	favorable	favorable	favorable
criterion 4	favorable	favorable	favorable	favorable
Preservation of isolation performance				
criterion 5	favorable	favorable	not favorable	not favorable
criterion 6	favorable	favorable	rel. favorable	rel. favorable
Other safety-relevant properties				
criterion 7	favorable	favorable	rel. favorable	rel. favorable
criterion 8	favorable	favorable	favorable	favorable
criterion 9	less favorable	less favorable	rel. favorable	rel. favorable
criterion 10	not favorable	not favorable	favorable	not favorable
criterion 11	favorable	rel favorable	favorable	rel. favorable

Safety Significance of Criteria

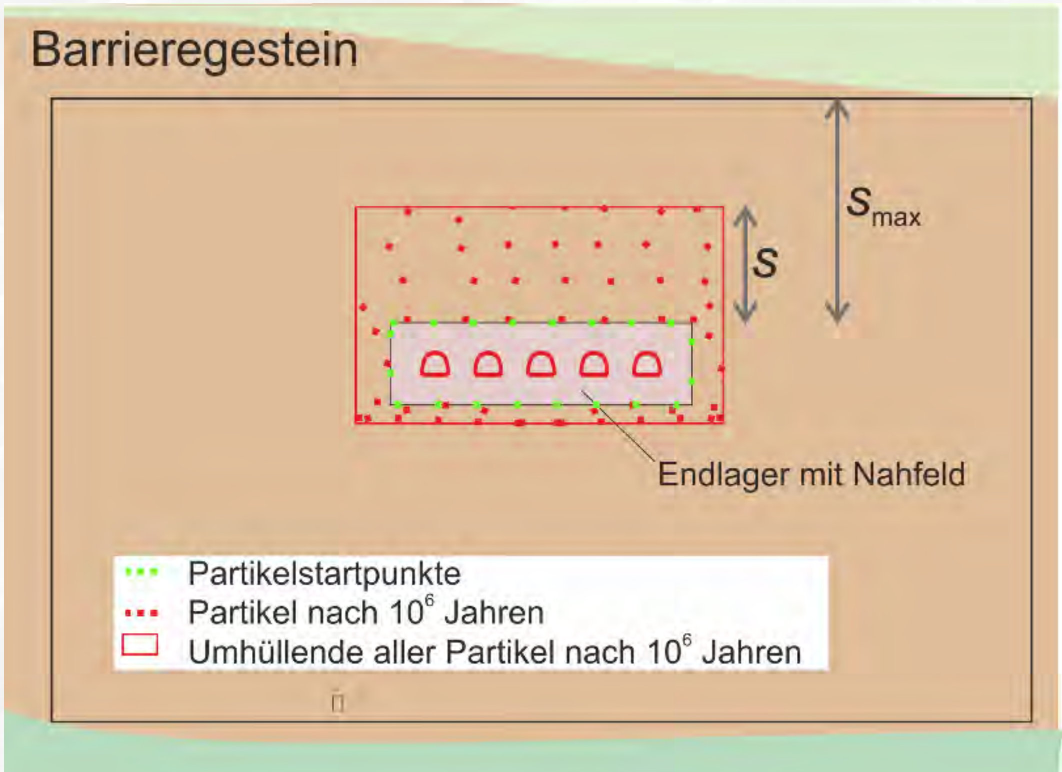
- Significance assessment based on model calculations regarding
  - Integrity of geological/geotechnical barriers
  - Radionuclide transport
- Model parameter reflect transition between assessments groups
  - favorable / relativlely favorable
  - relatively favorable / less favorable

  - But … approach only applicable for indicators given in siting act that can be related to model parameters

Analysis of Barrier Integrity

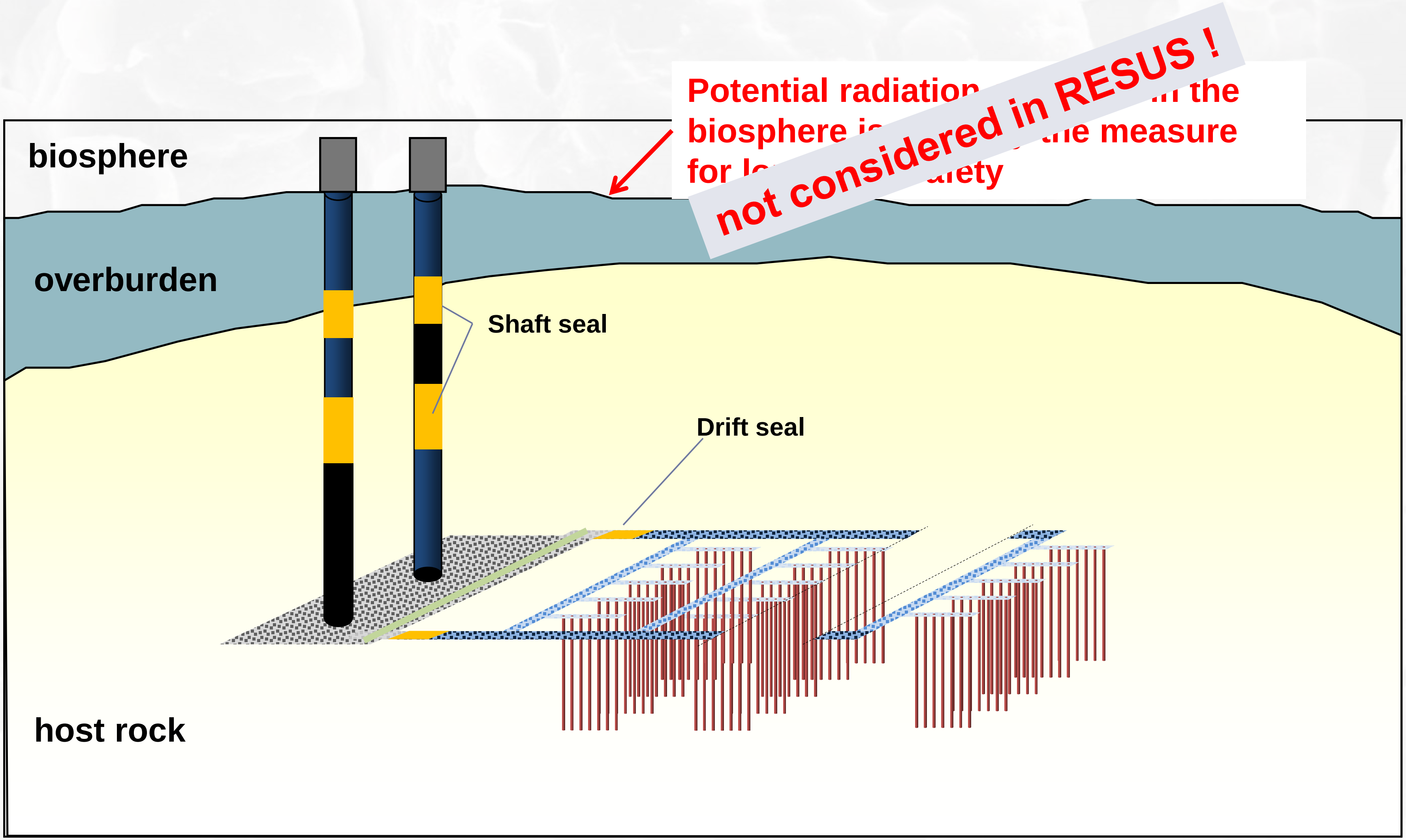
- Integrity indicators for rock salt and claystone
  - Dilatancy
  - Fluid pressure
- Additional integrity indicators for repositories in claystone
  - Temperature
  - Advection
- Indicator definition and application adapted to repository system investigated

Integrity Indicator Advection



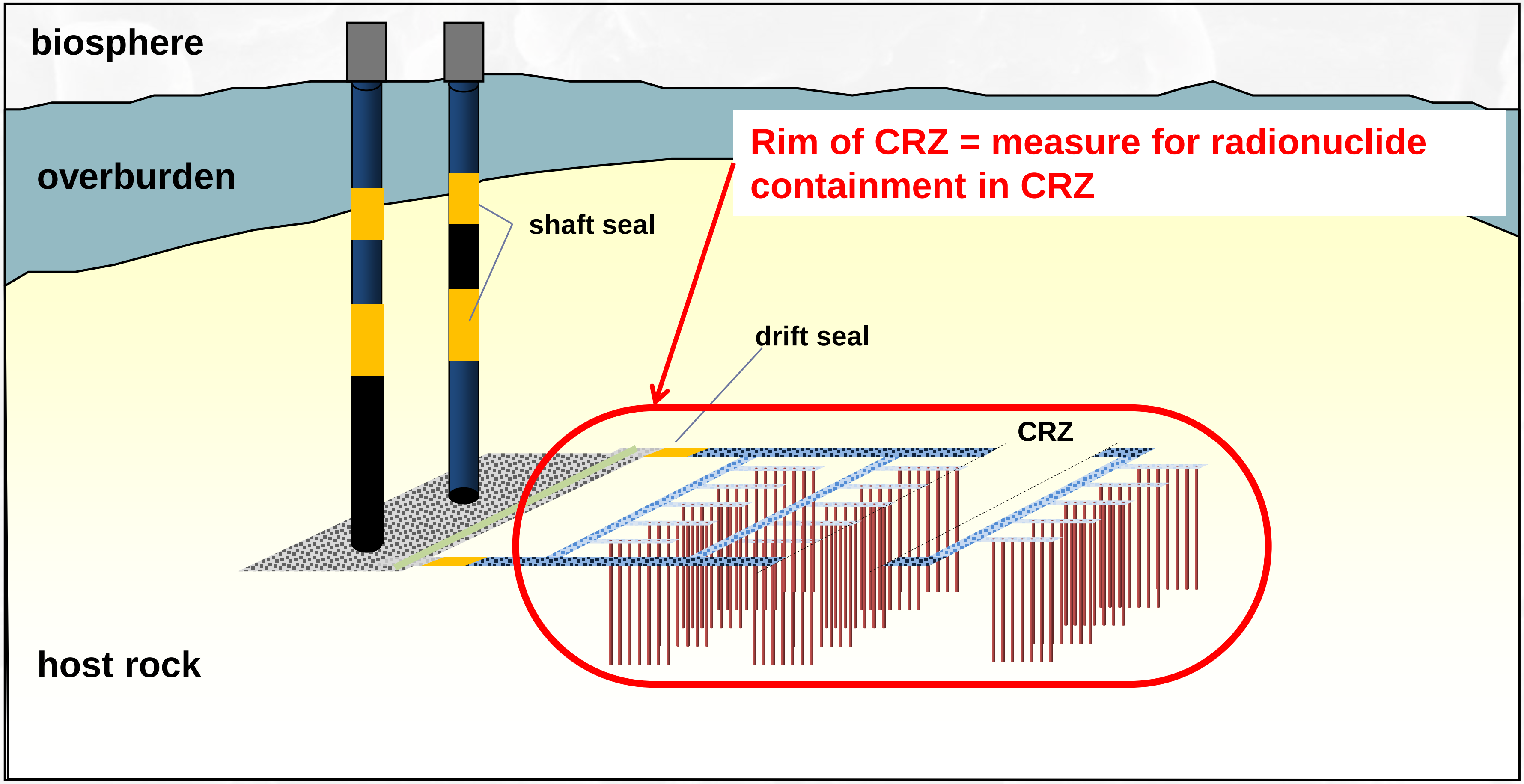
- used for repository systems in claystone
- modelling of advective particle transport in 1 mio years
- Integrity indicator = S / S_{max}

Measure for Long-term Safety



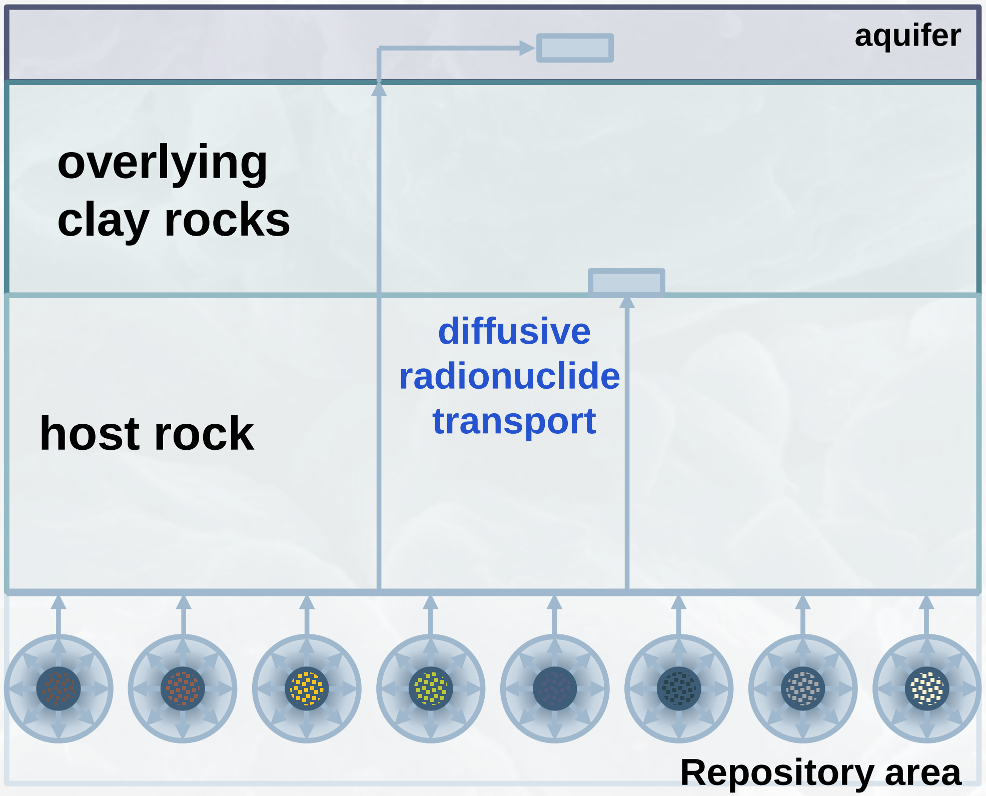
Safety Measure in RESUS

- Conversion of calculated radionuclide fluxes into a virtual radiation exposure that is normalized to regulatory limit values ➔ RGI (German acronym)



Containment Assessment in Clay

Repository system in claystone



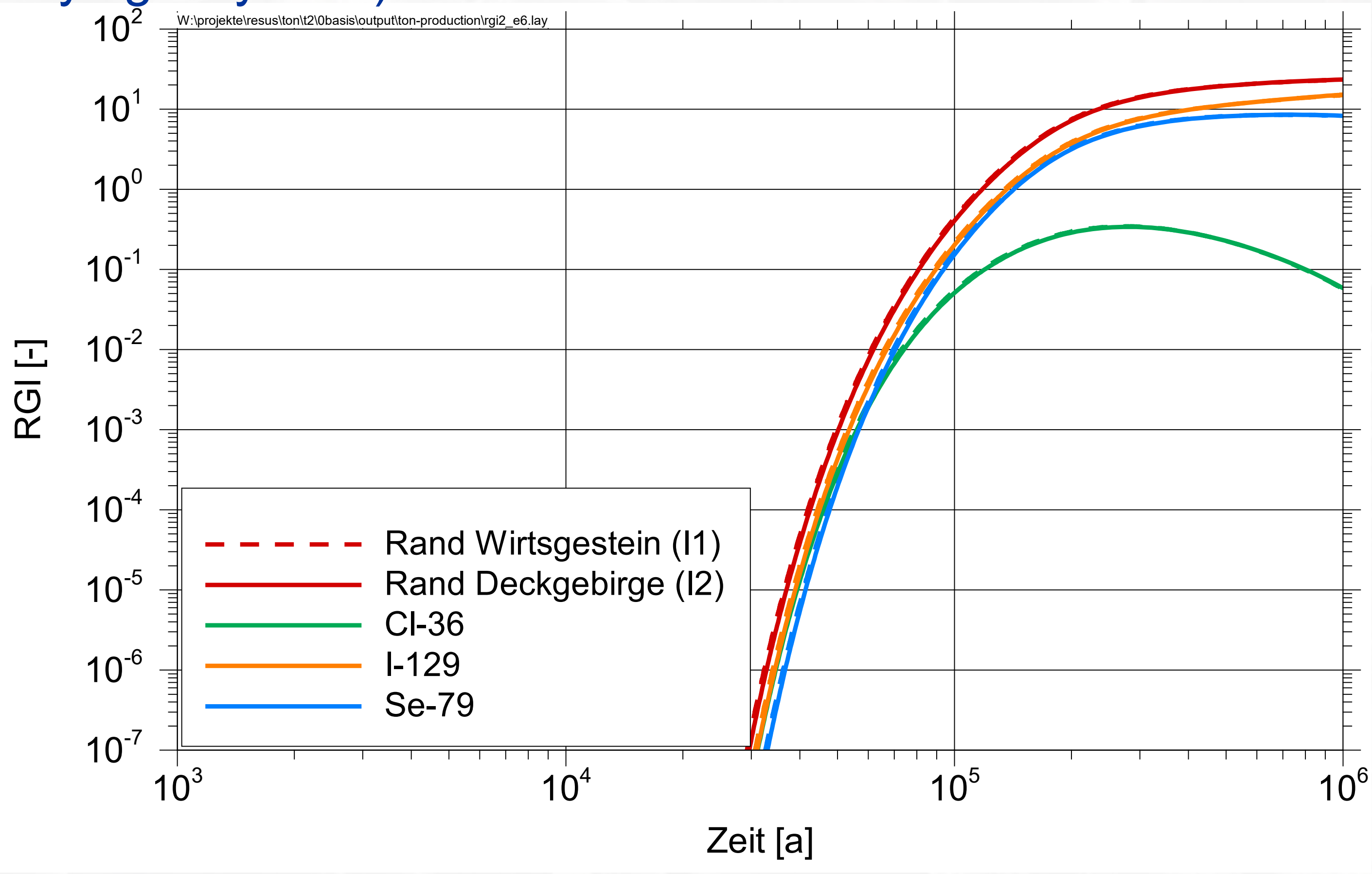
Assessment point 2
= nearest aquifer [RGI]

Assessment point 1
= rim of CRZ [RGI]

8 waste types: spent fuel from diff. reactor types, waste from SF reprocessing

RN Containment Assessment

Repository system T2 in claystone with lower thickness (no overlying clay rock)



No overlying clay rocks ➔ assessment point 1 ≈ assessment point 2

RESUS Team

BGR

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- Ulrich Noseck
- André Rübel
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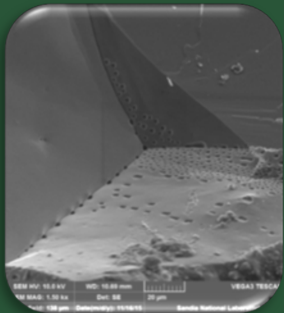
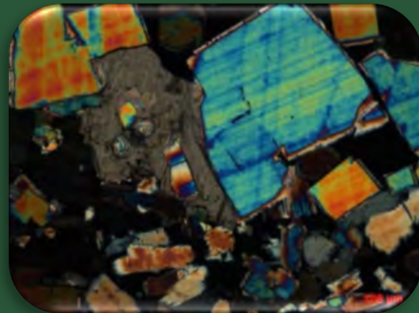
Last Words

Please keep in mind, RESUS is

therefore no summary & conclusions can be drawn yet

Hence … STAY TUNED !

10th US/German Workshop on Salt Repository Research, Design, and Operation

Jeroen Bartol PhD
COVRA, The Netherlands

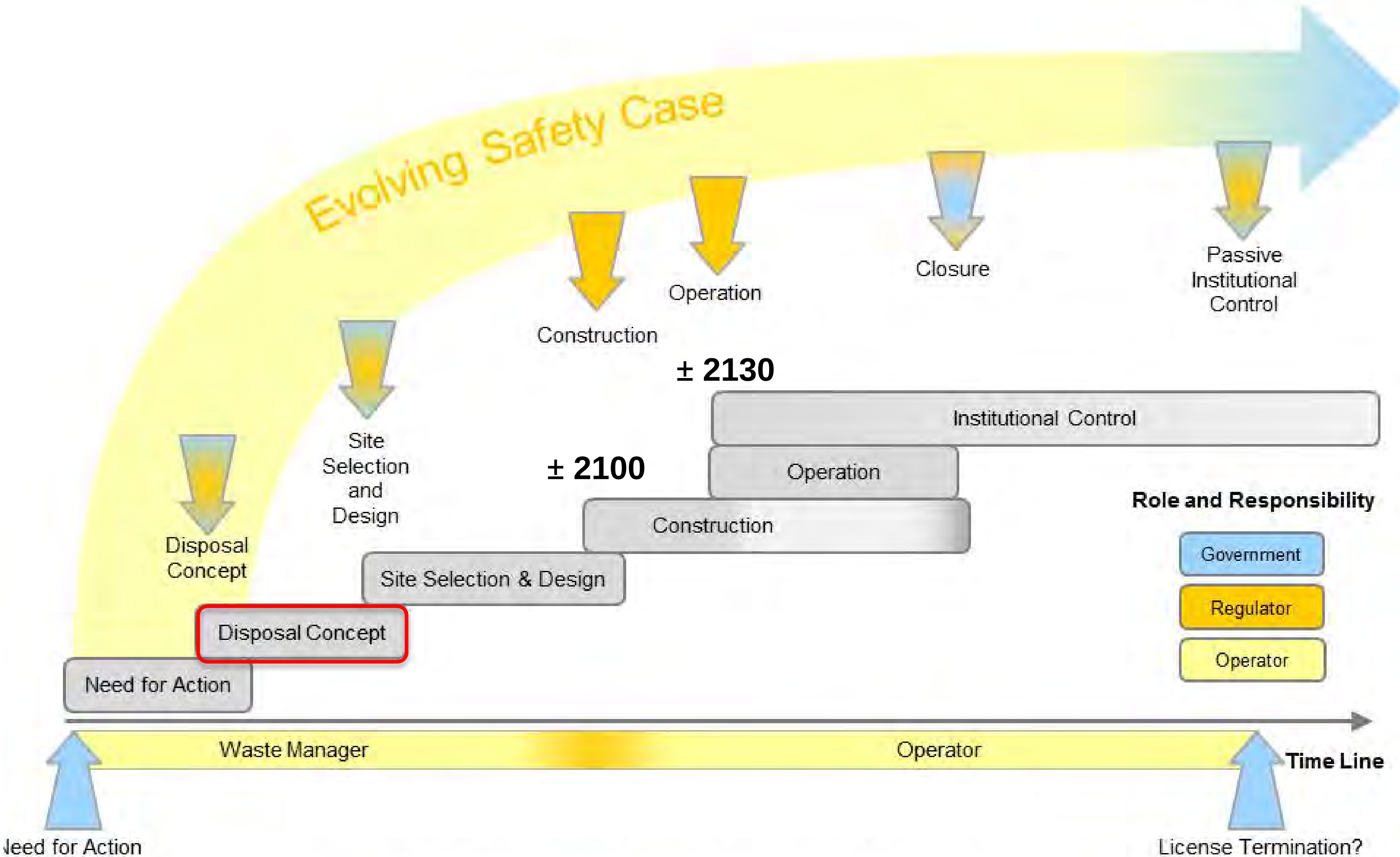
Rapid City, SD, United States
May 28-30, 2019

The Dutch national program: Towards a safety case in rock salt

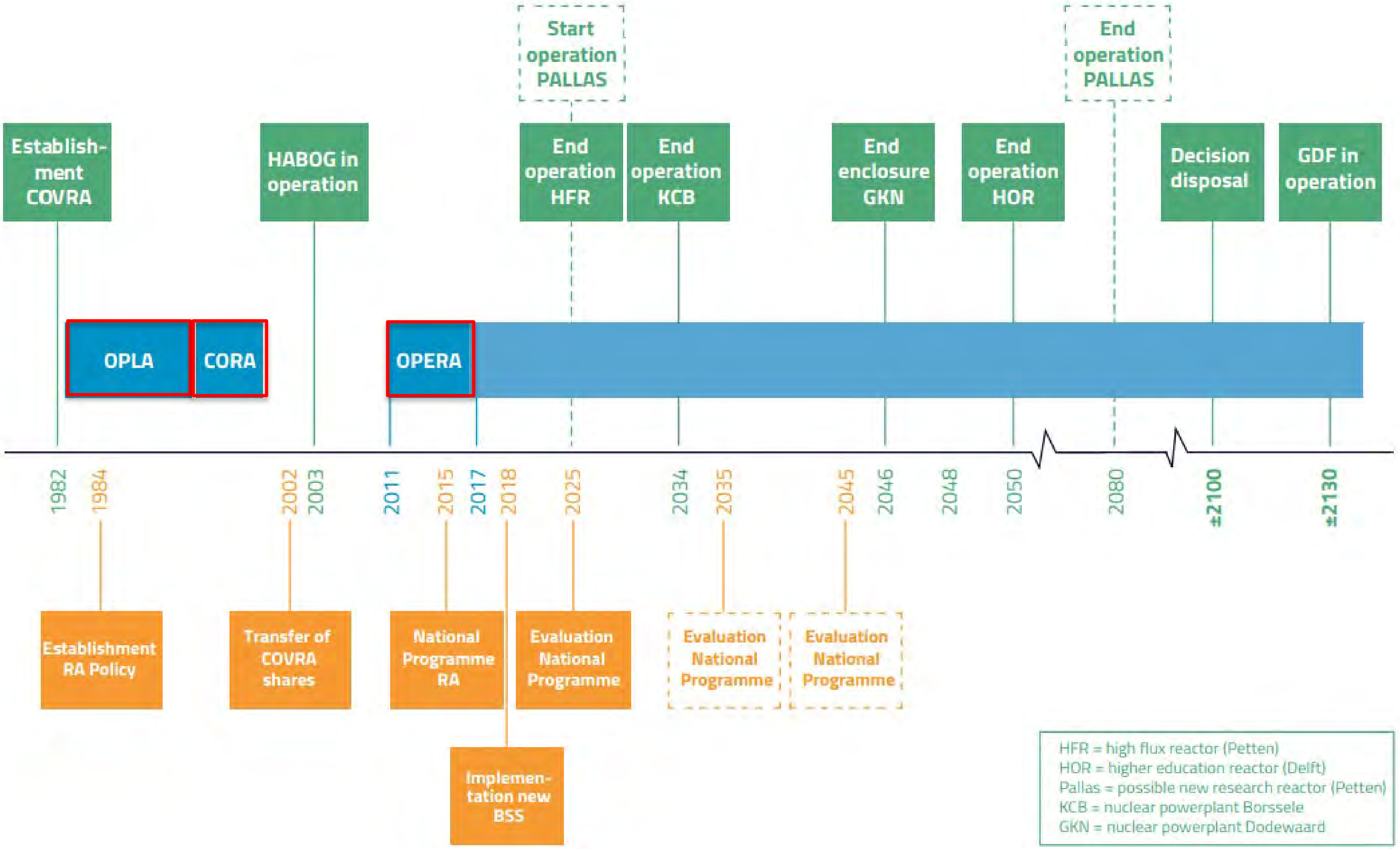
Outline

- **Dutch program in the past**
  - OPLA/CORA/OPERA
- **Current status of the Dutch program**
  - Outline of a disposal concept in domal salt
- **The future**
  - Short term research program
  - Intermediate term research program
  - Long term research program

The Dutch national program: Towards a safety case in rock salt



The Dutch national program:
Towards a safety case in rock salt



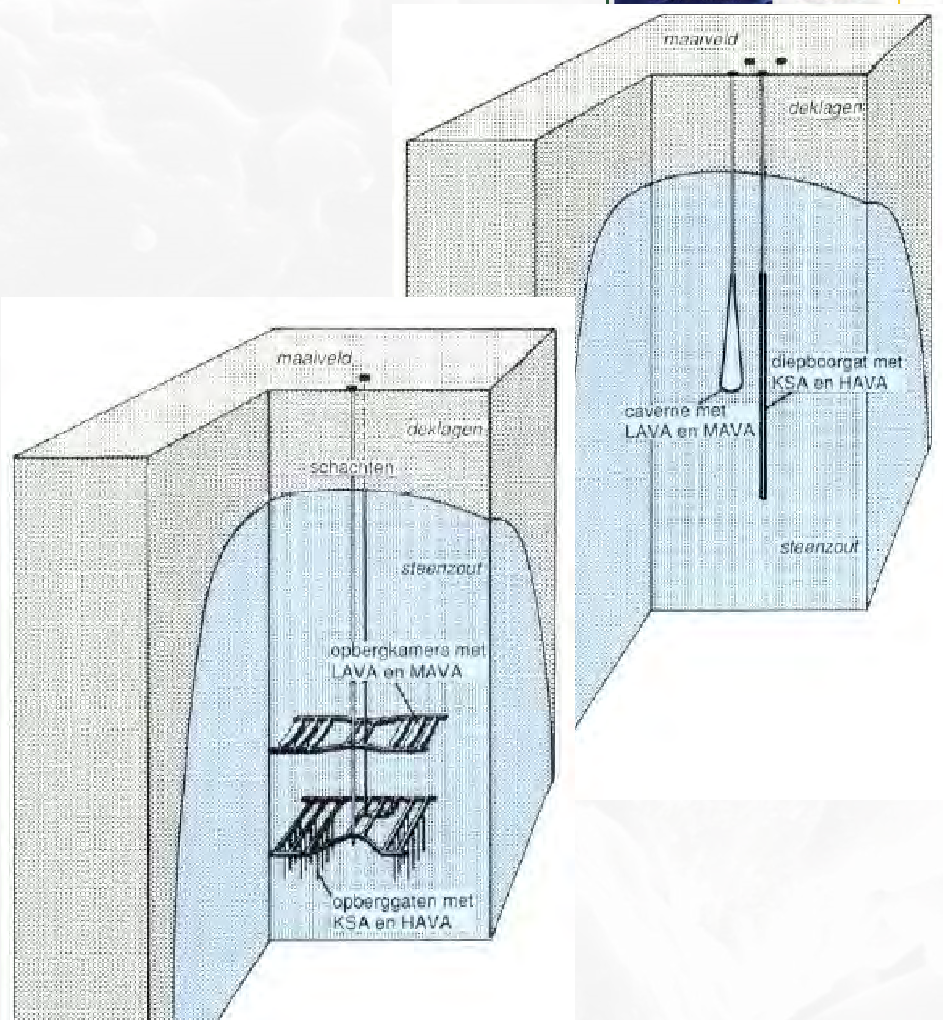
The Dutch national program: Towards a safety case in rock salt

In the past:

- More than 2 nuclear power plants.
- Construction (excavation) by dissolution and construction.
- Retrievability was (initially) not included.

Current:

- Construction ‘conventional’ mine techniques.
- No new nuclear power plants and operation of the present nuclear power plant until its intended closure in 2033.
- Retrievability included.



Disposal concepts investigated in OPLA [EZ,1989]; In the second part of the programme (in OPLA 1A) research the right disposal concept only continued [EZ, 1993]. Commissie Opberging te Land (OPLA), Onderzoek naar geologische opberging van radioactief afval in Nederland, Eindrapport fase 1 (1989) 1-130. Commissie Opberging te Land (OPLA), Onderzoek naar geologische opberging van radioactief afval in Nederland, Eindrapport Aanvullende onderzoek fase 1 (1993) 1-142.

The Dutch national program: Towards a safety case in rock salt

How much waste?

Waste Category	In storage		Packaged for disposal		
	Volume [m3]	Weight [tonne]	Number of containers	Volume [m3]	Max weight [tonne]
Processed LILW	45000	150000	152000	45000	150000
TENORM	34000	110000	9060	40000	182000
Vitrified HLW	93	191	478	3388	9560
Spent research reactor fuel	104	99	75	638	1800
Other HLW	256	600	700	5104	14400

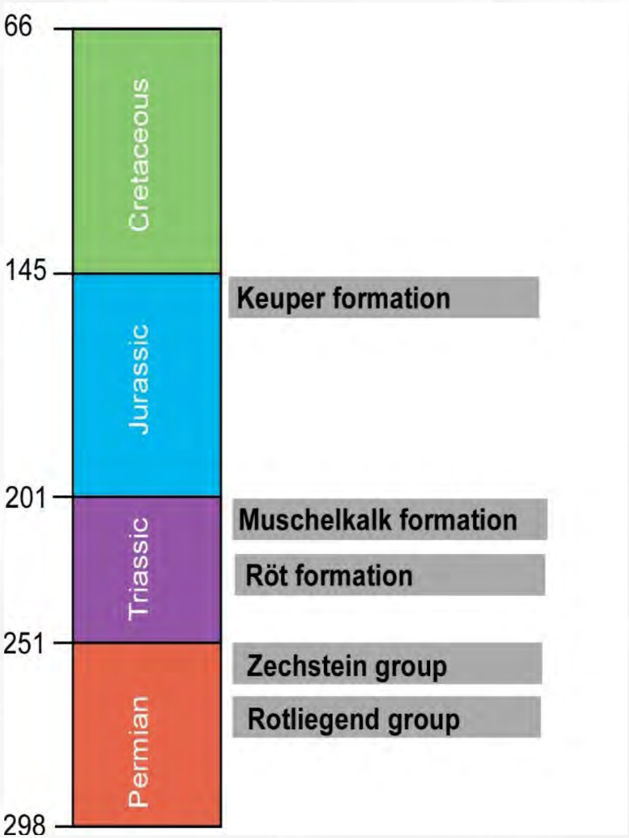
Expected eventual inventory of wastes for disposal, showing their mass and volume in storage and their mass and volume when packaged for disposal. From Verhoef, E., Neeft, E., Chapman, N., and McCombie, C., 2017, Opera safety case.

The Dutch national program: Towards a safety case in rock salt

Assumptions

- **Period**
  - 100.000 years. Crossover time between of the radiotoxicity of HLW and natural uranium ore.
- **Pure rock salt**
  - Ignoring impurities in the salt.
- **Subglacial channels**
  - Up to 600 m deep in northern Netherlands.
- **Diapirism**
  - 0.11 mm/year or **11 m** in 100.000 years..
- **Subrosion**
  - 1-0.06 mm/year for sides and 0.08 mm/year for the top. **100 m** from the vertical sides and at least **8 m** below the caprock.

The Dutch national program:
Towards a safety case in rock salt



Possible salt formations/groups

Keuper formation – Only offshore.

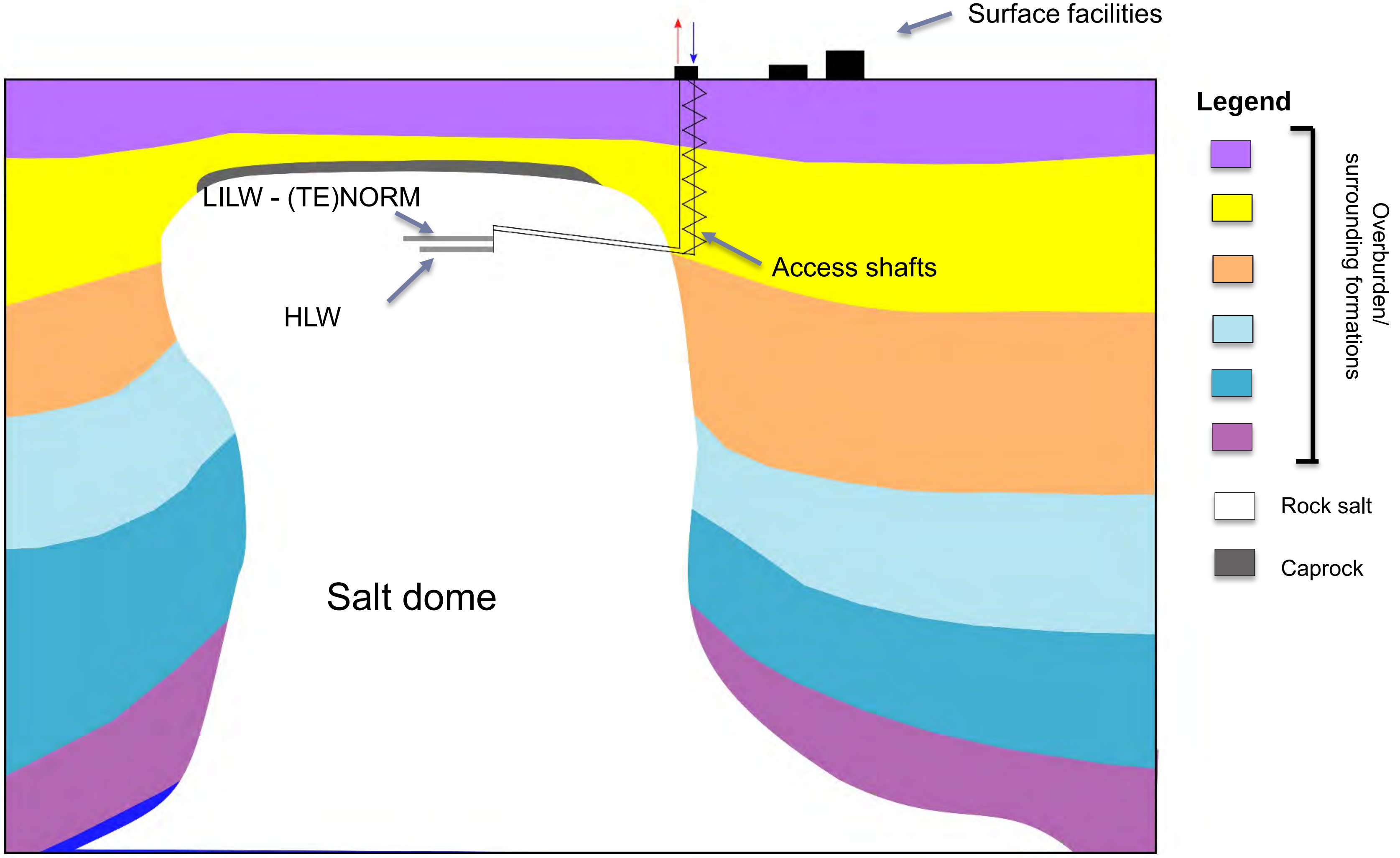
Muschelkalk formation – Tens of meters thick (< 30 meter).

Röt formation – 100 - 200 m but is used for salt winning (bedded salt).

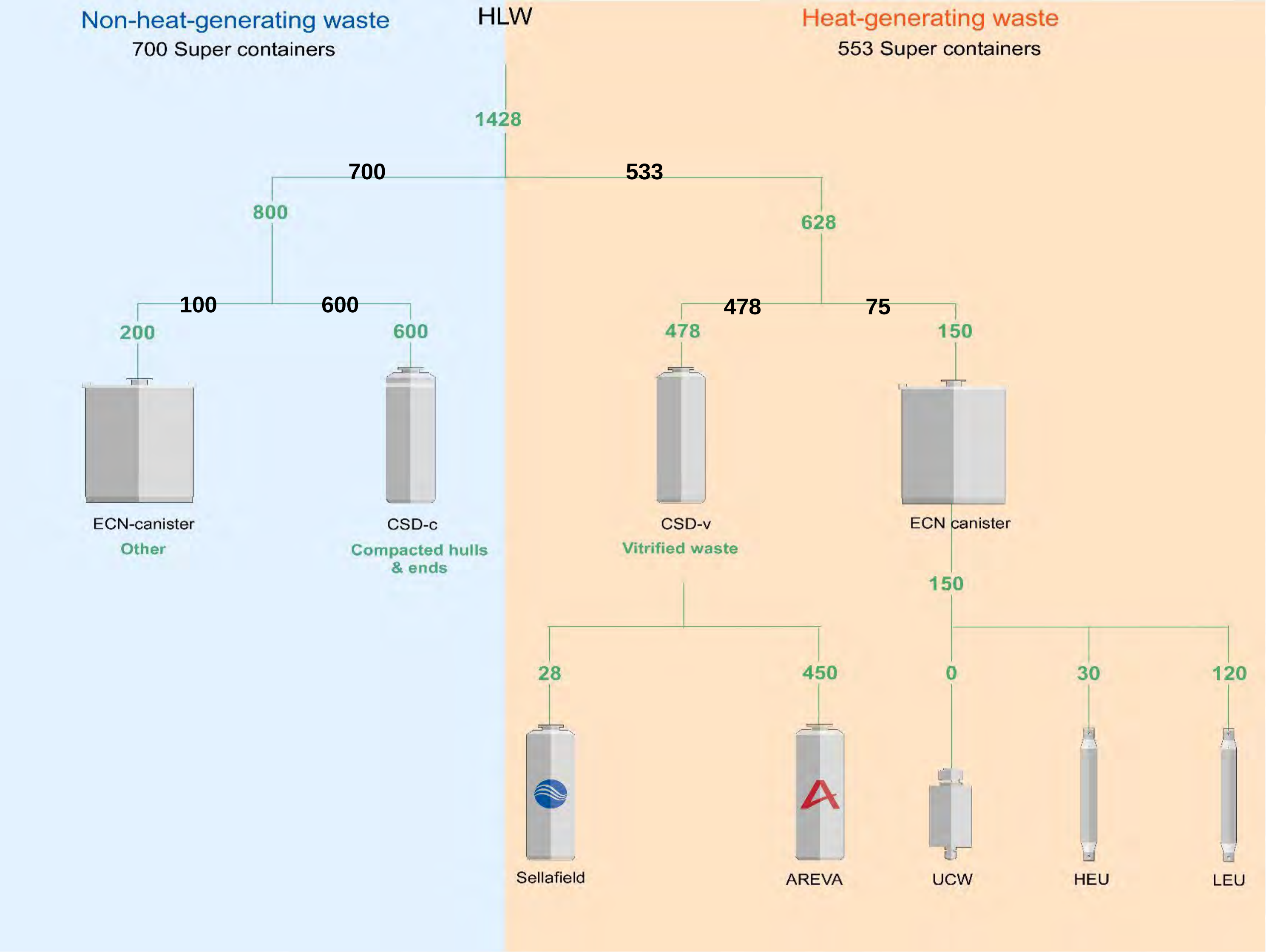
Zechstein groep – Salt domes and very thick salt (domal / bedded salt).

Rotliegend groep – Limited thickness (< 50 m thick and relative deep)

The Dutch national program: Towards a safety case in rock salt



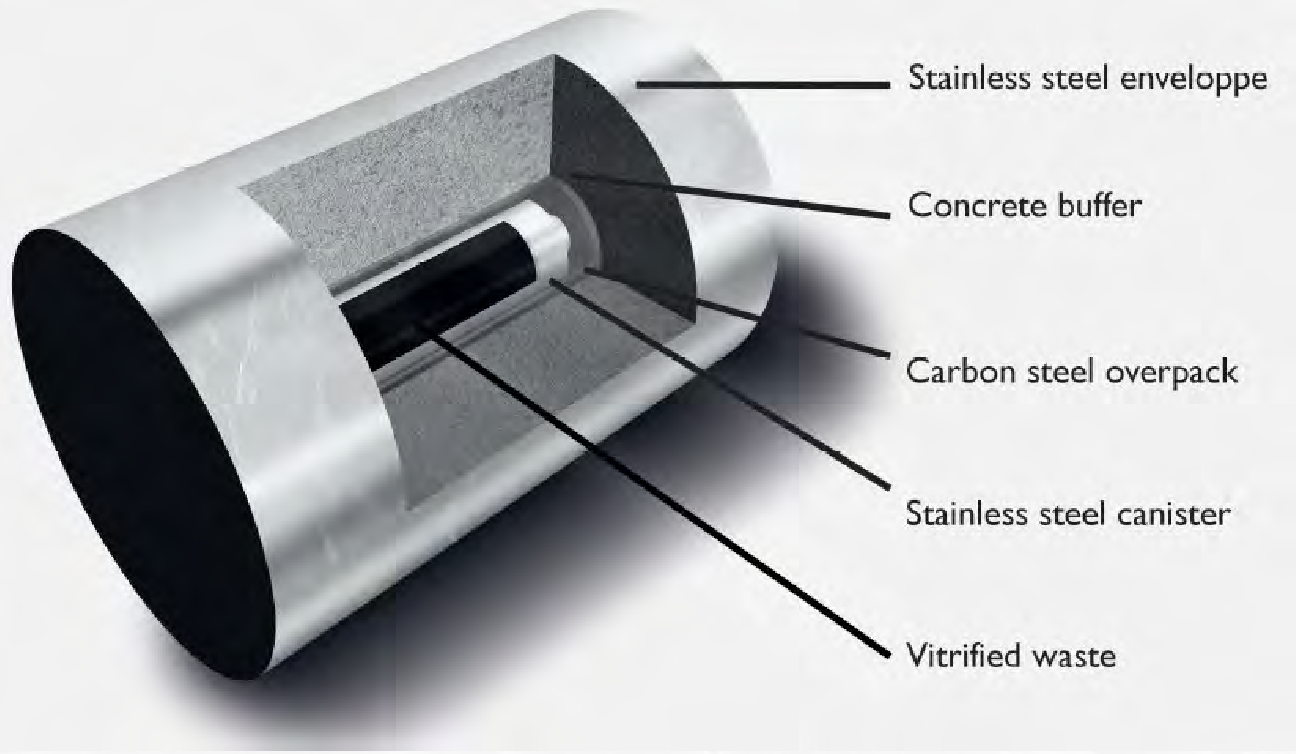
The Dutch national program: Towards a safety case in rock salt



Two ECN canisters will be in one super container. One CSD-v will be in one super container.

From Verhoef, E., Neeft, E., Chapman, N., and McCombie, C., 2017, Opera safety case.

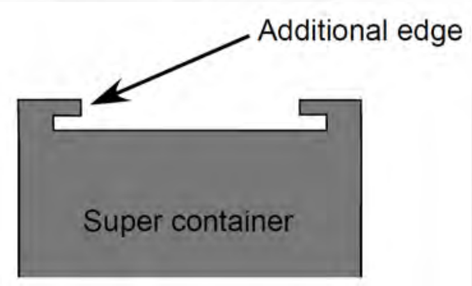
The Dutch national program: Towards a safety case in rock salt



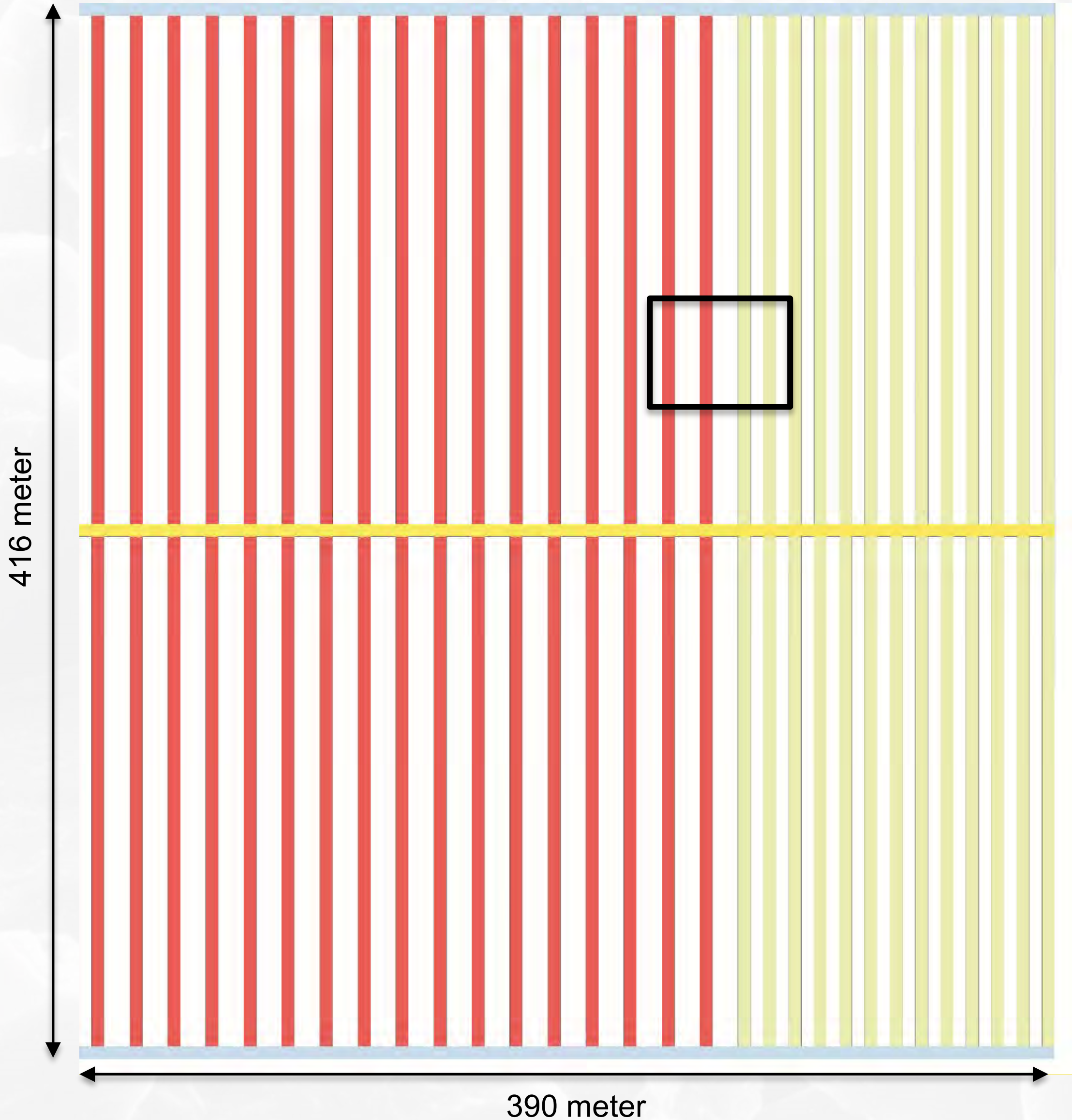
The concrete shielding of the OPERA supercontainer is designed to limit the surface dose rate of the heat generating HLW to a maximum of 10 mSv per hour.

The waste can be hand-handled making it easier to retrieve it when needed.

Note that an additional edge will be present.



The Dutch national program: Towards a safety case in rock salt



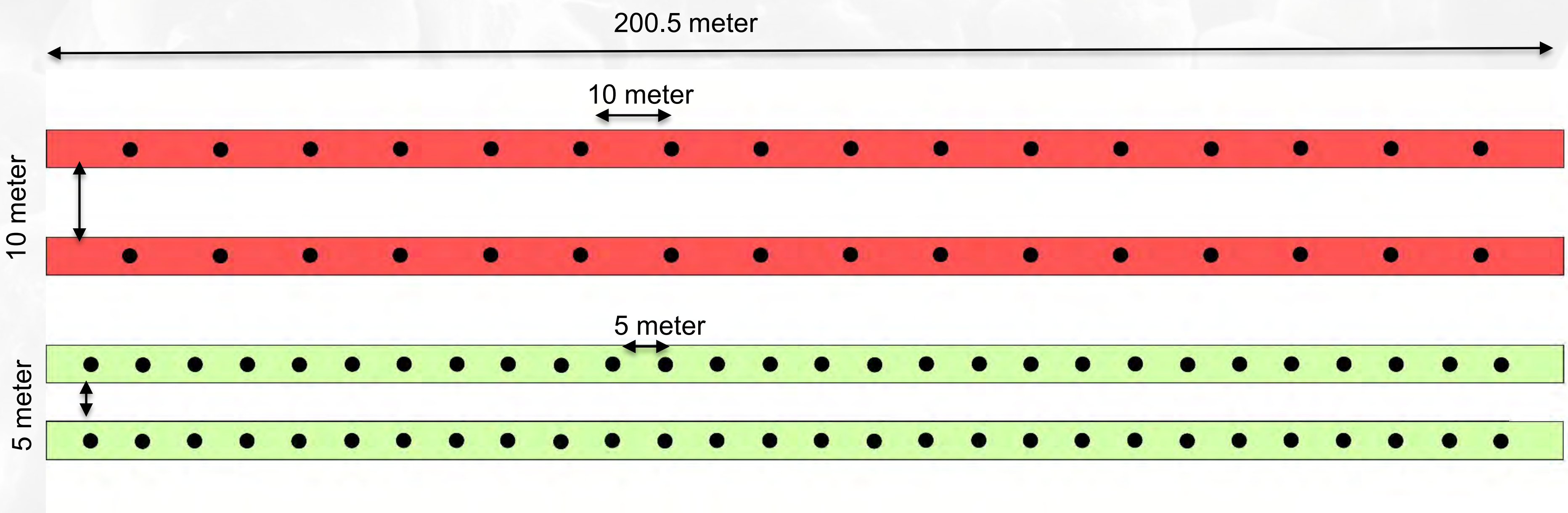
Legend

- Heat generating waste
- Non-heat generating waste
- Ventilation shaft
- Main shaft

The lower HLW section of the GDF.

Repository is based on: Ernest Hardin, Engineering Solutions for Disposal of Large Spent-Fuel Packages in Salt

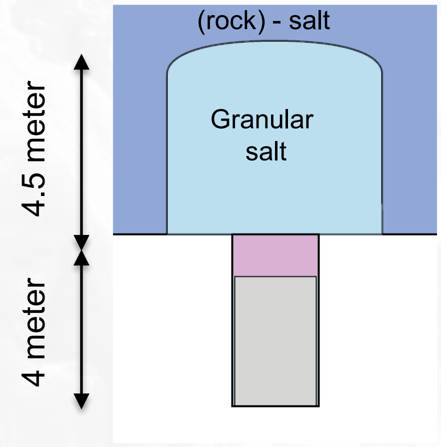
The Dutch national program: Towards a safety case in rock salt



Legend

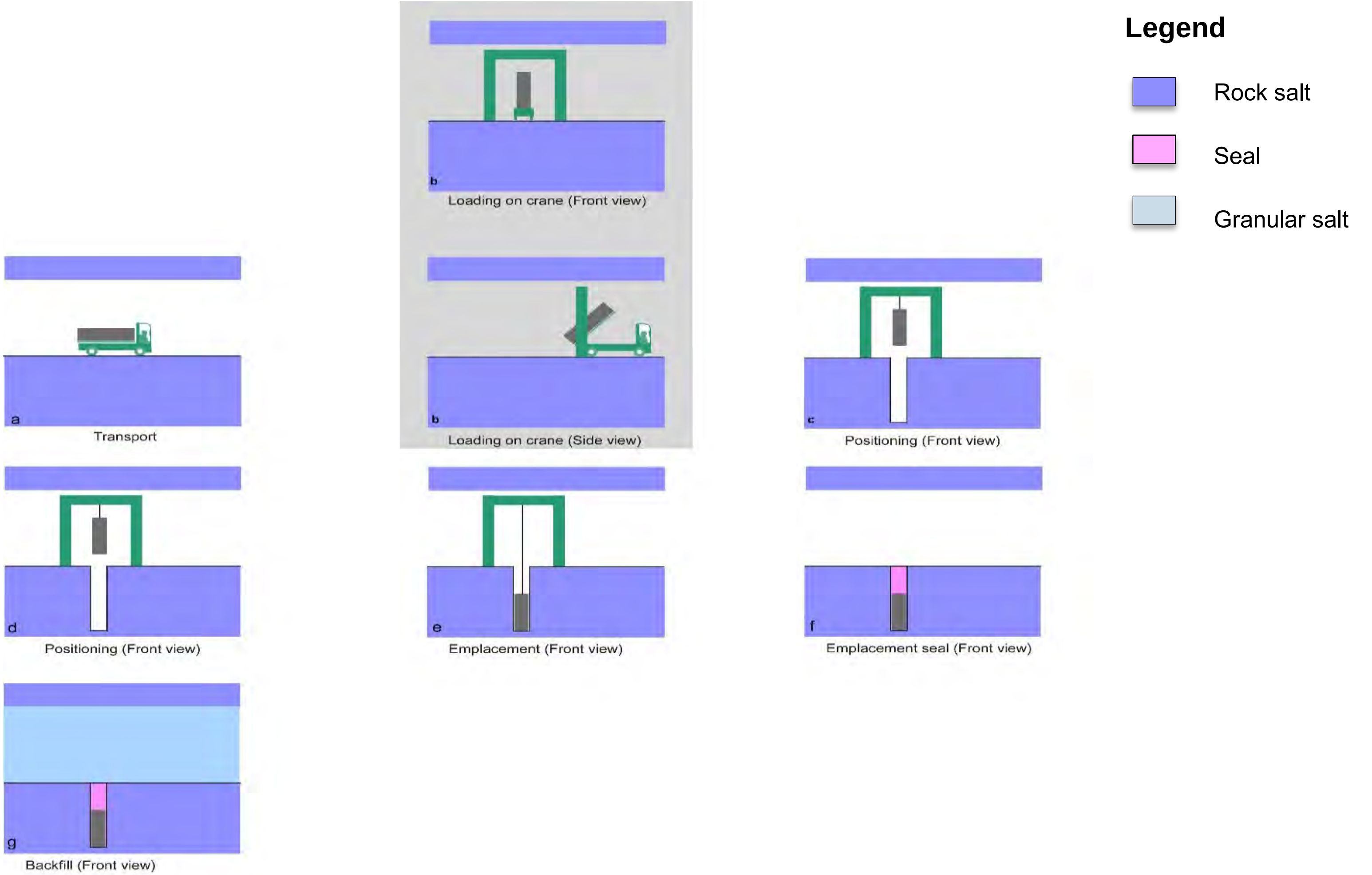
Heat generating waste

Non-heat generating waste



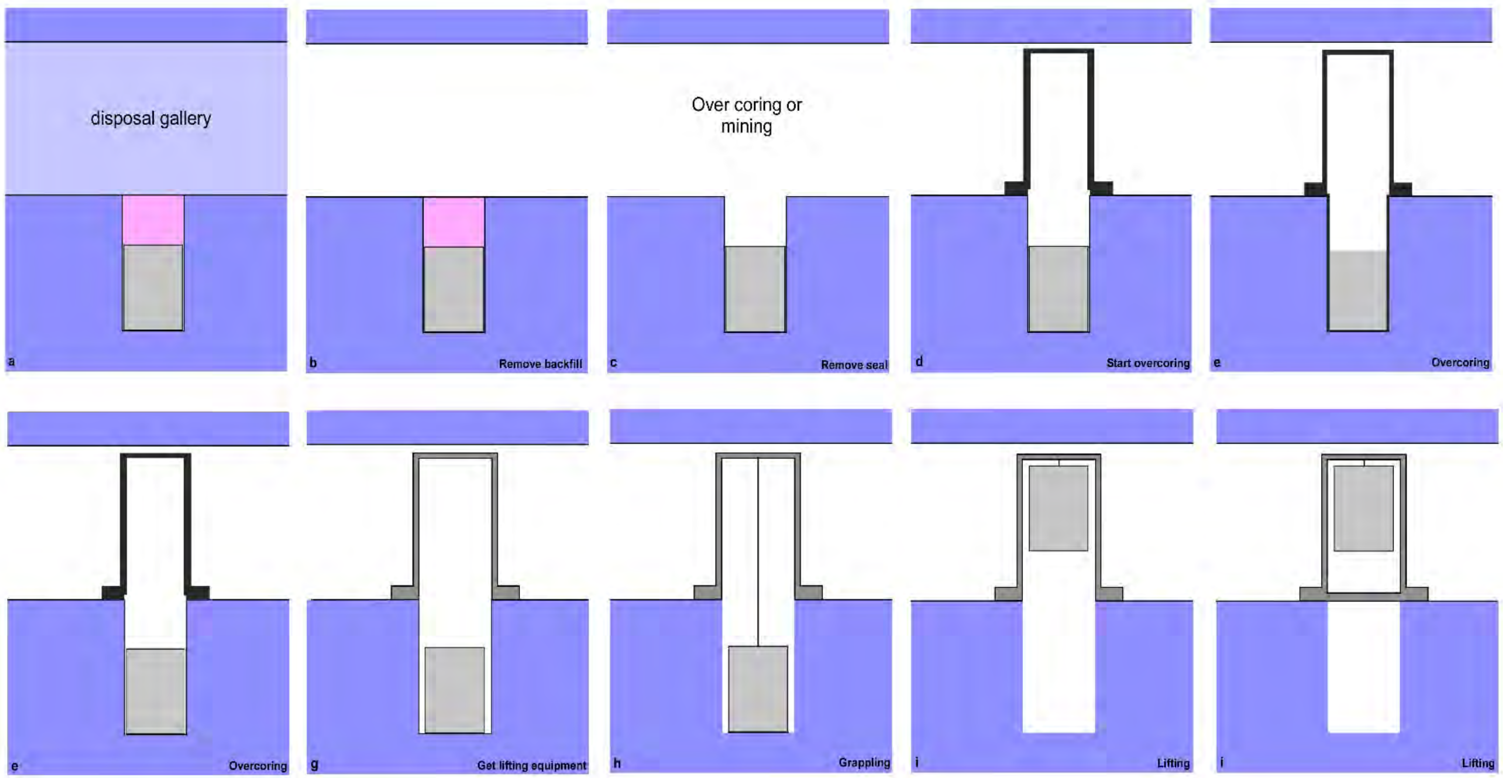
The Dutch national program: Towards a safety case in rock salt

Placement of the HLW



The Dutch national program: Towards a safety case in rock salt

Retrievability of the HLW



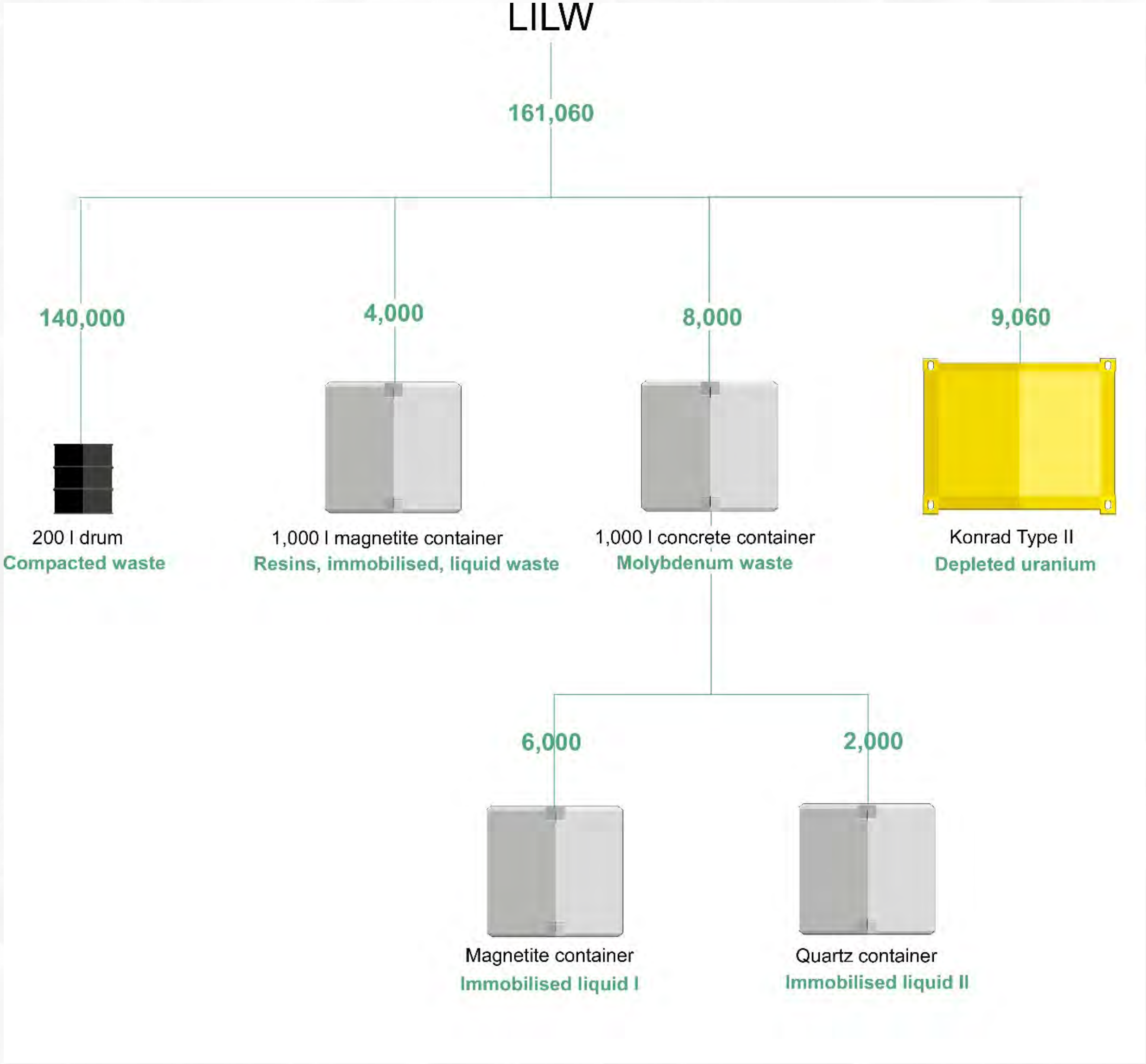
Legend

Rock salt

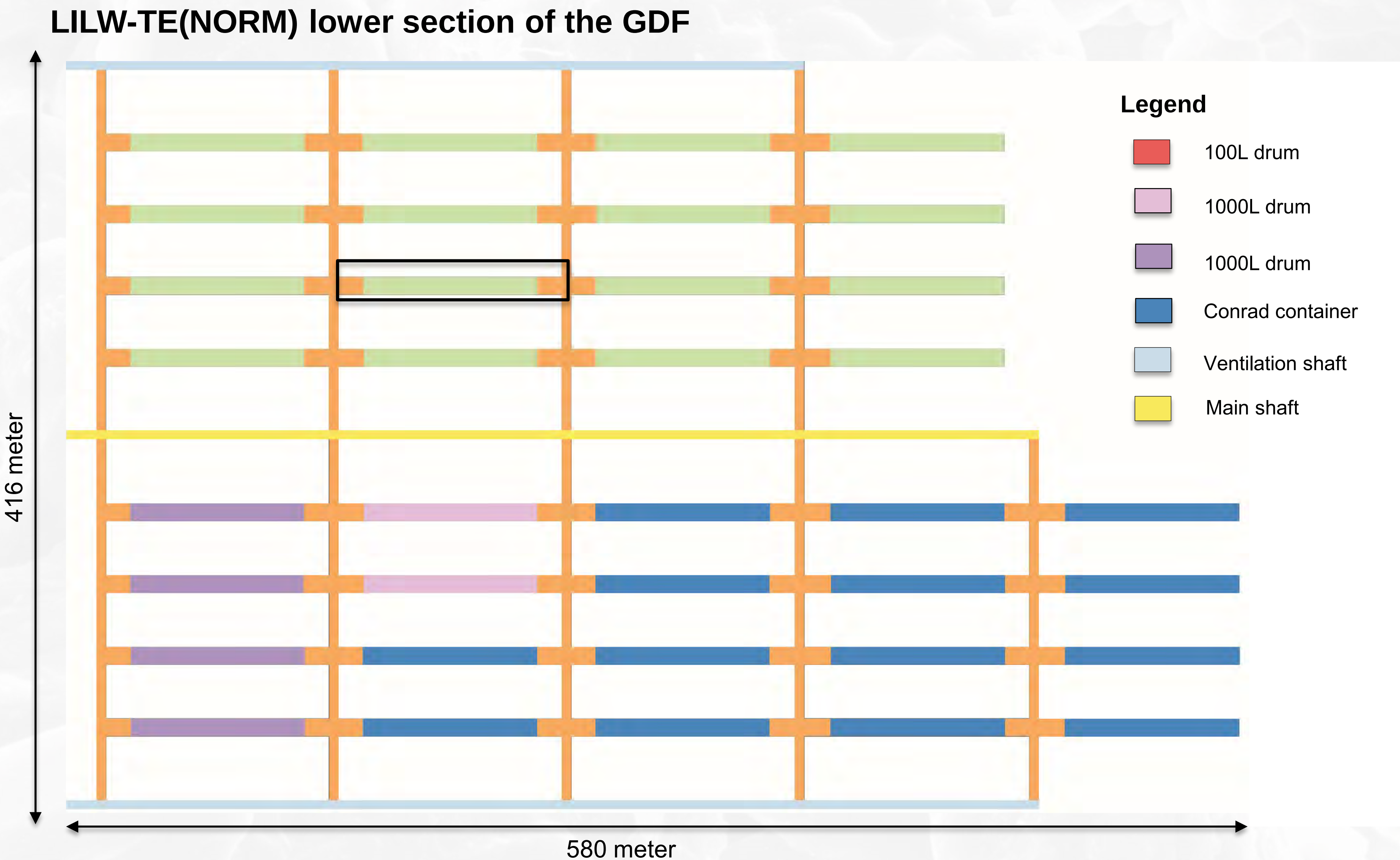
Seal

Granular salt

The Dutch national program: Towards a safety case in rock salt

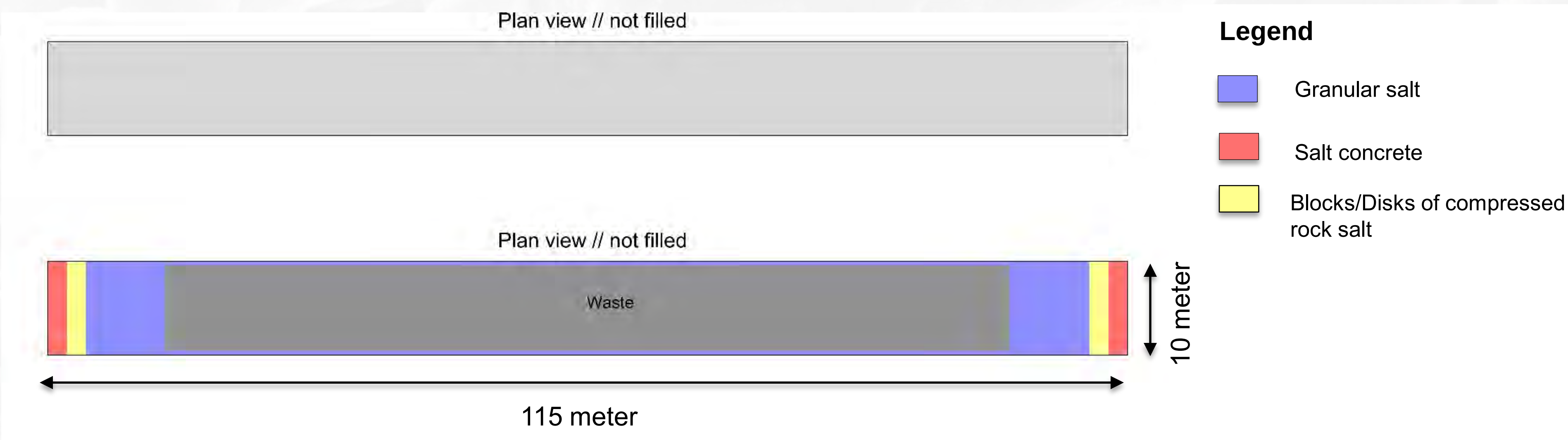


The Dutch national program: Towards a safety case in rock salt

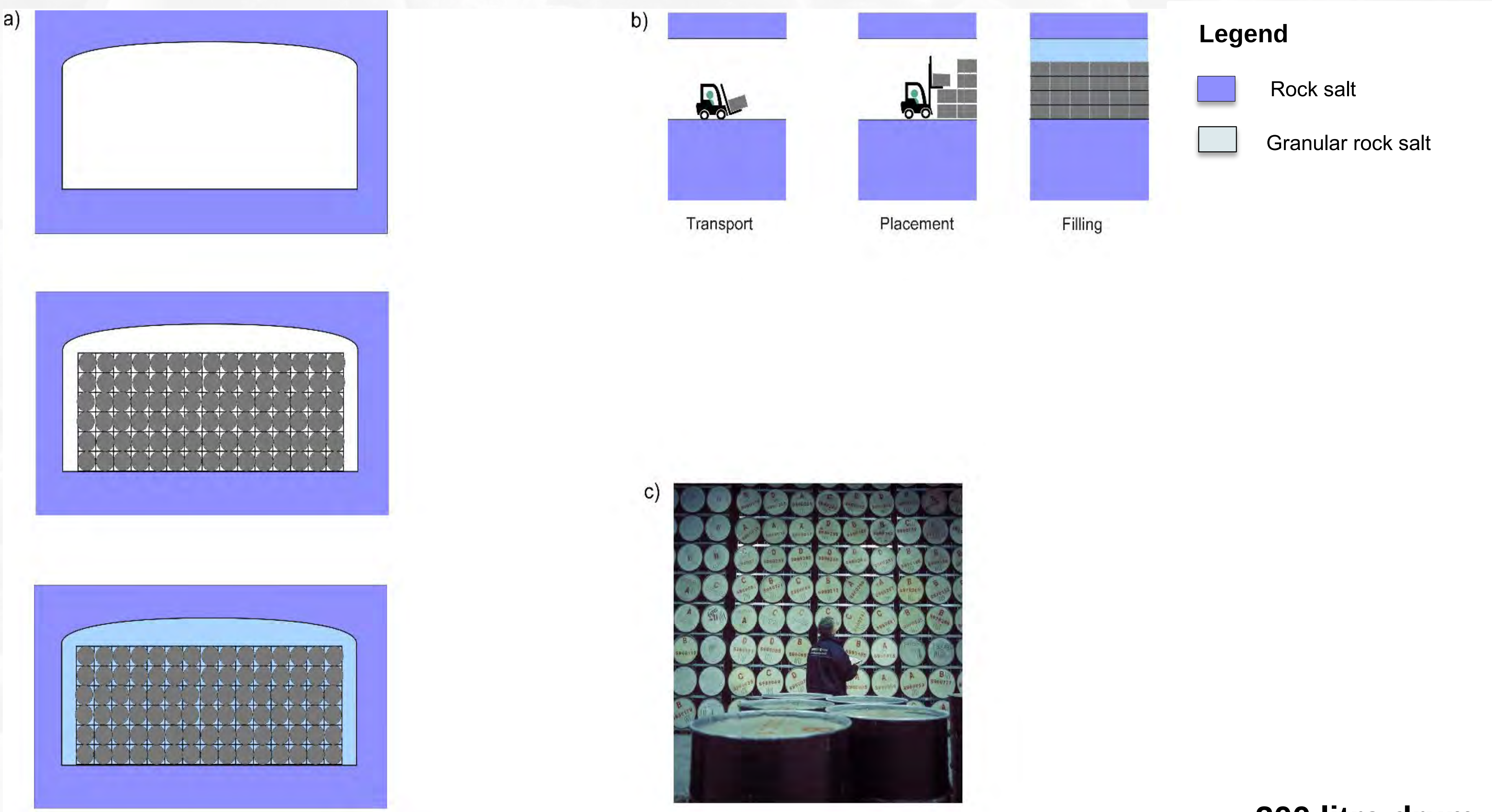


The Dutch national program:
Towards a safety case in rock salt

Cross section

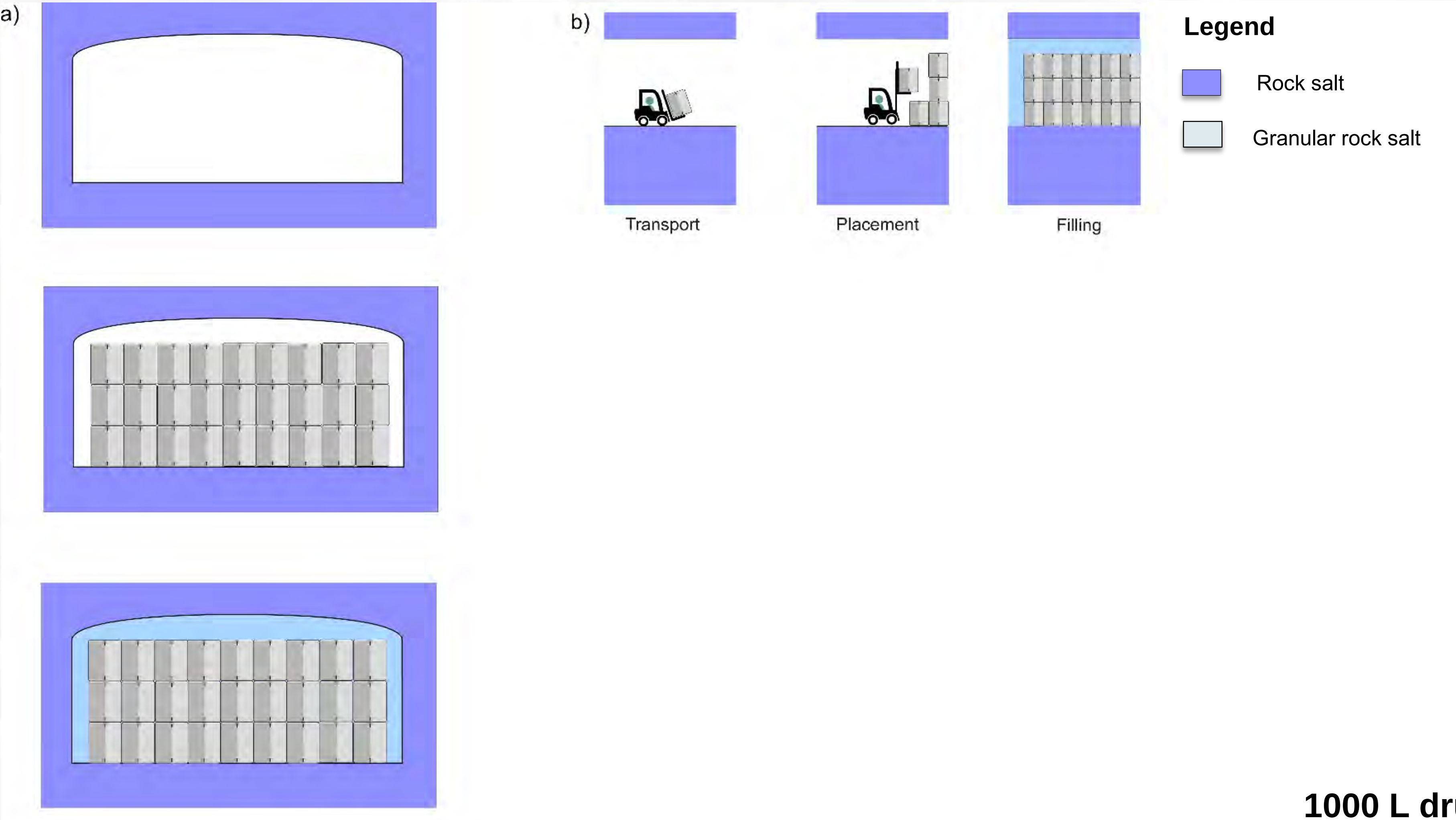


The Dutch national program:
Towards a safety case in rock salt



200 litre drum

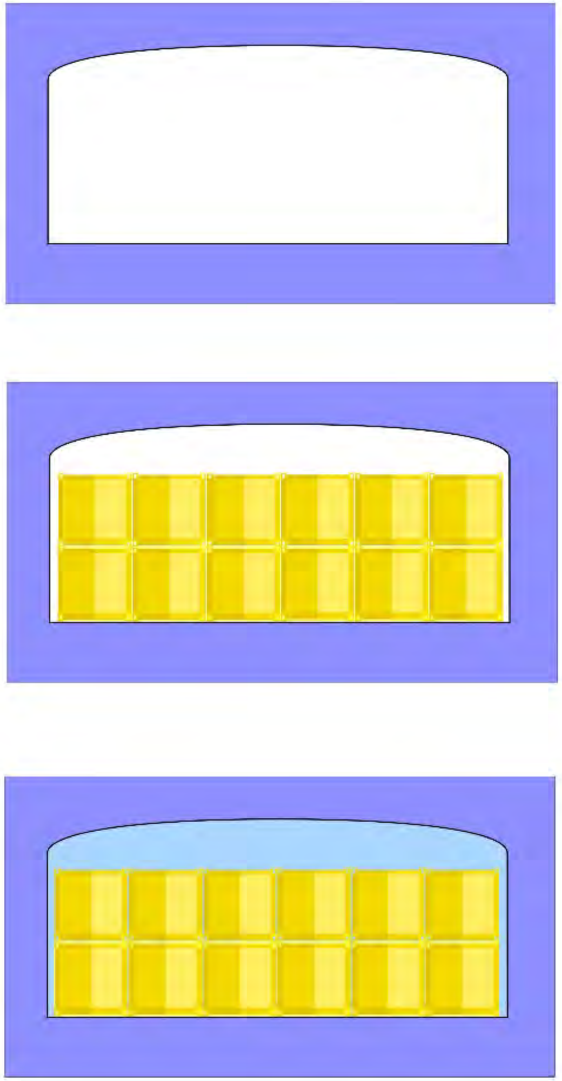
The Dutch national program: Towards a safety case in rock salt



1000 L drum

The Dutch national program: Towards a safety case in rock salt

a)



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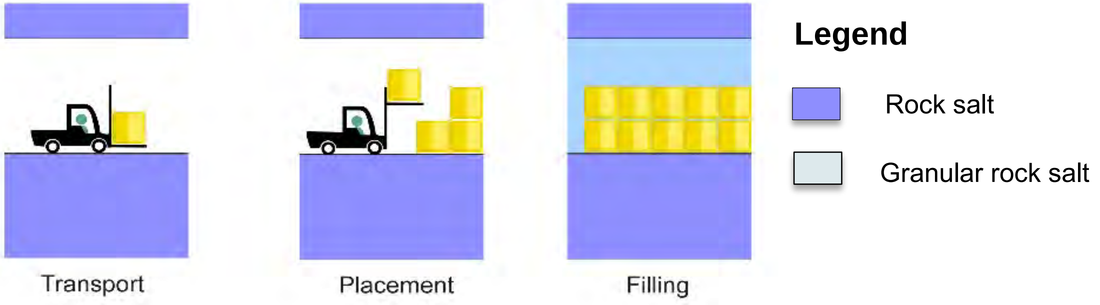
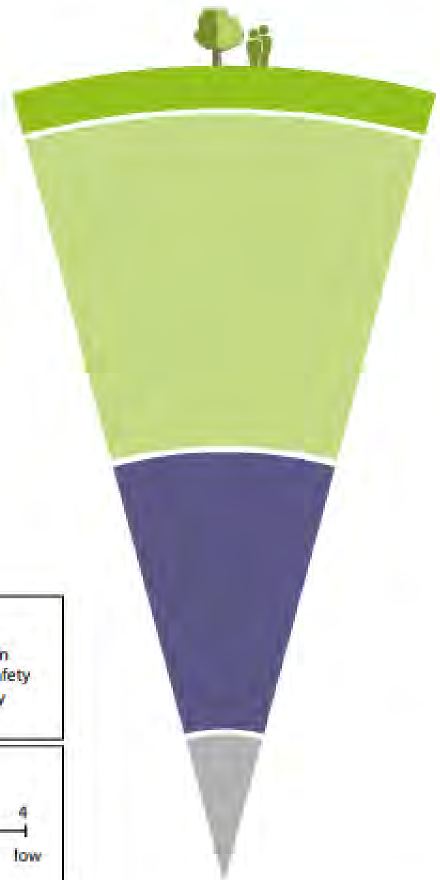


Conrad container

The Dutch national program: Towards a safety case in rock salt



Component	Key topics	Drivers	Priority
Society	Integrating societal aspects into technical research	S ■■■ D ■□□ C ■□□	2
Biosphere	- (Current knowledge sufficient)	S ■□□ D ■□□ C ■□□	4
Surrounding rock formations	Salinity in deeper ground water model Effect of climatic change	S ■■□ D ■□□ C ■■□	3
Host rock	Geotechnical properties Diffusion dominated transport Retardation Long-term evolution	S ■■■ D ■■□ C ■■■	1
Engineered barrier system	Concrete evolution Waste package design Tunnels and galleries	S ■■□ D ■■■ C ■■□	2

Drivers
S = confidence in long-term safety
D = disposability
C = costing

Priority
1 2 3 4
high low

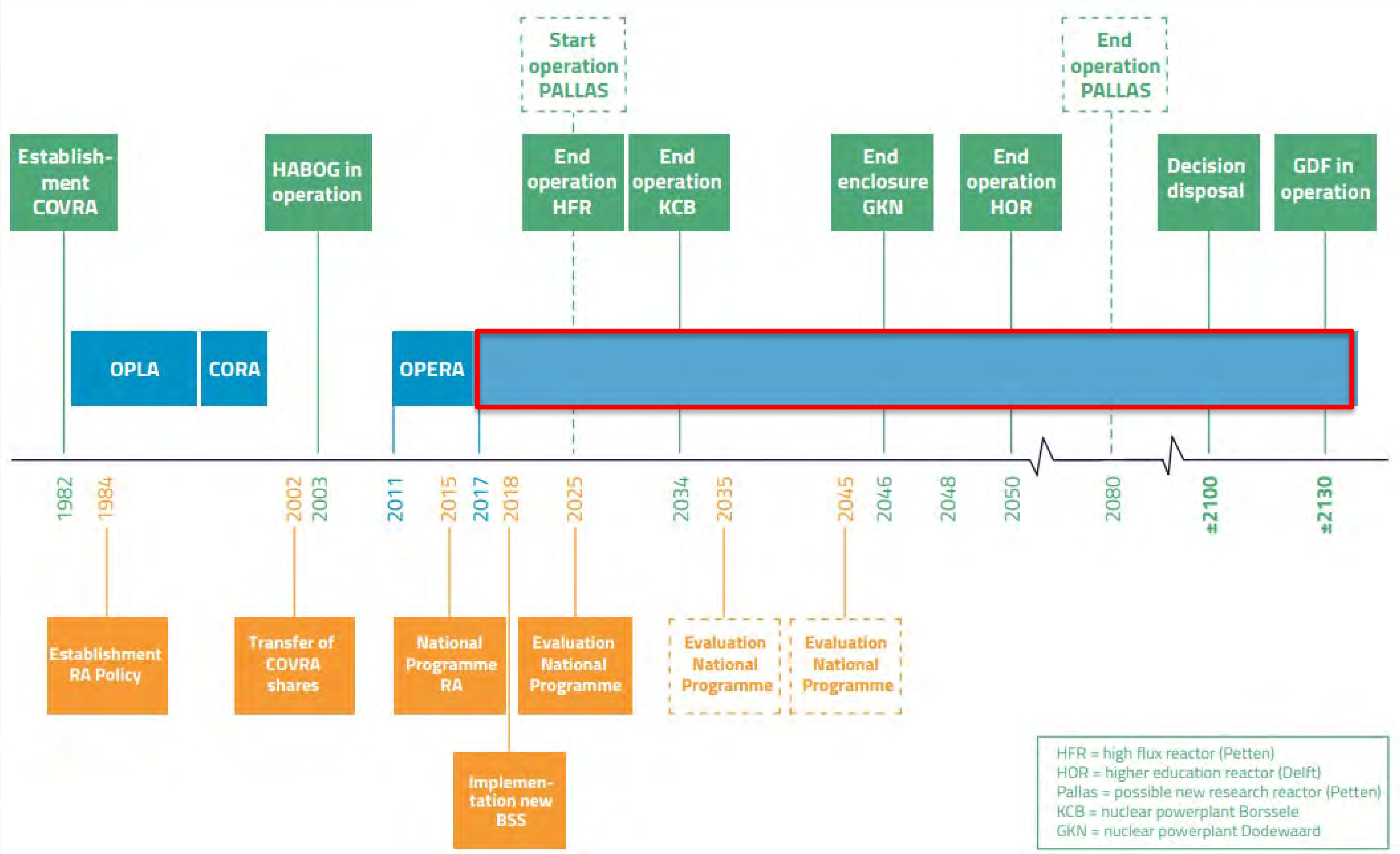
The Dutch national program: Towards a safety case in rock salt

Host rock - Research should be focused on **thermal** and **mechanical properties**.

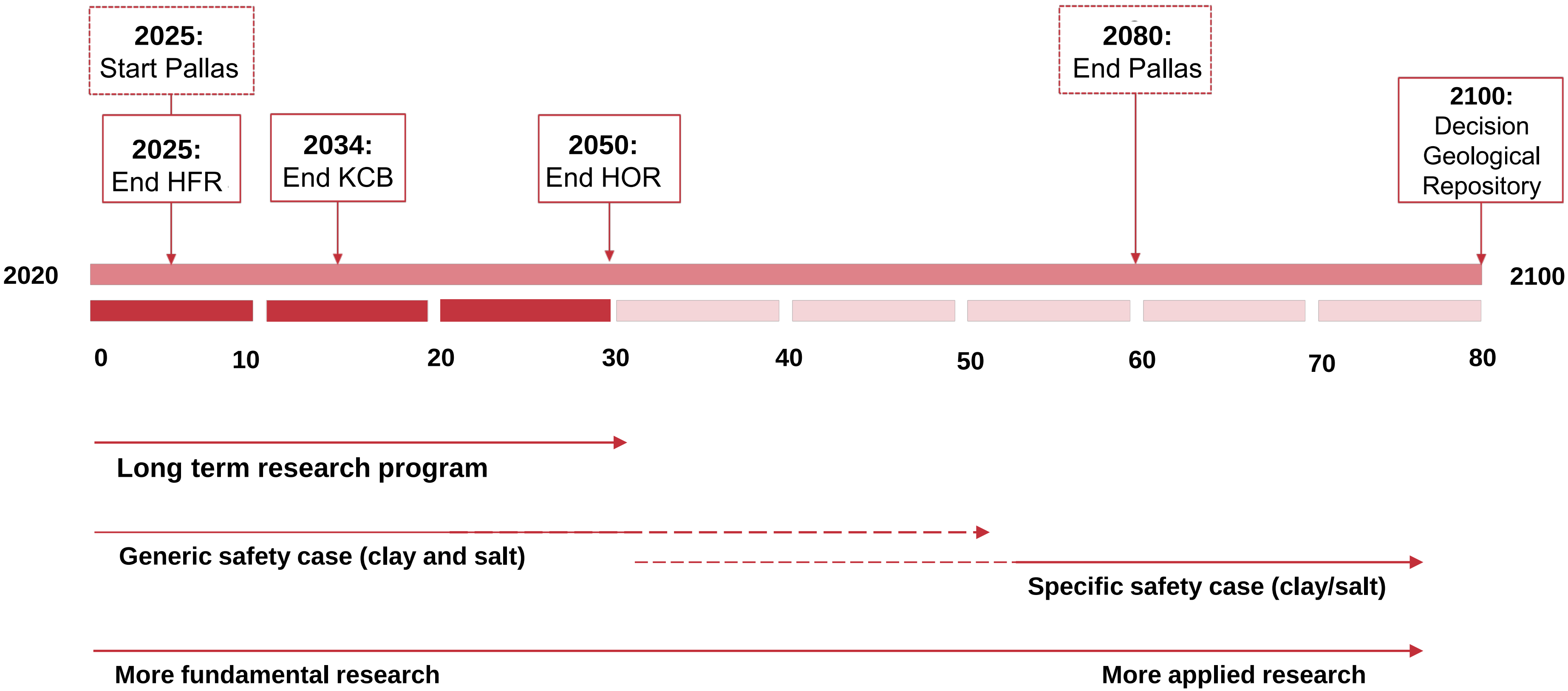
Surrounding rock formations - Research should also be focused on the effect of **climate change** and particularly **ice ages** and associated erosion and meltwater.

Engineered-Barrier System - Research should be focused on **waste package** design, layout of the repository and the evolution of concrete and specifically on the nature and rates of interactions between the host rock and the concrete.

The Dutch national program: Towards a safety case in rock salt

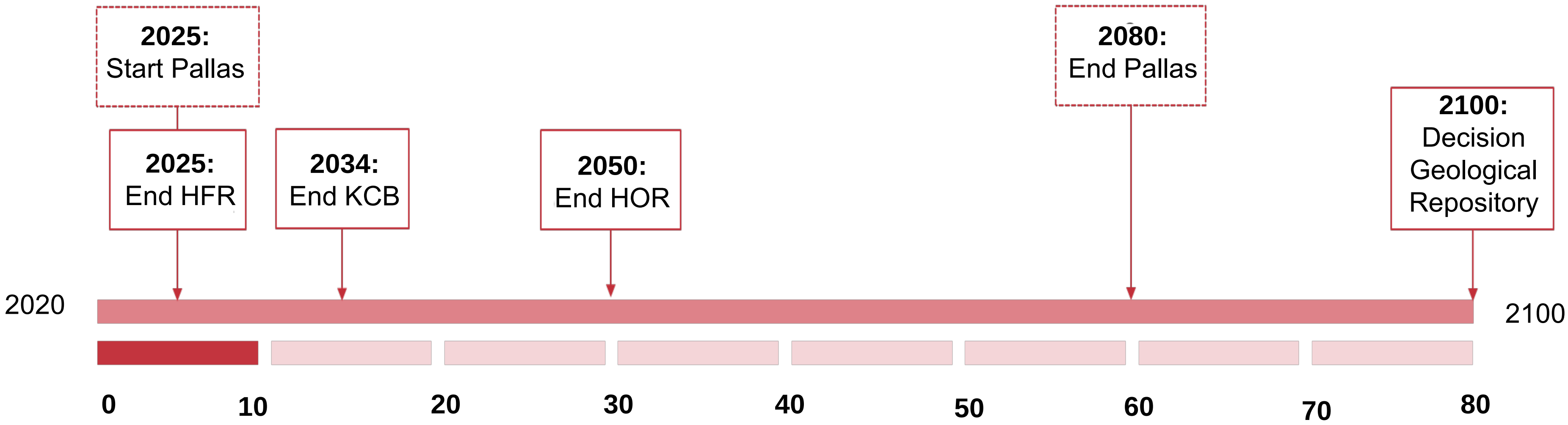


The Dutch national program: Towards a safety case in rock salt



The Dutch national program: Towards a safety case in rock salt

Vision 2020-2030

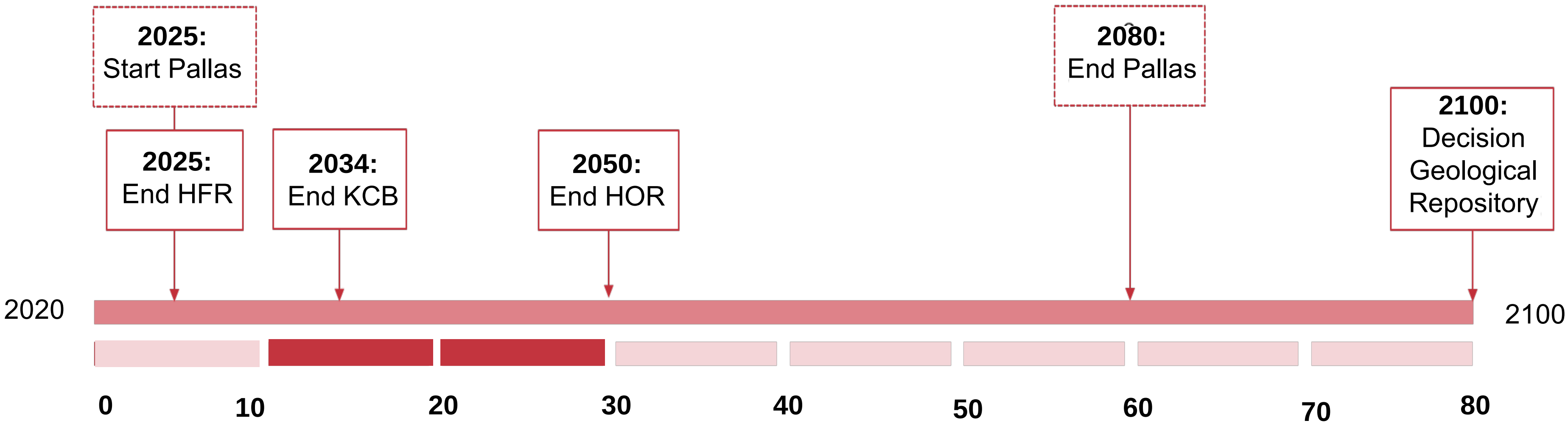


Expansion of knowledge: Increasing and extending the knowledge level of disposal.
Result: Initial safety cases.
Knowledge: Increase knowledge (literature/abroad/joint experimental research).

KCB = Nuclear power plant Borselle
HFR = Petten nuclear research reactor
HOR = Delft nuclear research reactor

The Dutch national program: Towards a safety case in rock salt

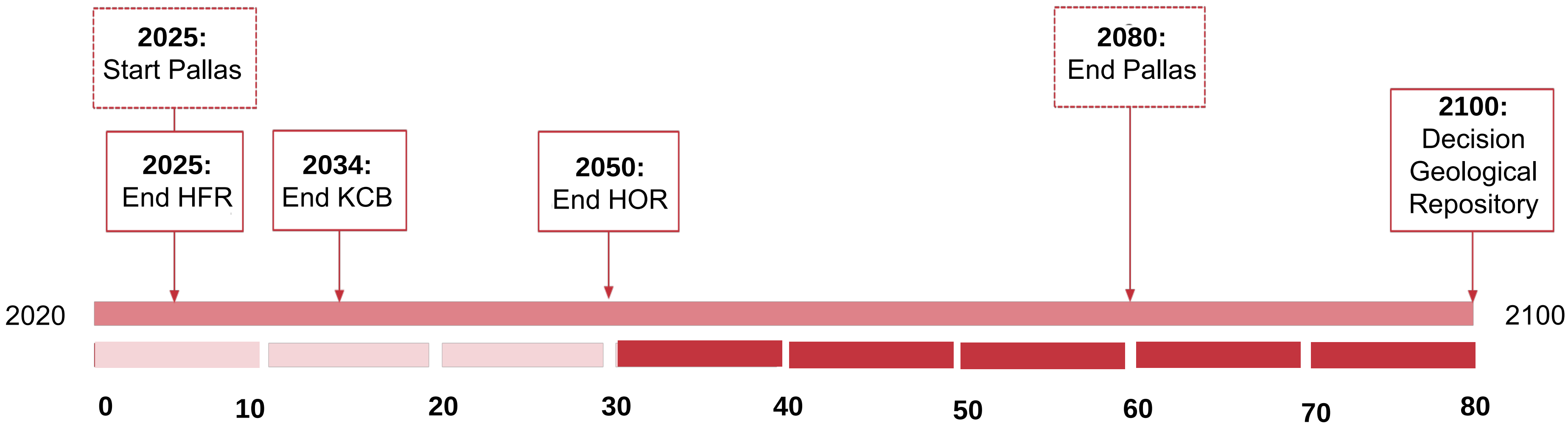
Vision 2030-2050



Expansion of knowledge: Increasing and extending the knowledge level of disposal.
Result: Well-developed safety cases (Safety calculation and concept of final disposal facility).
Knowledge: Increase knowledge (literature/abroad/joint experimental research).

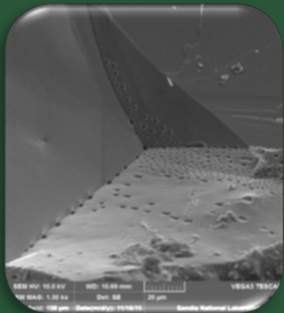
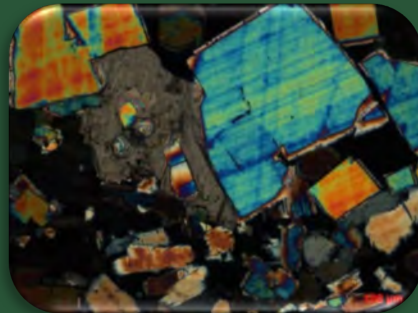
The Dutch national program:
Towards a safety case in rock salt

Vision 2050-2100



Expansion of knowledge: Increase knowledge about disposal in a specific host rock and specific location(s).
Result: Location-specific safety case(s) suitable for decision-making about a disposal facility in the Netherlands
Knowledge: More location-specific research (test drilling) and research into the construction / construction of a repository

The Dutch national program: Towards a safety case in rock salt

10th US/German Workshop on Salt Repository Research, Design, and Operation

Dr Amy Shelton
Radioactive Waste Management

Rapid City, SD, United States
May 28-30, 2019

Update on the UK Geological Disposal Facility Siting Process

Radioactive Waste Management Limited (RWM)

Wholly-owned NDA subsidiary

- Current headcount around ~165 staff
- Plan for continued development into Site Licence Company

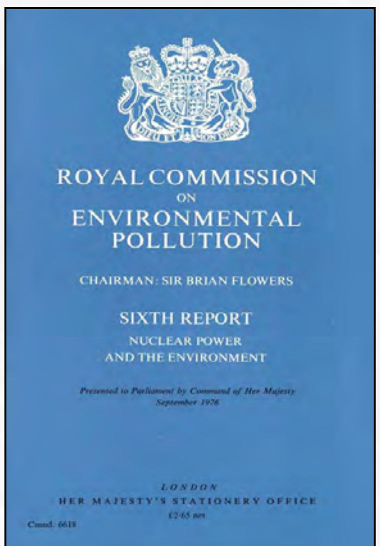
Vision

- A safer future by managing radioactive waste effectively, to protect people and the environment

Mission

- Deliver a geological disposal facility and provide radioactive waste management solutions

Why do we need a GDF?


ROYAL COMMISSION
ON
ENVIRONMENTAL
POLLUTION

CHAIRMAN: SIR BRIAN FLOWERS

SIXTH REPORT
NUCLEAR POWER
AND THE ENVIRONMENT

Presented to Parliament by Command of Her Majesty
September 1976

LONDON
HER MAJESTY'S STATIONERY OFFICE
£2·65 net

Cmnd. 6618

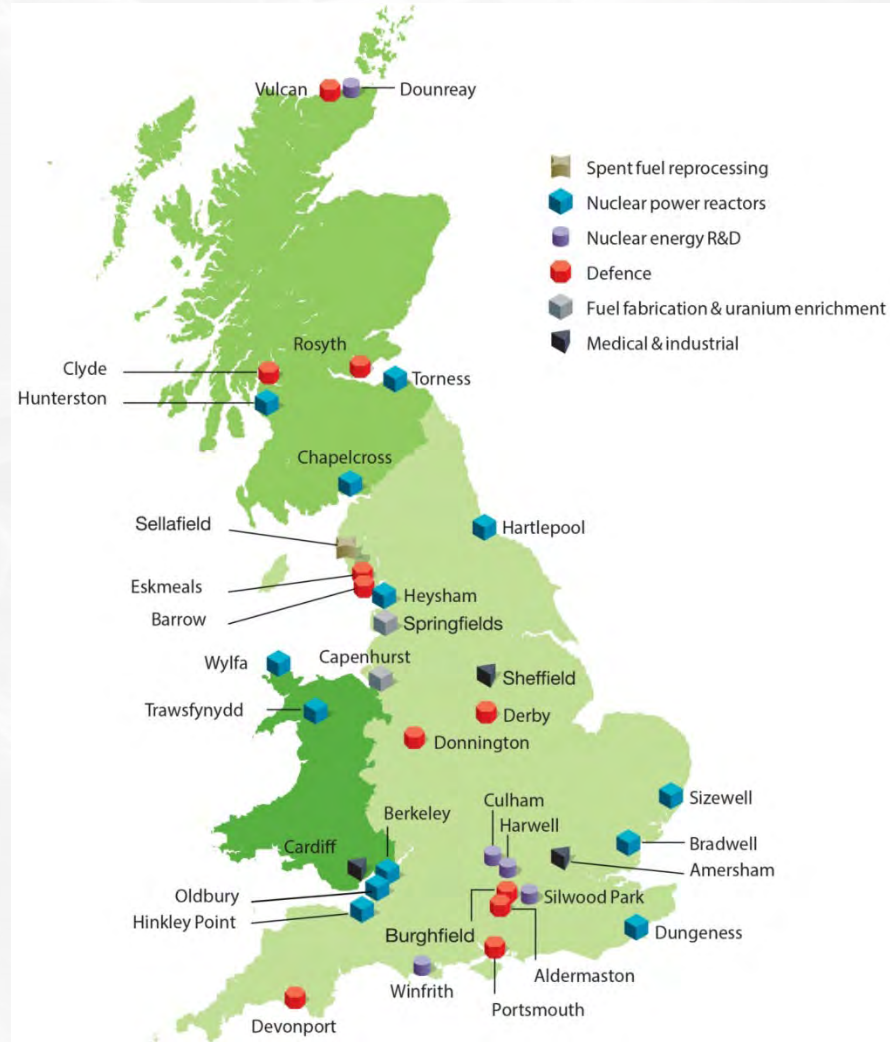
Wastes (& potential wastes) for disposal

Low heat generating waste (LHGW)

- Intermediate Level Waste (ILW)

High heat generating waste (HHGW)

- High Level Waste (HLW)
- Spent Fuel (SF)
- Uranium and Plutonium



Government Policy


Department of Energy & Climate Change

Implementing Geological Disposal

A Framework for the long-term management of higher activity radioactive waste

July 20

Llywodraeth Cymru Welsh Government

www.gov.wales

Welsh Government Policy on the Management and Disposal of Higher Activity Radioactive Waste

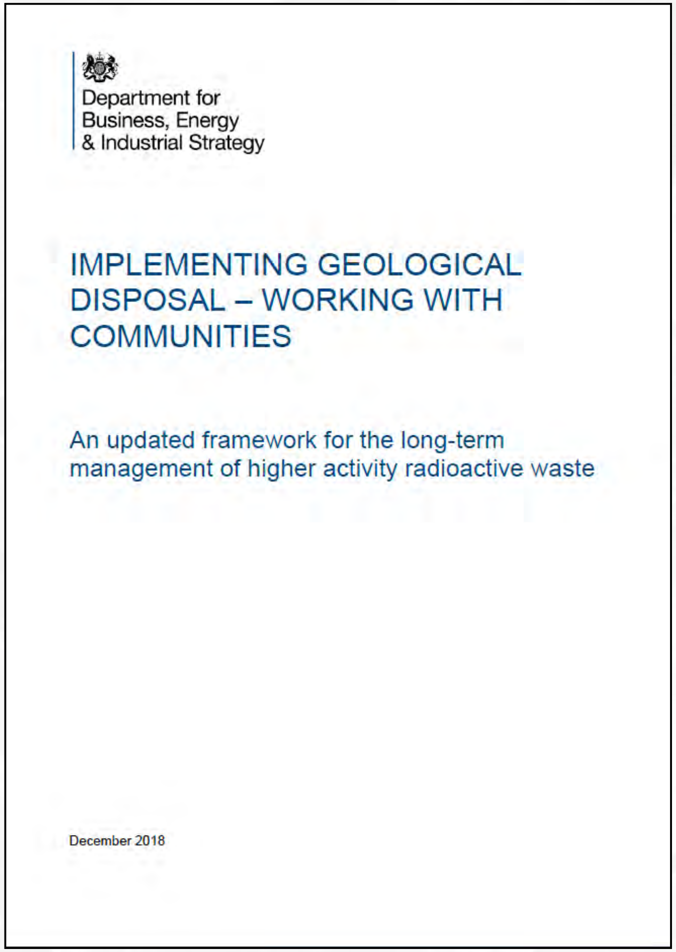
SCOTLAND'S HIGHER ACTIVITY RADIOACTIVE WASTE POLICY 2011

natural scotland

SCOTTISH GOVERNMENT

Higher Activity Waste Policy - England

- 2015 legislation makes GDF a Nationally Significant Infrastructure Project (NSIP)
- 2018 consultations on Working With Communities and National Policy Statement (part of NSIP planning process)
- Updated GDF siting policy framework published December 2018
  - replaces 2014 White Paper in England



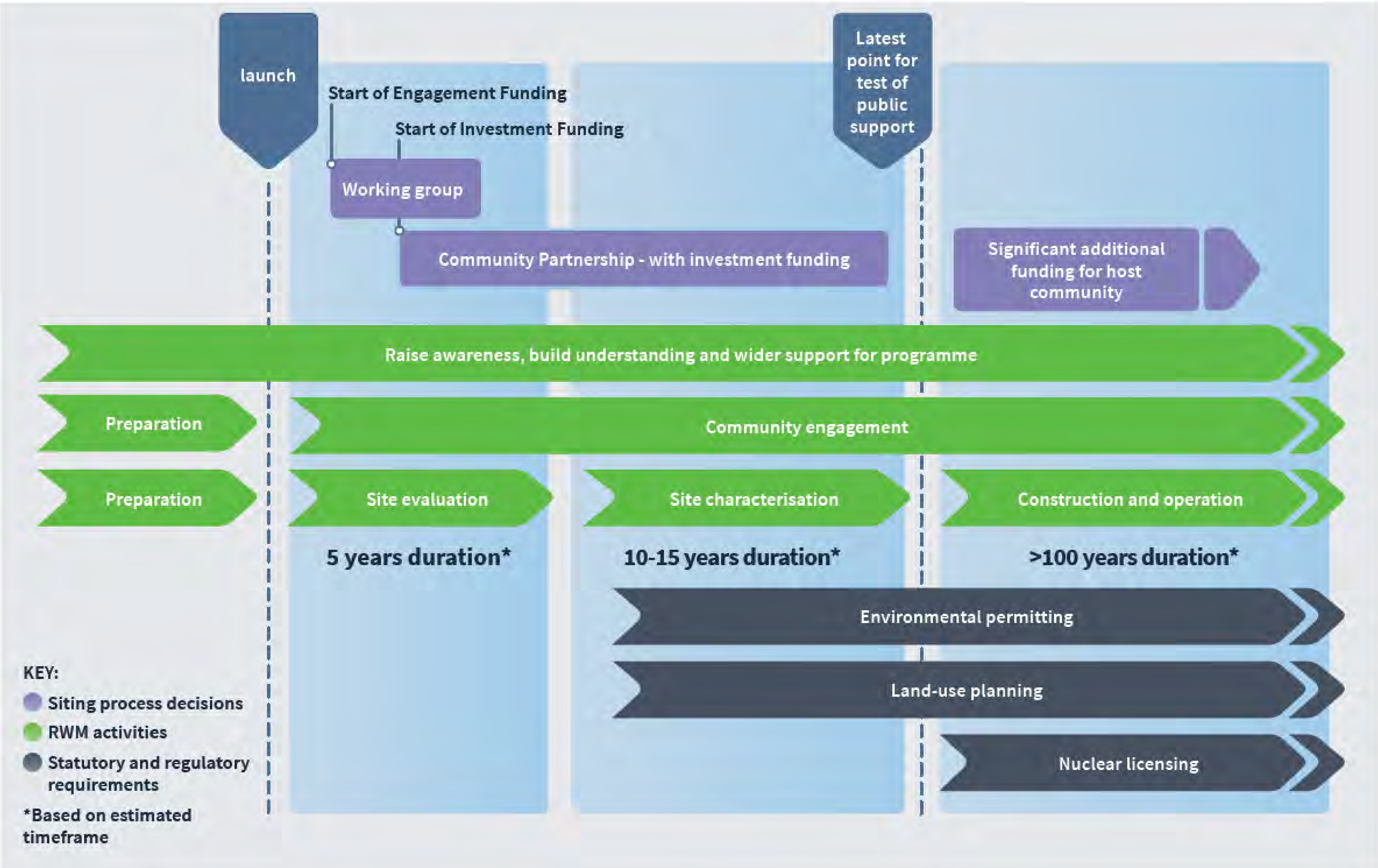
Department for Business, Energy & Industrial Strategy

IMPLEMENTING GEOLOGICAL DISPOSAL – WORKING WITH COMMUNITIES

An updated framework for the long-term management of higher activity radioactive waste

December 2018

Siting Process



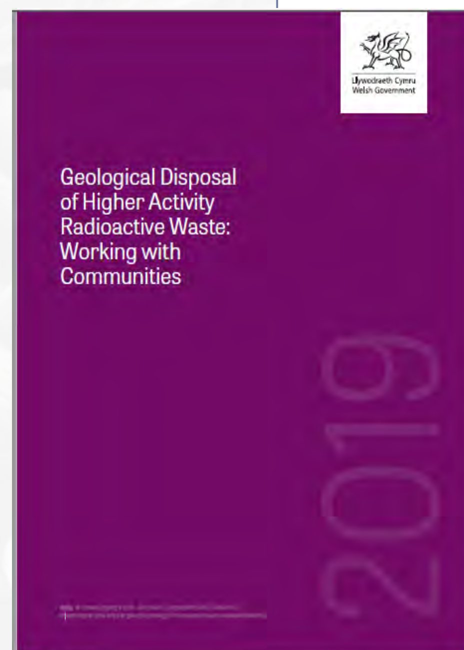
Working with communities

Community Investment

- There were no clear commitments in the previous MRWS process – just the possibility of something “to be agreed” in the future if a site was selected for development.
- Updated policy commitments are already in place for early Community Investment Funding for communities who take part in the siting process
- £1m per year then £2.5m per year for those who proceed to deep borehole drilling investigations
- Also greater emphasis on working in partnership with communities to help them build their own “community vision” for their future
- This should help build clearer picture of future investment possibilities that will work for each community

Higher Activity Waste Policy - Wales

- The Welsh Government has adopted a policy for the geological disposal of higher activity radioactive waste similar to that adopted in England
- Welsh policy on geological disposal published in two parts in 2015
- Welsh policy on Working With Communities in GDF siting published in January 2019



Higher Activity Waste Policy - Scotland

- Policy – near-surface facilities, located as near to the site where the waste is produced as possible

Updated Siting Process

- Siting process now led by RWM as a dedicated Waste Management Organisation engaging directly to raise awareness and build relationship with communities
- RWM web portal for access to basic information in layered manner designed to allow people of all levels of knowledge to find their own way through the questions they need answered – including National Geological Screening results
- RWM preparing to deliver outreach events across the country following launch – already testing tools like virtual reality at national events (New Scientist, Big Bang, Local Government conferences)
- Siting Process policy allows for early information gathering with interested local groups working flexibly in communities to build effective Partnerships

National Geological Screening

GOV.UK

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Departments Worldwide How government works Get involved
Policies Publications Consultations Statistics Announcements

Home > National Geological Screening > Mockup

Guidance

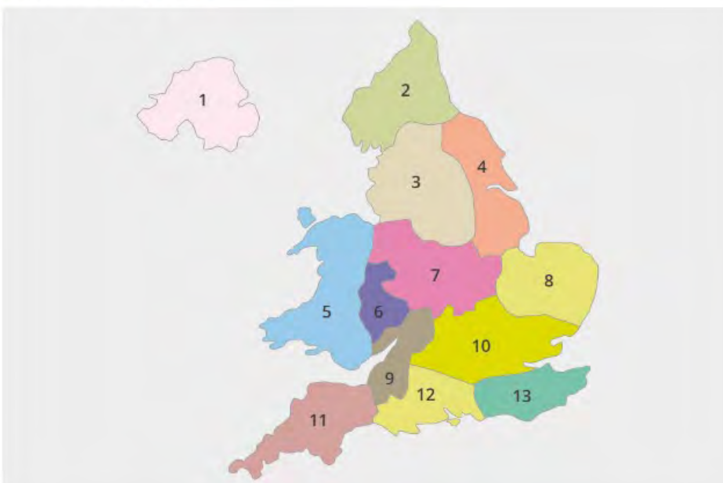
About National Geological Screening

From: National Geological Screening
Part of: Mockup
First published: 1 January 2017
Last updated: 10 April 2017, see all updates

National Geological Screening.

Contents

The 13 Regions



Eastern England Sub Regions

Map of the sub regions

Click on the links below for more information on the relevance to the safety of a GDF for a sub-region.

1. North York Moors
2. The Wolds and Humberside
3. Vale of York and Trent Valley
4. Lincoln Area

Click here for more information on the geological attributes of the Eastern Region.

NSG – Example Video

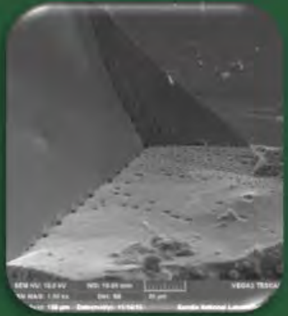
https://youtu.be/8YiUiVcIe9w

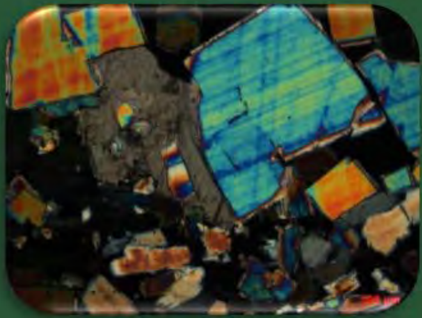
Thanks very much for your attention.

You can contact GDFenquiries@nda.gov.uk or you can reach me directly at: amy.shelton@nda.gov.uk

You can visit our website at: www.nda.gov.uk/rwm

For regular updates please subscribe to our e-bulletin news alerts at: http://www.nda.gov.uk/rwm/subscribe





10th US/German Workshop on Salt Repository Research, Design, and Operation

Selected Modeling Challenges in R&D Project WEIMOS

A. Hampel, Hampel Consulting
S. Sobolik, Sandia National Laboratories

Rapid City, SD, USA
May 28-30, 2019

Joint Project WEIMOS:

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

April 2016 – March 2019 -> extended: **September 2021**,
(writing of synthesis report until March 2022)

Partners

Germany:

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

United States:

- Sandia National Laboratories, Albuquerque & Carlsbad

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

MANAGED BY
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

Joint Project WEIMOS:

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

Work Packages

WP 1: Deformation behavior at small deviatoric stresses

WP 2: Influence of temperature and stress state on damage reduction ("healing")

WP 3: Deformation behavior resulting from tensile stresses

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

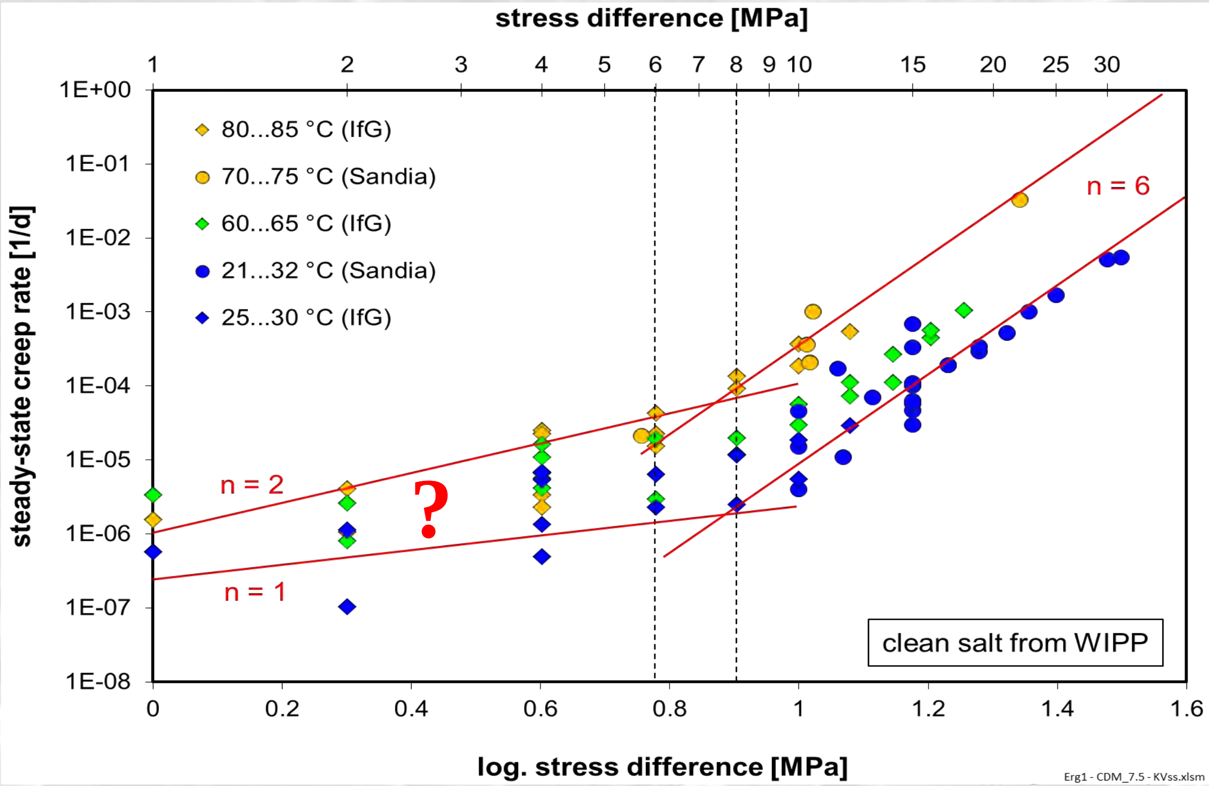
WP 5: Virtual demonstrator and 2nd demonstration model

WP 6: Administration

Basis for further development of the modeling: extended lab test program

WP 1: IfG: **Triaxial creep test series** with WIPP salt in 3 new test rigs

- Long (~ 100 days) initial consolidation phase at T = 120 °C, $\sigma_{1,2,3}$ = 20 MPa ($\Delta\sigma$ = 0)
- Series 1: $\Delta\sigma$ = 2 / 4 / 6 MPa, Series 2: $\Delta\sigma$ = 1 / 3 / 5 MPa, both at T = 80 - 60 - 30 °C (each stage: 100 d)
- Accompanying microscopic investigations (Melissa Mills, Sandia)



Basis for further development of the modeling: extended lab test program

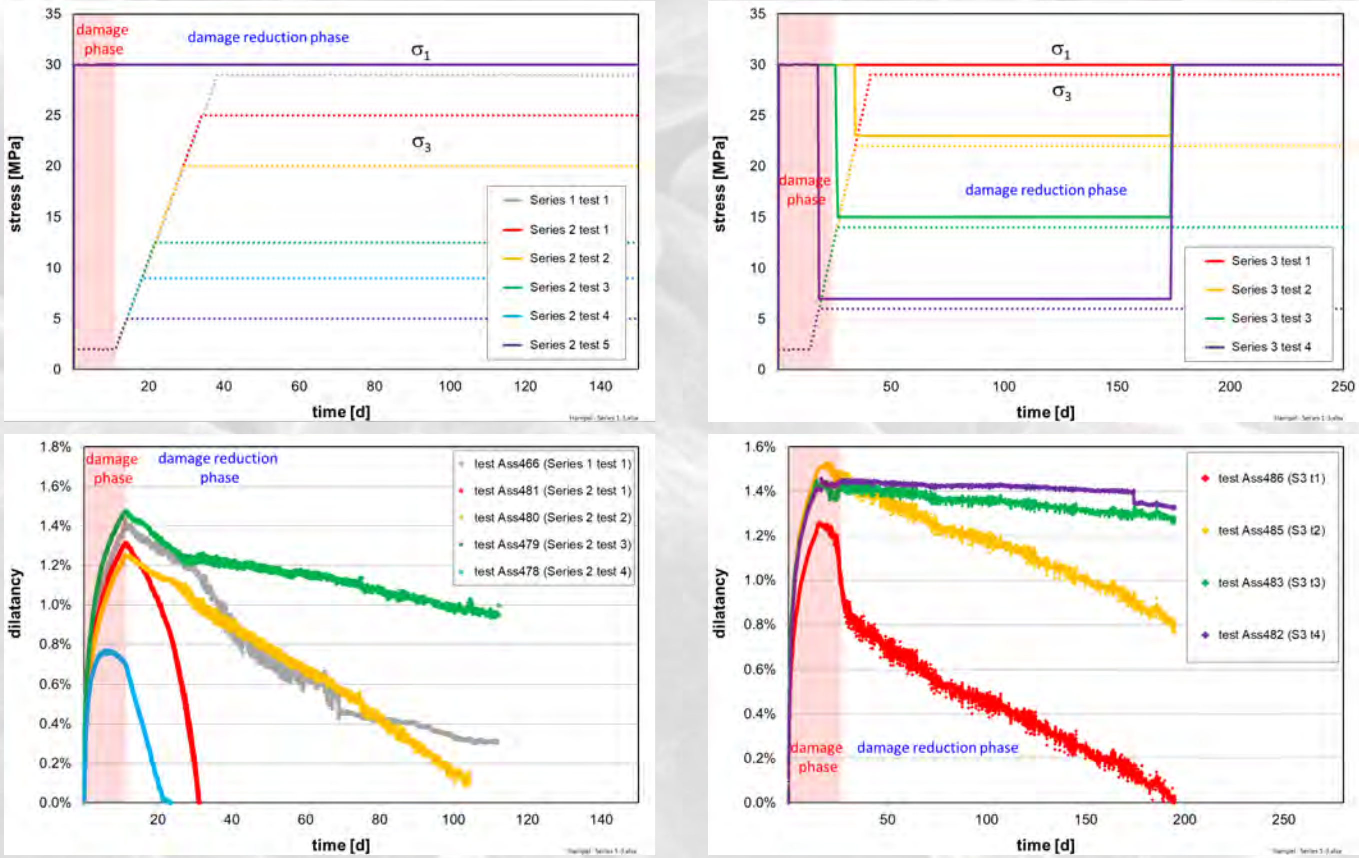
WP 2: TUC: Several **healing test series** with Asse salt, additional tests with WIPP salt:

- different stress paths in the healing phase
- different temperatures: 35 and 70 °C

Due to extremely sensitive measurements, previous test series did not give clear results of how healing depends on stresses σ_1, σ_3 and $\Delta\sigma$.

The planned test series will be conducted by TUC in new high-precision test rigs.

Previous TUC test series with Asse salt at 35 °C



Basis for further development of the modeling: extended lab test program

WP 3: IfG and TUC: **Direct tension tests** with WIPP salt

- specimens pre-damaged at σ_3 = 0.2 ... 5 MPa up to ε_{vol} = 0,5 ... 3 %
- uniaxial and triaxial tests

WP 4: Sandia / RESPEC: More **direct shear tests** with bedded salt interfaces / clay seams

-> Presentation of Steve Sobolik

WP 5: Virtual Demonstrator and 2nd demonstrator model

Planned simulations in WP 5 until Sept. 2021:

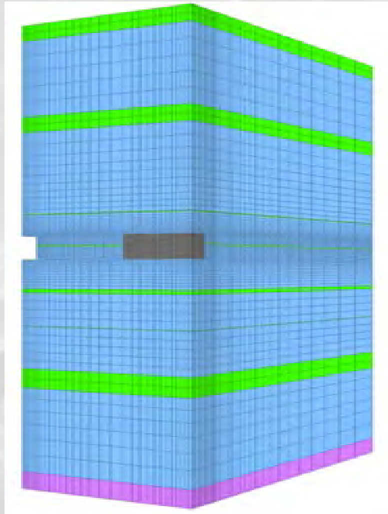
I. Simulations of current Virtual Demonstrator (cont'd)

focusing on

creep at small deviatoric stresses (WP 1),

damage reduction and healing (WP 2),

influence of interfaces/clay seams (WP 4)

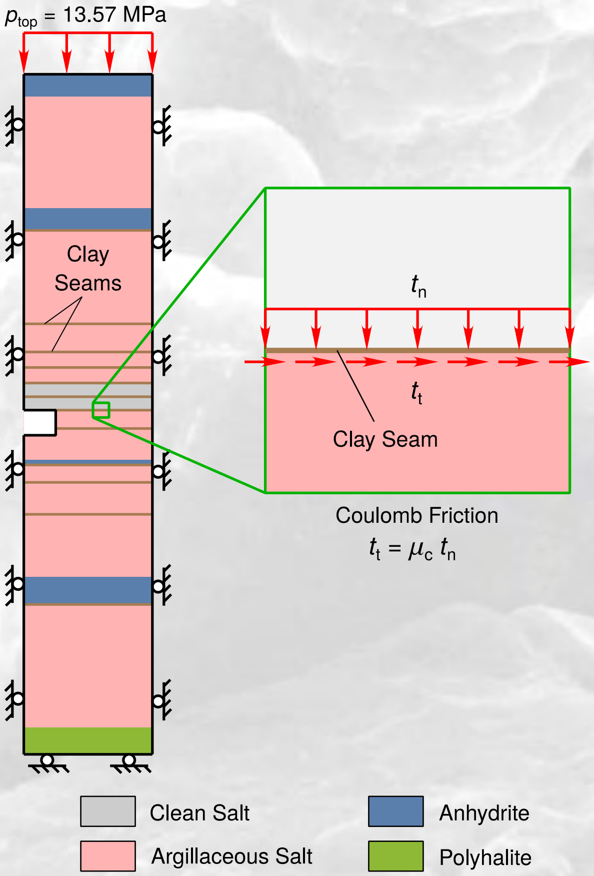


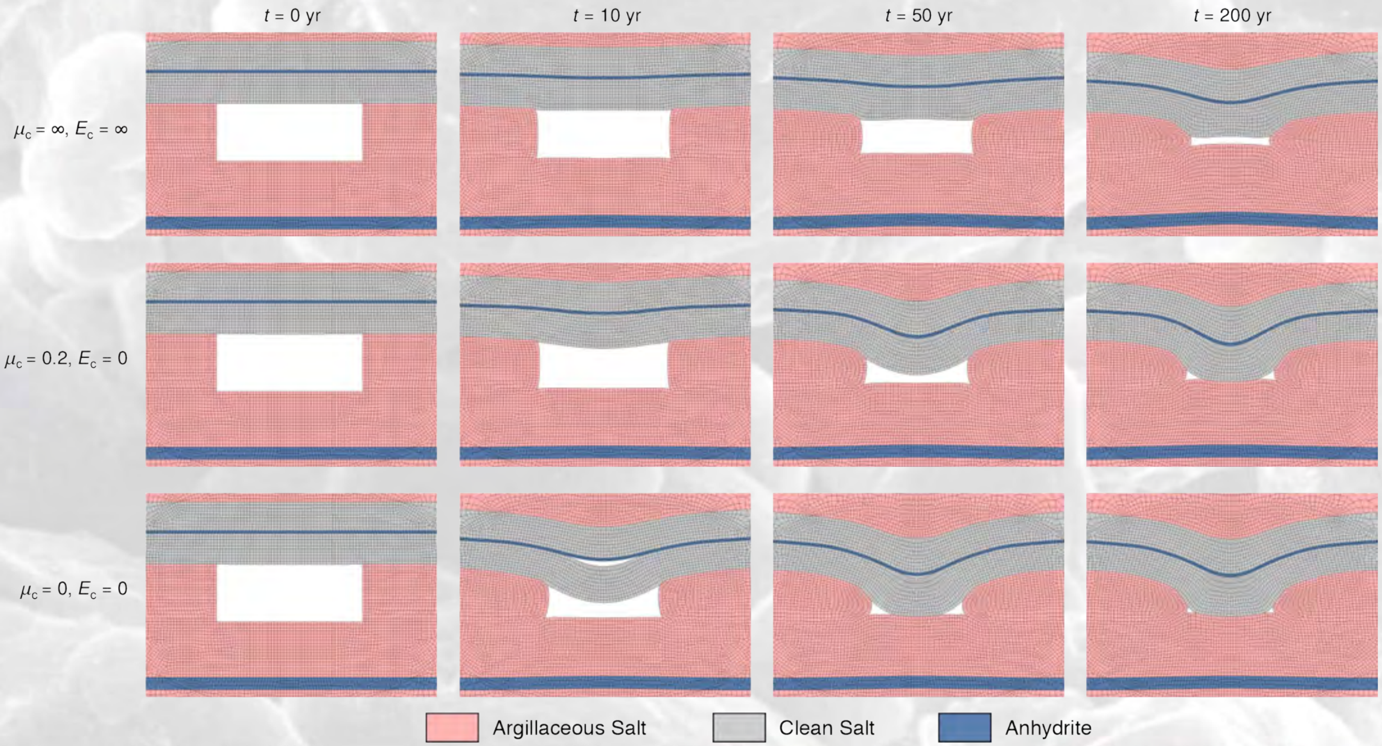
II. Simulations of 2nd demonstrator model

focusing on

intense tensile damage up to tensile failure (WP 3)

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





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

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

Shear tests of interfaces in salt

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

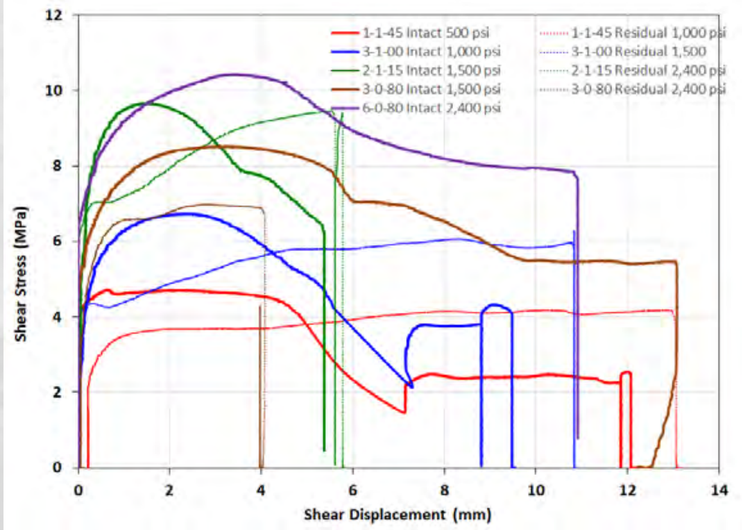
Tests performed at four different normal stresses (3.4, 6.8, 10.3, 16.6 MPa), shear velocity of 0.25 mm/min.

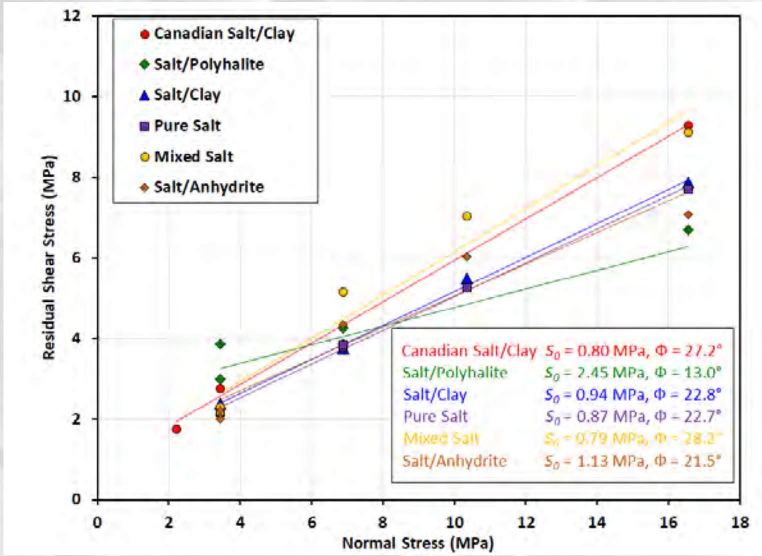
Some repeatability observed in maximum residual shear stress at same normal stress after interface fractured in intact test, fractured samples sheared in residual test.

Clay/salt contacts much stronger than anticipated.

Sample stiffness much higher than anticipated.

Consistent behavior among different samples on intact tests.





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

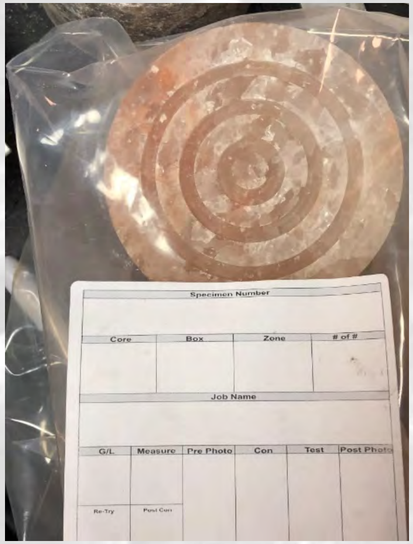
Proposed additional tests

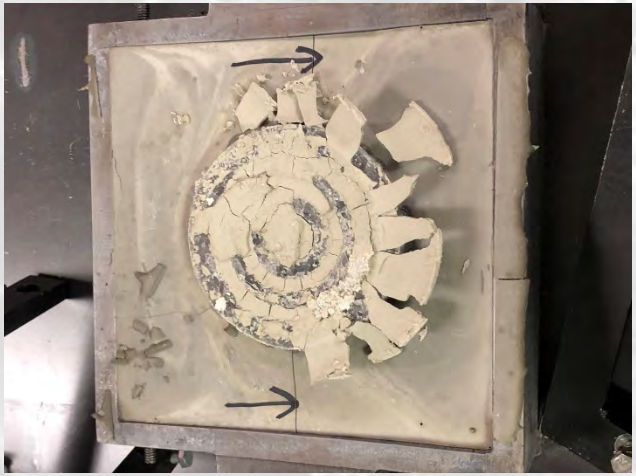
<u>Artificial clay seam</u>:

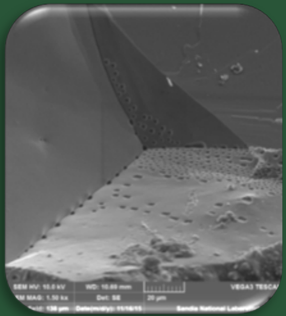
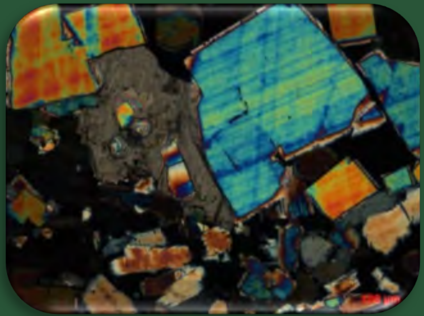
- Shear tests with manufactured clay seam (consolidated in pressure chamber) using bentonite/brine mixture, available salt core samples.
- Prototype test performed at 3.4 MPa yielded at 0.6-0.7 Mpa (friction coefficient ~ 0.2).
- Currently revising test plan for additional shear tests: minimum 6 tests, with pre-consolidation thicknesses of 6 mm, 12 mm; 3 different normal pressures of 3.4, 6.8, 10.3 MPa.

Additional shear tests with core obtained from WIPP: Clay seams D through K (particularly G), MB 139.

Tension tests on WIPP samples (dependent upon condition of seams after retrieval).





KOMPASS - Compaction of granular salt for the save enclosure: WP3 Modeling

Sandia National Laboratories

BGE TEC BCE TECHNOLOGY GmbH

PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology

RESPEC

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

L. Friedenberg[*1], U. Heemann[*2], C. Lerch[*3], S. Lerche[*4], C. Lüdeling[*5], B. Redlunn[*6], D.Stührenberg[*2], J. Zhao[*4]

[*1]GRS, [*2]BGR, [*3]BGE TEC, [*4]TUC, [*5]IfG,[*6]SNL

Rapid City, SD, United States

May 28-30, 2019

Topics

KOMPASS – The project

Why KOMPASS – Changed backfill requirements

KOMPASS – WP 3

- physical process classes
- modeling thermal class
- modeling hydraulic class
- modeling mechanical class

Summary

KOMPASS – The project

Why KOMPASS – Changed backfill requirements

KOMPASS – WP 3

- physical process classes
- modeling thermal class
- modeling hydraulic class
- modeling mechanical class

Summary

KOMPASS – Partners

Germany:

- BGE TECHNOLOGY GmbH (BGE TEC), Peine
- Federal Institute for Geosciences and Natural Resources (BGR), Hannover
- Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Braunschweig
- Institute for Rock Mechanics GmbH (IFG), Leipzig
- TU Clausthal: Institute of Mineral and Waste Processing, Waste Disposal and Geomechanics (TUC)

United States:

- Sandia National Laboratories (SNL)

KOMPASS – Project

WP 1: Experimental investigations

WP 2: Microstructural analysis for process understanding

WP 3: Model technical strategy

- WP 3.1: Requirements for process models
- WP 3.2: Analysis of model approaches
- WP 3.3: Evaluation of the process models with respect to the requirements of the safety demonstration

WP 4: Documentation and Synthesis

➥ WP 2: Presentation by Melissa (SNL) just before

➥ Presentation by Jens & Oliver (GRS) tomorrow

KOMPASS – The project

Why KOMPASS – Changed backfill requirements

KOMPASS – WP 3

- physical process classes
- modeling thermal class
- modeling hydraulic class
- modeling mechanical class

Summary

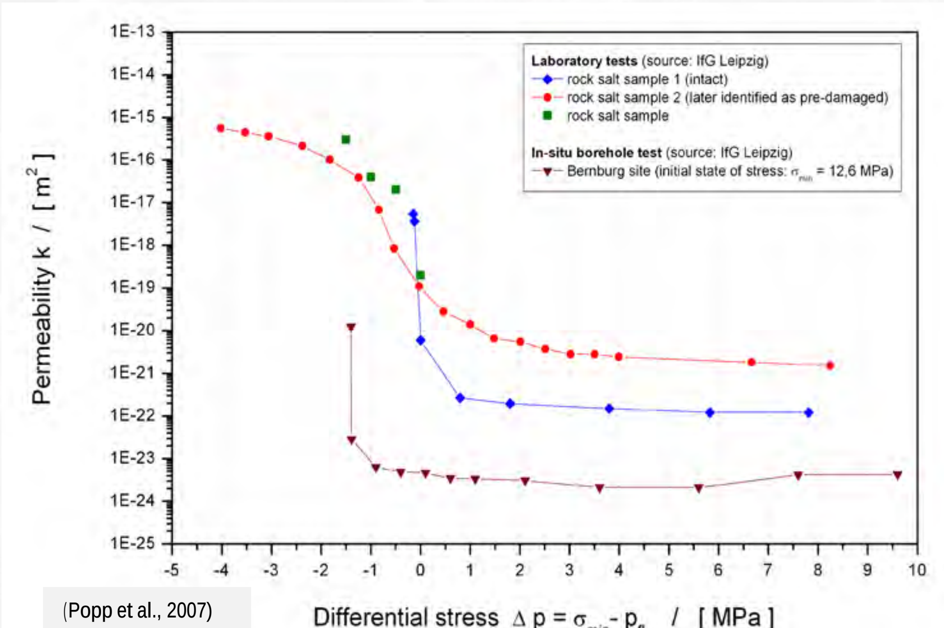
Paradigm shift in long-term safety

Release scenarios to biosphere

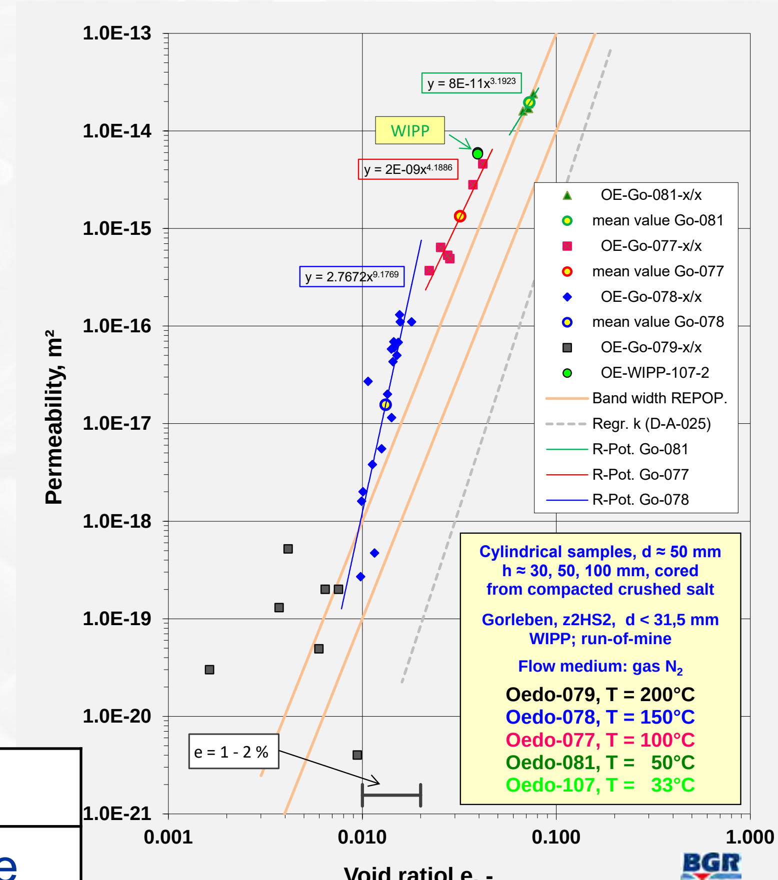
- 2010 BMU
- Introduction of CRZ (ewG)
- Increasing demands on backfill material regarding
  - sealing capacity
  - long-term stability

Demonstration of limited release from CRZ

Paradigm shift in long-term safety



Permeability tests with gas on laboratory samples and in-situ on rock salt



Permeability tests with gas on crushed salt samples compacted in oedometer tests

Rock salt	Crushed salt
Fluid pressure criterion	Stress state → Effective stress
Dilatancy criterion	Permeability → Demon-stration of limited release

KOMPASS – The project

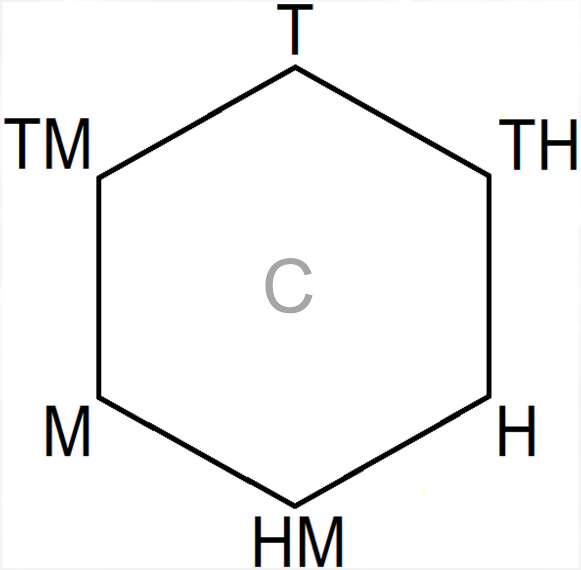
Why KOMPASS – Changed backfill requirements

KOMPASS – WP 3

- physical process classes
- modeling thermal class
- modeling hydraulic class
- modeling mechanical class

Summary

Process classes and coupling



T: thermal class

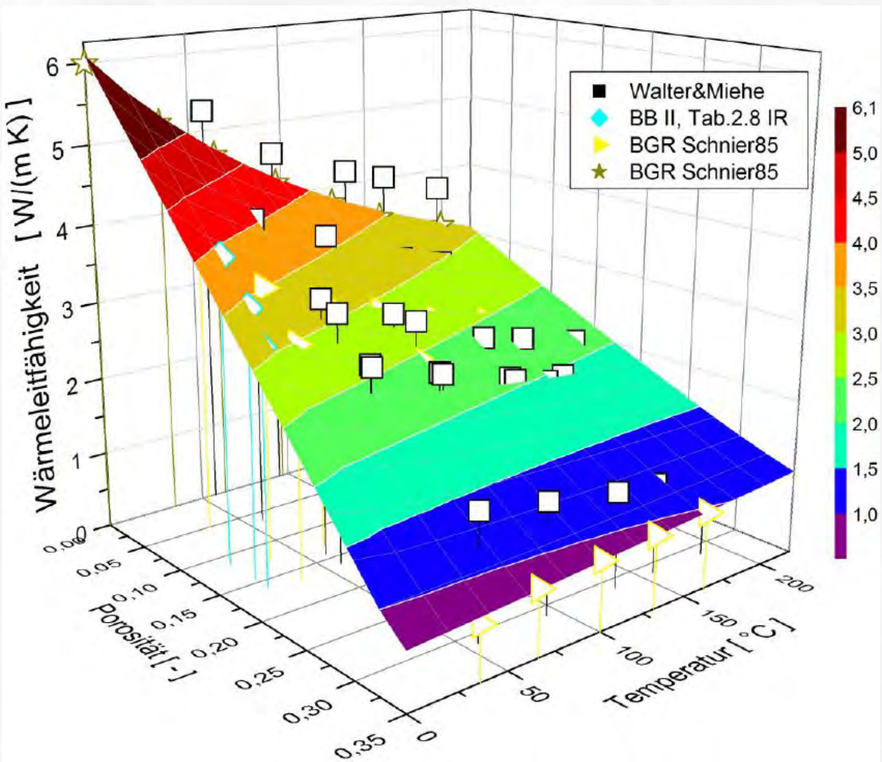
H: hydraulic class

M: mechanical class

C: chemical class

T→M:	thermal expansion of matrix; influence on material properties
M→T:	heat generation due to compaction and friction
H→M:	enables sub-processes; effective stress; influence on material properties
M→H:	compaction changes permeability
T→H:	thermal expansion of fluid; influence on material properties
H→T:	advective heat transport

Thermal class – Processes



(Wieczorek et al., 2012)

Conduction – Thermal energy transport between grains over their contact areas, initially small and increasing with compaction

Radiation – Initially significant, decreasing with compaction

	Influenced (nearl. dry)
Conduction	T, ϕ
Radiation	T, ϕ

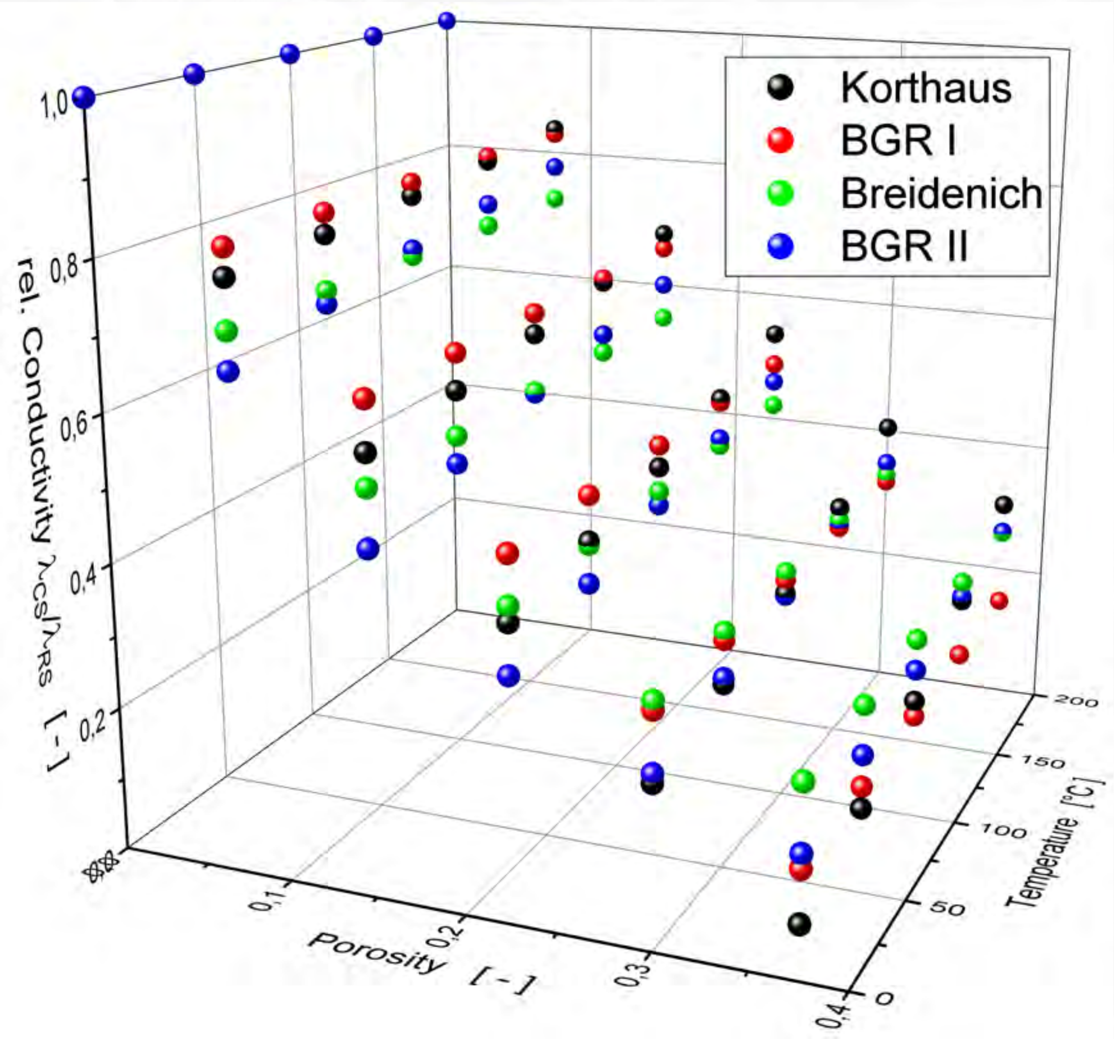
Thermal class – Modeling

Introduction of radiation into conduction

$$\varrho c_p \frac{\partial T}{\partial t} = div(\lambda \cdot grad\, T) + \dot{q}$$

		Remark
BGR I: $\lambda_{CS}(\lambda_{RS}(T), \phi)$	$\frac{\lambda_{CS}}{\lambda_{RS}(T)} = 1 - c_{,\phi}\phi$	$c_{,\phi} = {}^{1}/_{\phi} \longrightarrow \lambda_{CS} = 0$
Breidenich: $\lambda_{CS}(\lambda_{RS}(T), \phi, \phi_0)$	$\frac{\lambda_{CS}}{\lambda_{RS}(T)} = \frac{1-\phi}{a(1-(1-\phi)^b) + (1-\phi)^b}$ $b = \frac{ln\, {}^{2}/_{3}}{ln(1-\phi_0)}$	ϕ_0
Korthaus: $\lambda_{CS}(\lambda_{RS}(T), T, \phi, \phi_0)$	$\frac{\lambda_{CS}}{\lambda_{RS}(T)} = \left(1 - \frac{\phi}{\phi_0}\right)^a + \frac{\phi}{\phi_0}\frac{\lambda_L(T)}{\lambda_{RS}(T)}$	ϕ_0
BGR II: $\lambda_{CS}(\lambda_{RS}(T), T, \phi)$	$\frac{\lambda_{CS}}{\lambda_{RS}(T)} = \frac{(1-\phi)}{1 + \frac{\lambda_{RS}(T)}{\lambda_L(T)} a \frac{\phi}{1-\phi}}$	

Thermal class – Comparison

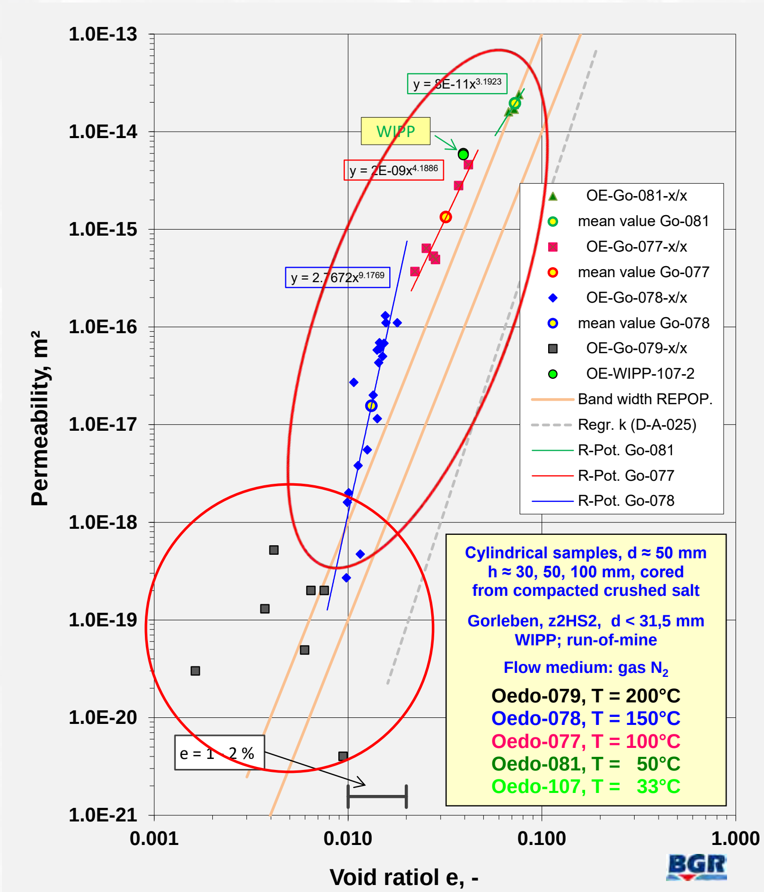


Thermal class – Summary

- Thermal energy transport from waste and hydrating material into host rock
- Influence on material properties
- Thermal expansion of matrix and fluid material
- Duration of the thermal phase in relation to mechanical phase depends on point of interest
- Project BAMBUS I & II have shown a good adaptation of thermal DOF, differences primarily caused by mechanical behavior

↳ Uncertainties and inaccuracies in the thermal class are of secondary importance

Hydraulic class – Processes



Permeability tests with gas on crushed salt samples compacted in oedometer tests

Advection – The dominant process over a wide range of porosity

Diffusion – Transition from advection to diffusion has to be scrutinized

	Influenced (dry)
Advection	ϕ, T, p
Diffusion	c, T, ϕ

Hydraulic class – Modeling

Combination within Dracy-law

$$\boldsymbol{q} = -\frac{k}{\mu}\boldsymbol{\kappa}(grad\, p - \varrho \boldsymbol{g})$$

- Assumption: isotropic permeability

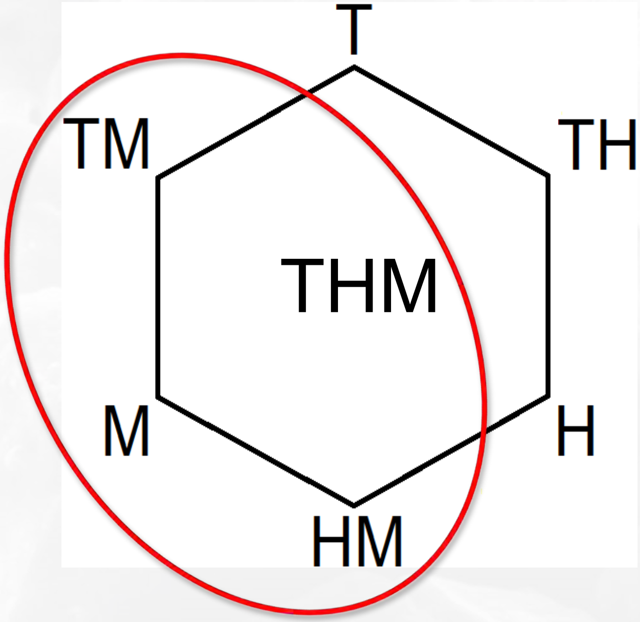
		Remark
common	$k = k_0 \cdot \phi^n$	
Popp [2002], Heemann [2004] (for rock salt)	$k = \dfrac{k_{tp}}{\left(\dfrac{\phi_{tp}}{\phi}\right)^{n_1} + \left(\dfrac{\phi_{tp}}{\phi}\right)^{n_2}}$ $k_{tp} = k_0 e^{b_k \cdot \sigma_{max}}$ $\phi_{tp} = \phi_0 e^{b_\phi \cdot \sigma_{max}}$	$k(\sigma_{max} + \Delta\sigma)$

Hydraulic class – Summary

- Low hydraulic requirements for the backfill material of the drifts before BMU 2010
- Today, crushed salt as backfill material has to become a barrier over time
- Project RepoPerm I & II have shown a functional relation between porosity and permeability down to ~2% for standardized crushed salt
- Two-phase flow can only be mapped with limited accuracy using approaches from Brooks & Corey or van Gnuchten

➥ A reliable approach with respect to long-term safety is still a challenge in the range of small porosities

Mechanical class (MC)



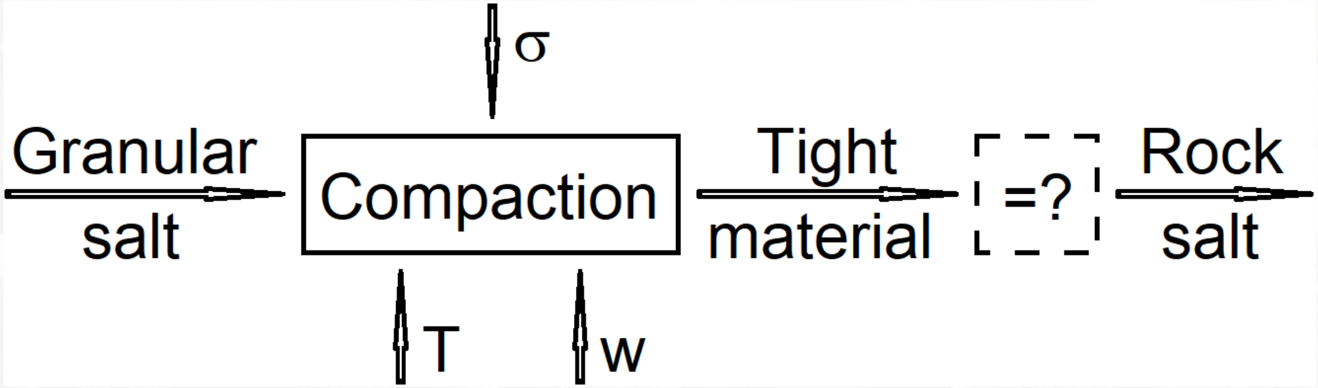
M: mechanical class

T→M: thermal expansion of matrix; influence on material properties, e.g. creep rate

M→T: heat generation by compaction and friction

H→M: enables sub-processes; effective stress; influence on mat. props, e.g. creep rate

M→H: compaction changes permeability



MC – Physical behavior I

- Elasticity $\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{el}} = f(\boldsymbol{\sigma}, \phi)$:
  - Increasing with porosity.
- Grain fracture $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{GF}}^{\boldsymbol{vpl}} = f(\boldsymbol{\sigma}, \phi, \overline{D})$:
  - Initially high due to local stress concentration, later decreasing due to broadening of contact areas despite higher global stress.
  - Fragments fill open spaces and change grain distribution $\overline{D}$ to a lesser extent.
- Grain boundary sliding $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{BS}}^{\boldsymbol{vpl}} = f(\boldsymbol{\sigma}, \phi, w, p_{Fl})$:
  - At the beginning, grains slide easily into free spaces.
  - Increasing resistance and lack of space hinder possible changes of position.
  - Moisture on the grain surfaces reduces resistance significantly, thus, strong connection to GF in case of dry condition.

MC – Physical behavior II

- Dislocation creep $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{DC}}^{\boldsymbol{vpl}} = f(\boldsymbol{\sigma}, \phi, T, \bar{D})$:
  - Initially high local stresses lead to high rates of dislocation generation and creep in contact areas; contact zones broaden, which in turn reduces local stress and deformation rate.
  - If porosity is small, the dominant deformation is similar to a single pore (and convergence of caverns).
  - Physically hardening is an important effect; minor influence due to steady change of contact area at least in case of moderate change of stress; possibly more important close to complete compaction
  - At final stage a creep rate lower than that of virgin rock salt.
  - Increase of temperature has an accelerating effect.

MC – Physical behavior III

- Pressure solution creep $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{PS}}^{\boldsymbol{vpl}} = f(\boldsymbol{\sigma}, w, T, p_{Fl})$:
  - In case of moisture, predominant at low stresses and low temperatures.
- Re-crystallization/Healing $f(w, T, \bar{D})$:
  - Possibly important in long-term behavior in the area of complete compaction.

MC – Model Expectations

Elasticity – Closing up to rock salt behavior with low residual porosity	$\mathbb{C}(\phi) \xrightarrow{\phi\to 0} \sim\mathbb{C}_{RS}$
Creep I – Closing up to rock salt behavior with low residual porosity	$\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{vpl}}(\boldsymbol{\sigma},\phi,T,\bar{D}) \xrightarrow{\phi\to 0} \sim\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{vpl}}_{\boldsymbol{RS}}(\boldsymbol{S},T)$
Creep II – Deviatoric rate and compaction rate are similar over a wide range of porosity	$\frac{\dot{\varepsilon}_0^{vpl}(\boldsymbol{\sigma},\phi,T,\bar{D})}{\dot{\tilde{\varepsilon}}^{vpl}(\boldsymbol{\sigma},\phi,T,\bar{D})} \sim c \quad \forall\phi \gg 0$
Deviatoric creep rate – Functional characteris-tics changes due to change in geometry dependence with low porosity	
Compaction rate – Tend to 0 with low residual porosity	$\dot{\varepsilon}_0^{vpl}(\boldsymbol{\sigma},\phi,T,\bar{D}) \xrightarrow{\phi\to 0} 0$
Creep III – Change in viscoplastic “Poisson ratio” with stress and porosity	$sign\left(\frac{\dot{\varepsilon}^{vpl}_{lat}}{\dot{\varepsilon}^{vpl}_{ax}}\right) \xrightarrow{\phi\to 0, \boldsymbol{S}\uparrow} var.$
Creep IV – Taking hardening into account	
Models – Similarity in geometric dependency (rate of void ratio over void ratio at constant outer field variables)	

MC – Modeling I

Developer, Modification		Code	Geom.	Elast.	Vpl: Fract. & BS	Vpl: DC
Heemann	BGR	Jife	X	ϕ, ν_v	na, $f(\sigma_0, \boldsymbol{S}, \phi, \bar{D})$	na, $g(\sigma_0, \boldsymbol{S}, \phi, T, \bar{D})$
Olivella	GRS	CB	X	ϕ, ν_c	na, $f(\sigma_0, \boldsymbol{S}, \phi, T, \bar{D})$	na, $g(\sigma_0, \boldsymbol{S}, \phi, T, \bar{D})$
Modified CWIPP DC: $f_1(\phi), f_2(\sigma_0, \boldsymbol{S})$	IfG	F3D		ϕ, ν_v	na, $Minkley$	ep, $g(\sigma_0, \boldsymbol{S}, \phi)$ + na, $Minkley$
Callahan et al.	SNL			ϕ, ν_v	-	na, $g(\sigma_0, \boldsymbol{S}, \psi, \phi, T)$
Modified CWIPP DC: $f_0(T), f_2(\sigma_0)$	TEC	F3D		ϕ, ν_v	-	ep, $g(\sigma_0, \boldsymbol{S}, \phi, T)$
Modified Hein, DC: $h_1(\phi), h_2(\phi)$	TEC	F3D	(X)	ϕ, ν_v	as, $f(\sigma_0, \boldsymbol{S}, \phi)$	as, $g(\sigma_0, \boldsymbol{S}, \phi, T)$
Modified CWIPP DC: $f_0(T), f_1(\phi), f_2(\sigma_0, \boldsymbol{S})$	TUC	F3D		ϕ, ν_v	na, $Lubby\ 2$	ep, $g(\sigma_0, \boldsymbol{S}, \phi, T)$ + na, $Lubby\ 2$

CB: Code_Bridght (UPC), F3D: FLAC3D (ITASCA); all bases on strain rate tensor $\dot{\boldsymbol{\varepsilon}} = \sum_{i=1}^{n} \dot{\boldsymbol{\varepsilon}}_i$

ep: empirical, as: associated flow rule, na: not associated flow rule

MC – Modeling II

Developer, Modification		Vpl: PS	Re-cryst. & healing
Heemann	BGR	ep, $h(\boldsymbol{\sigma}, \phi, T, \bar{D})$	-
Olivella	GRS	ep, $h(\boldsymbol{\sigma}, p_{Fl}, \phi, S_{Fl}, T, \bar{D})$	-
Modified CWIPP DC: $f_1(\phi), f_2(\sigma_0, \boldsymbol{S})$	IfG	-	-
Callahan et al.	SNL	na, $h(\sigma_0, \boldsymbol{S}, \psi, w, p_{Fl}, \phi, T, \bar{D})$	-
Modified CWIPP DC: $f_0(T), f_2(\sigma_0)$	TEC	-	-
Modified Hein, DC: $h_1(\phi), h_2(\phi)$	TEC	-	-
Modified CWIPP DC: $f_0(T), f_1(\phi), f_2(\sigma_0, \boldsymbol{S})$	TUC	-	na, $Lubby\ 2$

$w_{GS} \cong 0.8\ W\% \rightarrow f = (f(w)\ \forall\, w < w_{GS}\ \cup\ 1\ \forall\, w \geq w_{GS}) \hookrightarrow f(w) = 0/1$

WP 3: TK-031 – Identification

- Triax-Test: 5 loading steps, ~isotropic, $\Delta\sigma \approx 1MPa$, $\sigma_{min} = -[11;21]MPa$
- $\vartheta = 50^0C$
- $t_{tot} \approx 300d$

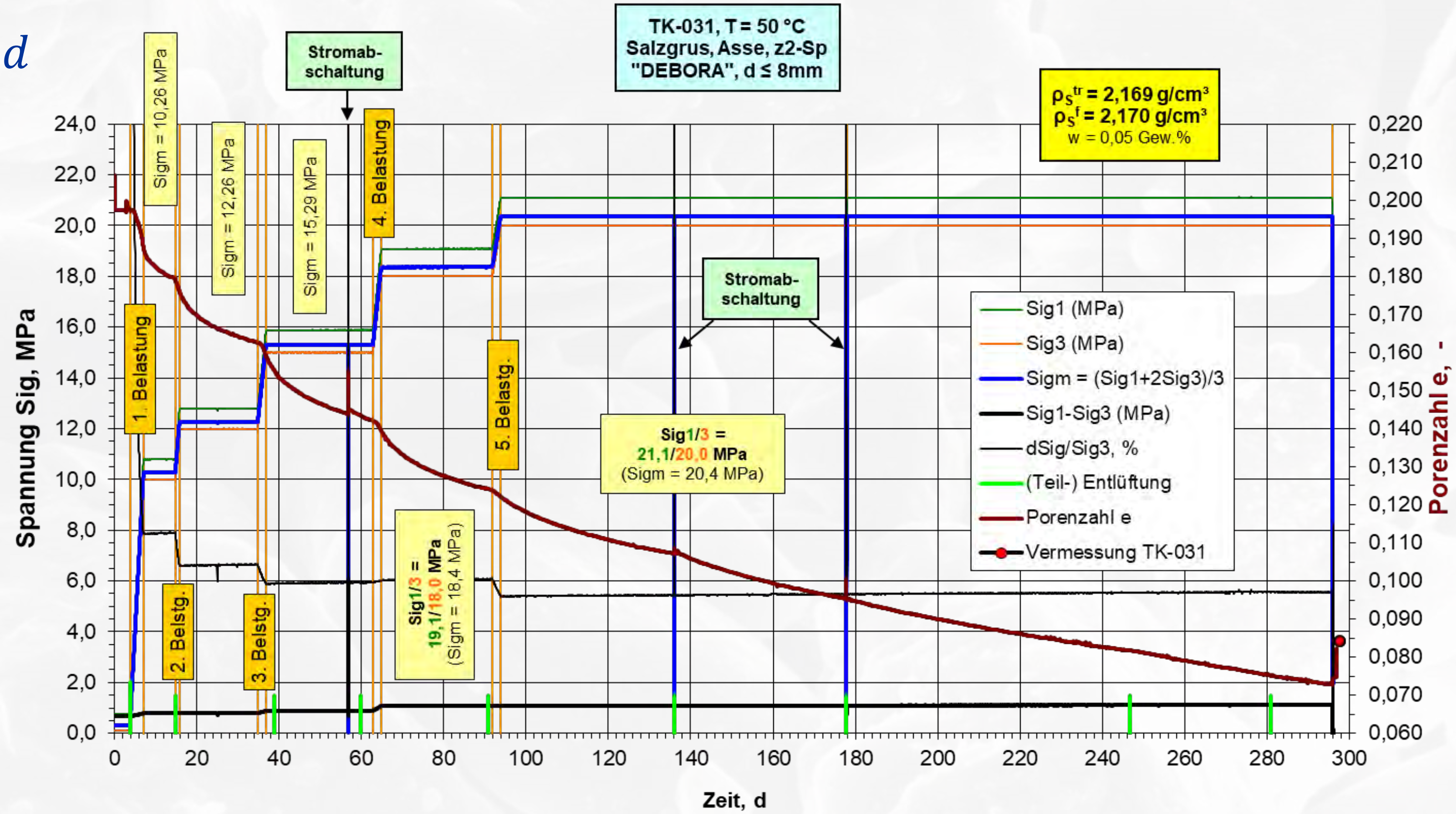
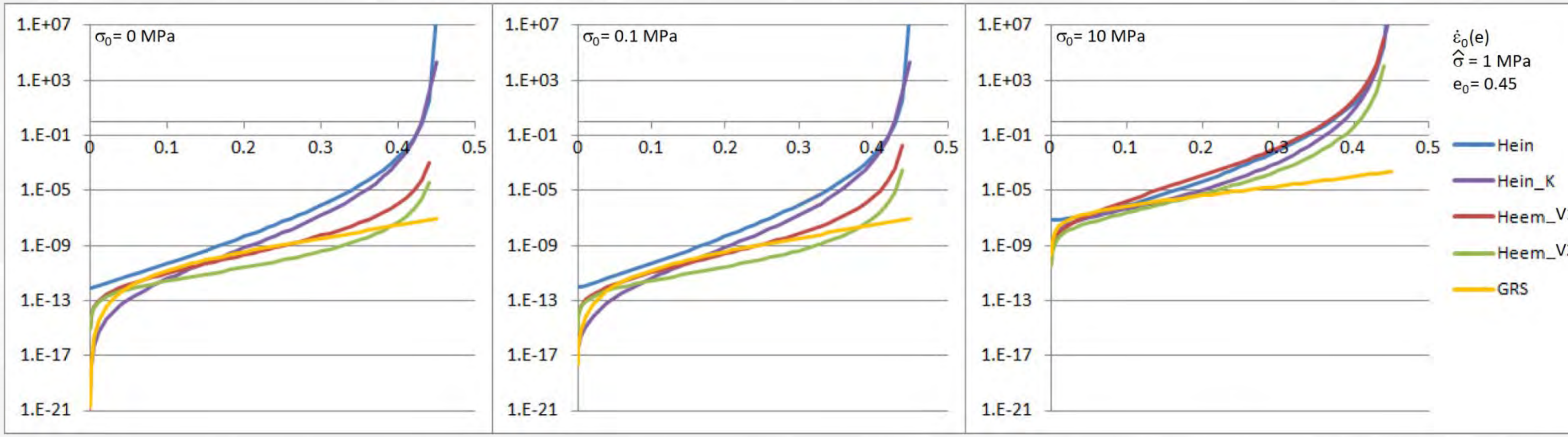


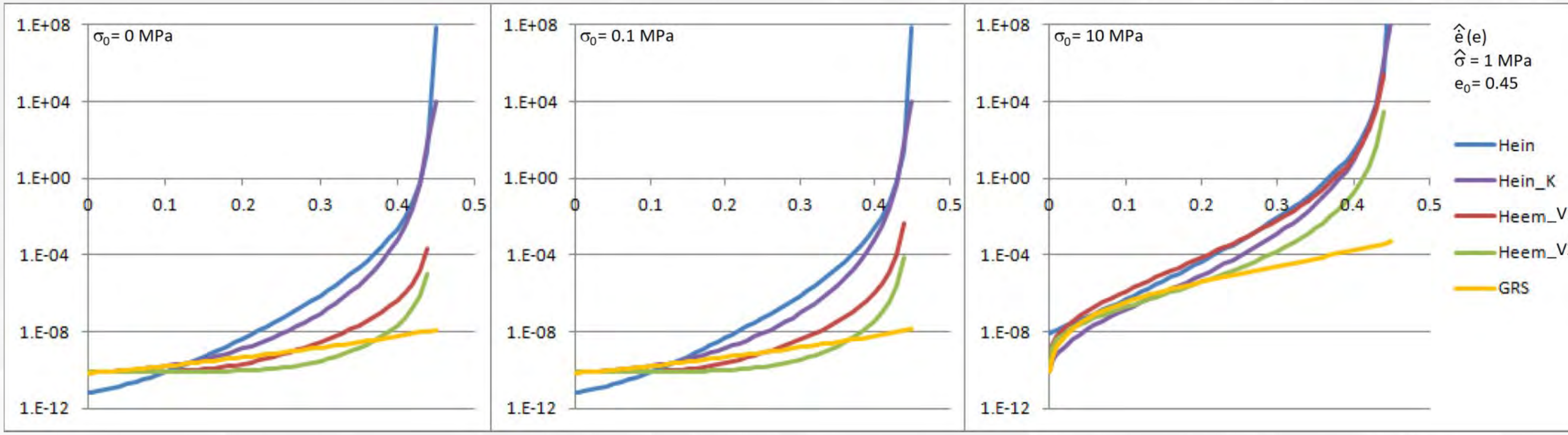
Abb. 3

Triax. Kompaktionsversuch TK-031, T = 50 °C
Zeitlicher Verlauf der Spannungen und Kompaktion

MC – Comparison of creep rates



RePoPerm II



RePoPerm II

WP 3: Current & Next Steps

Ongoing

- Identification strategy from lab. test for material properties
- Estimation of a set of material properties (dry): TK-031

Next

- Estimation of fundamental behavior
- Improvement of the dominant partial constitutive laws of mechanical behavior
- Effects and modeling of hydraulic behavior

KOMPASS – The project

Why KOMPASS – Changed backfill requirements

KOMPASS – WP 3

- physical process classes
- modeling thermal class
- modeling hydraulic class
- modeling mechanical class

Summary

Summary

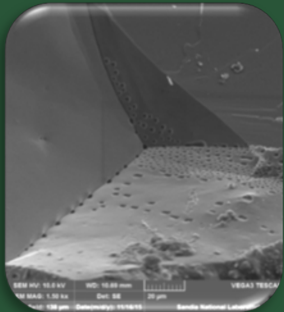
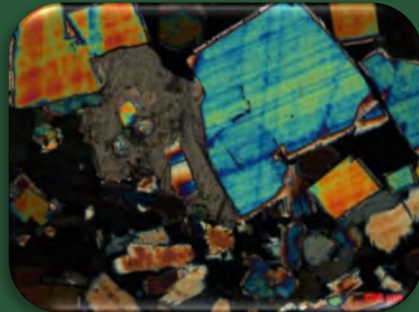
- Need of a reliable THM prognosis for crushed salt backfill due to paradigm shift in long-term safety
- Currently thermal constitutive laws seems to be sufficient
- Different number of THM coupled sub-processes within the constitutive laws with different complexity in representation of geometry and stress
- Geometry and stress contribution within the different parts of mechanical model is a serious part
- Validation process on constitutive laws for mechanical material behavior is ongoing
- Hydraulic modeling has to be improved
- Processes close to total compaction under discussion

Acknowledgement

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

Thank you for your attention

Photo by BGR: Sample from in-situ backfill

10th US/German Workshop on Salt Repository Research, Design, and Operation

Sandia National Laboratories

BGE TEC BCE TECHNOLOGY GmbH

PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology

RESPEC

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

Brett E. Belzer
RESPEC

Rapid City, SD, United States
May 28-30, 2019

WIPP Expansion

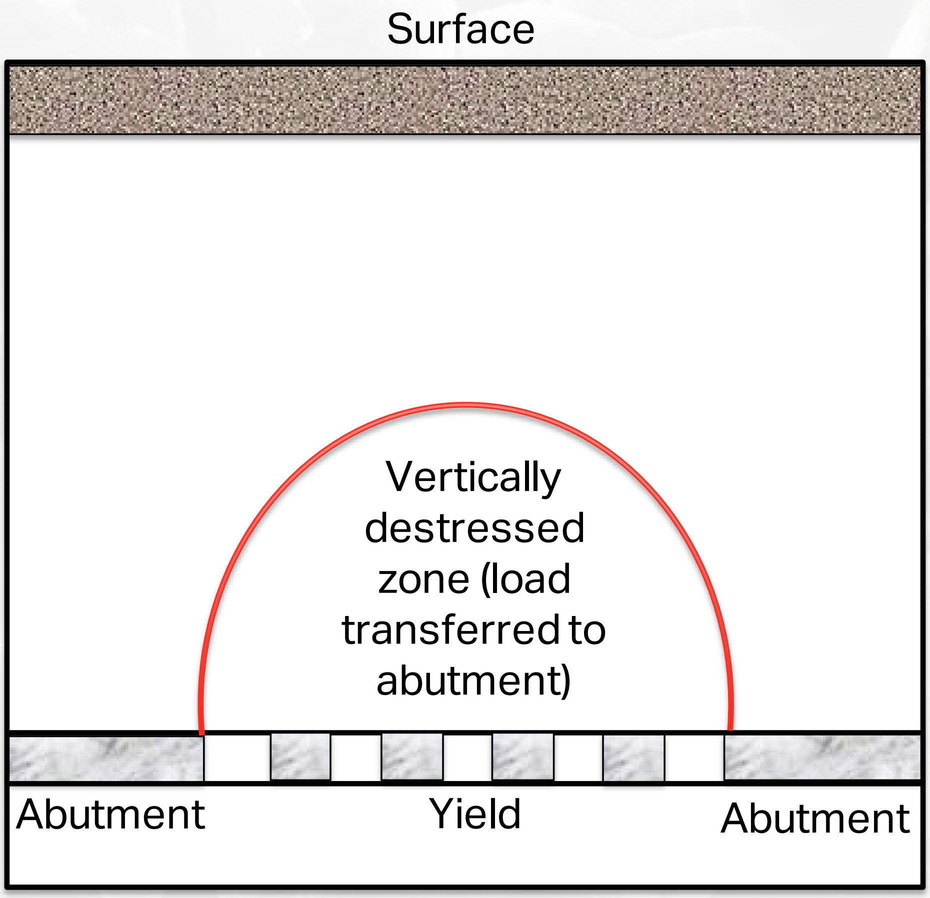
- Additional waste disposal capacity
- New mains design must benefit from past experience and solve the ground control problems encountered in the current mains system
  - Alternative yield pillar design
  - Empirical evidence of yield pillar designs in deep salt mines
- Current mains are 30+ years old and have developed severe ground-control issues with significant maintenance efforts every couple of years

Ground Control Problems at WIPP

- Current design based on full tributary loading
- Observations of typical fracture patterns in lower mine horizon
  - Low-angle shear fractures
  - Floor heave

Alternative Yield Pillar Design

- Empirical evidence of yield pillar designs improving ground conditions at other salt and potash mines throughout North America
- Yield pillar concept
  - Shape of pillars ensures they can not carry full tributary loading
    - Reduces creep driving stress in yield pillars by redistributing vertical stress onto more robust abutment pillars
    - Yield pillars have small horizontal stresses because they are "slender"
  - Allows yield pillars to creep slower than they normally would, yet forces abutment pillars to creep only slightly faster

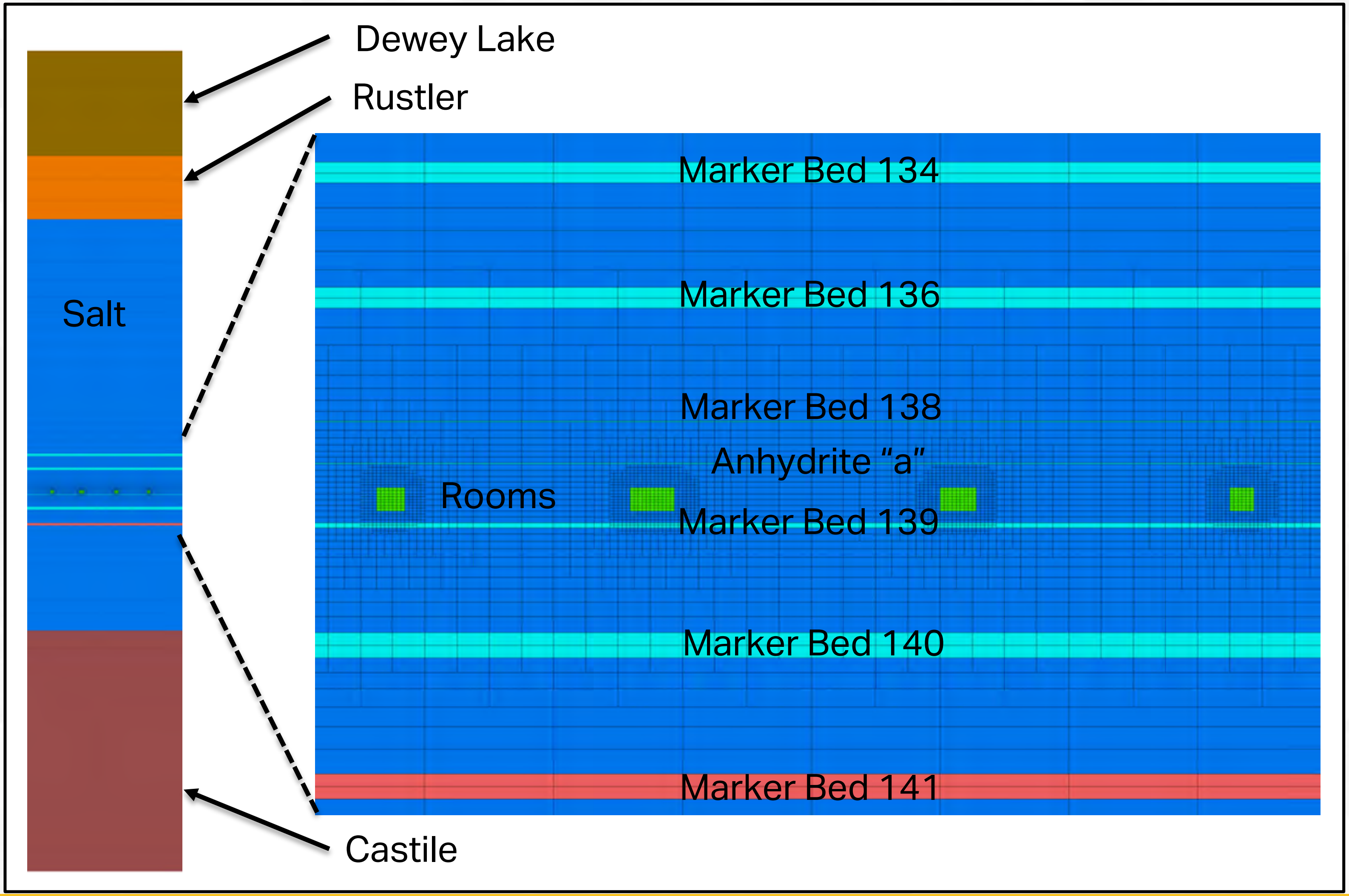


WIPP Design Process

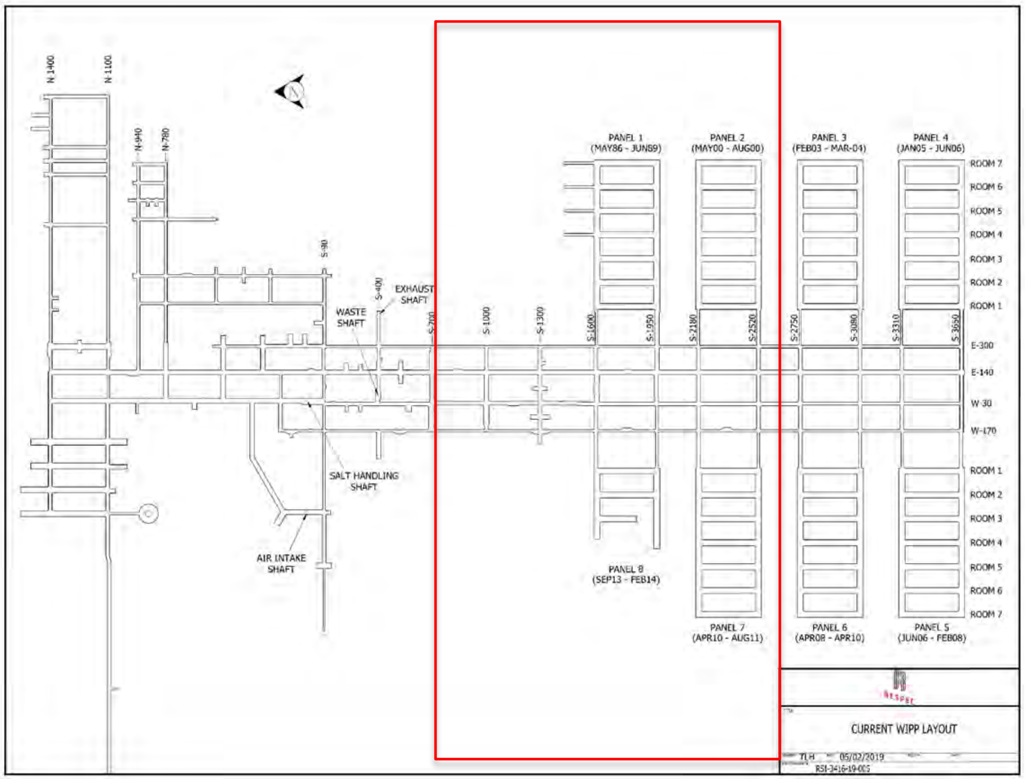
- 3 Step Process
  - 1. Van Sambeek salt-pillar equations to develop preconceptual designs (spreadsheet analysis)
  - 2. Model validation and development of stability metrics (current design)
  - 3. Detailed geomechanical analyses of conceptual designs (new design)

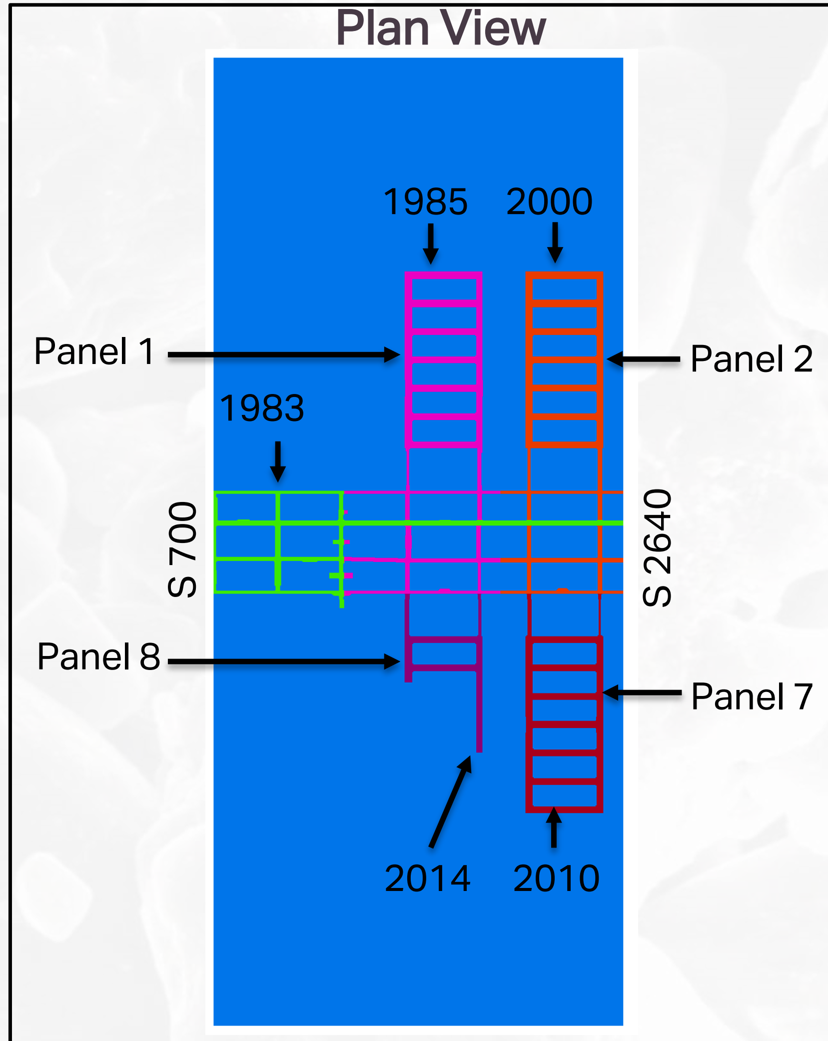
Model of Current Design

Elevation View



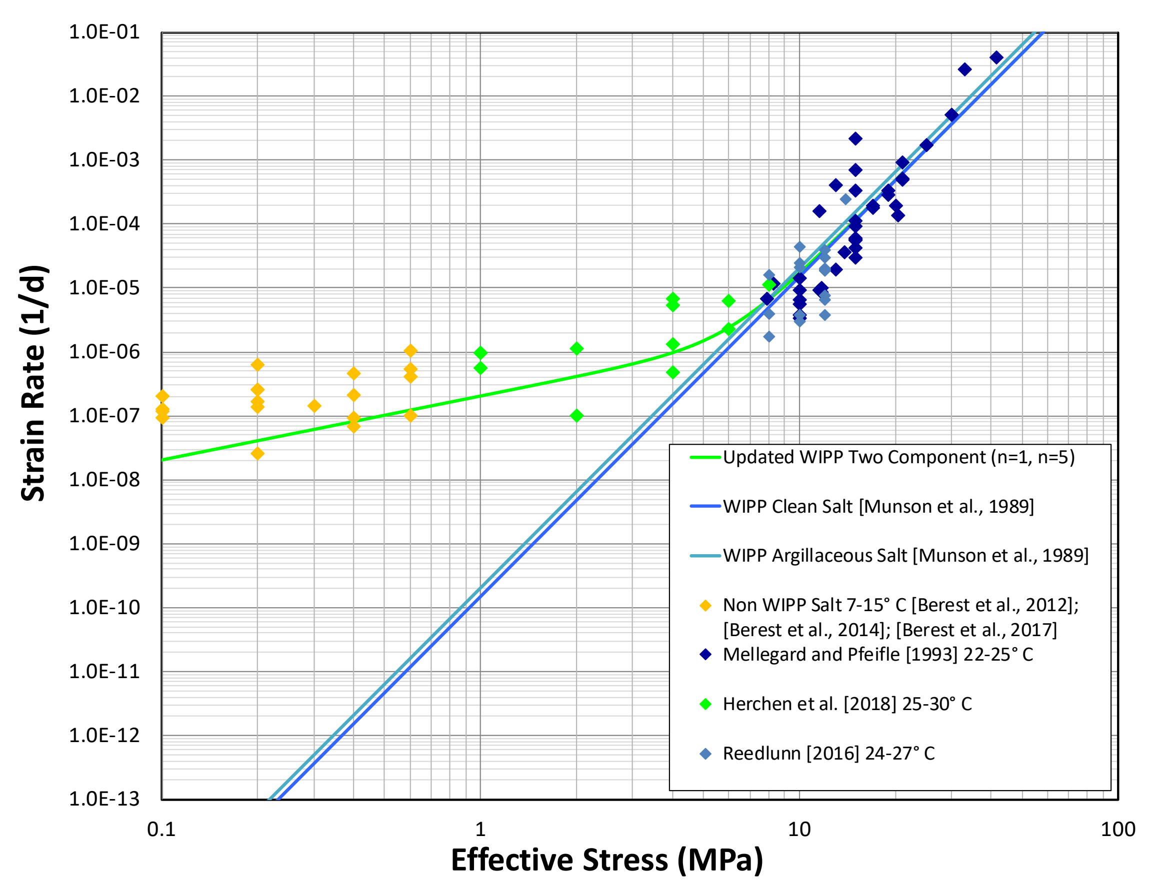
Model of Current Design





Modeling Approach

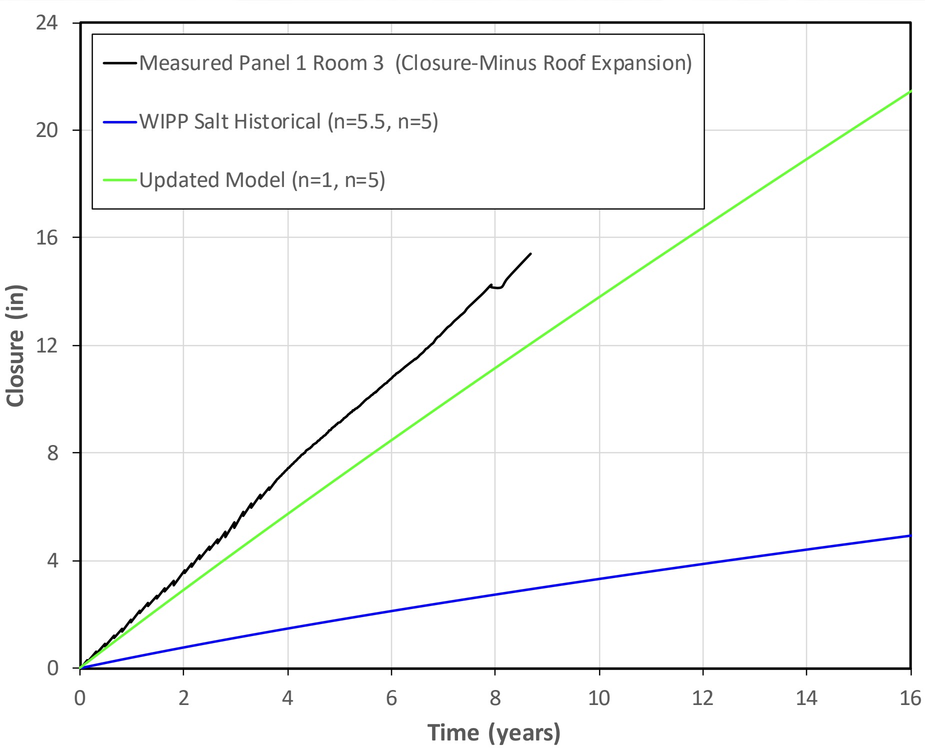
- New modeling approach to predicting behavior of excavations over the next 30-50 years.
  - Low stress creep mechanism
  - Updated anhydrite/polyhalite properties



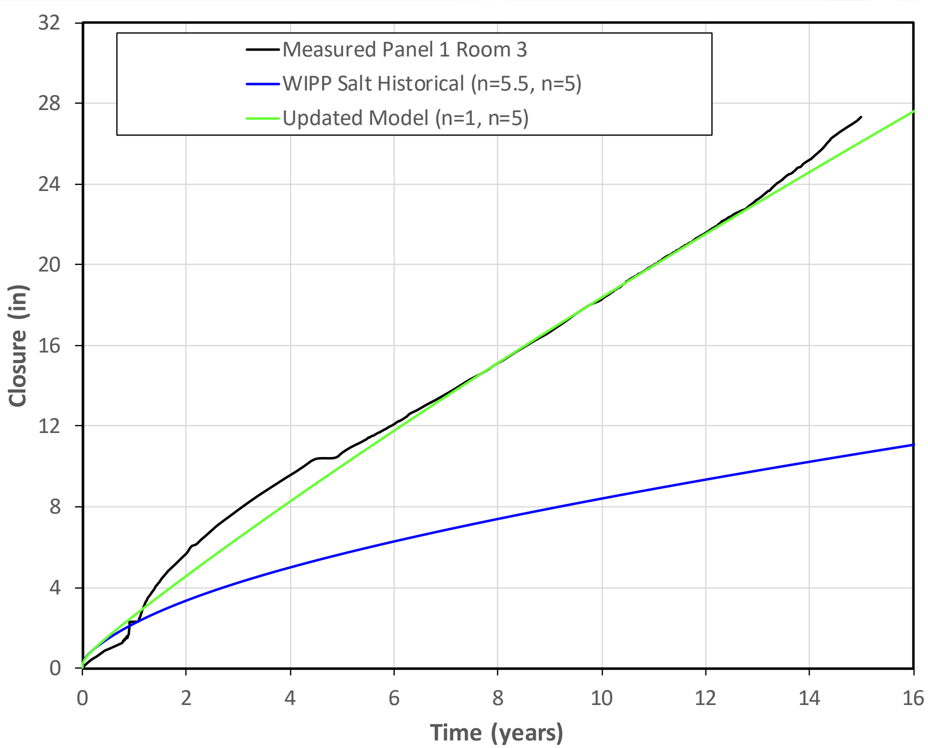
Model Validation

- Agreement between mine measurements and model predictions

Vertical Room Closure



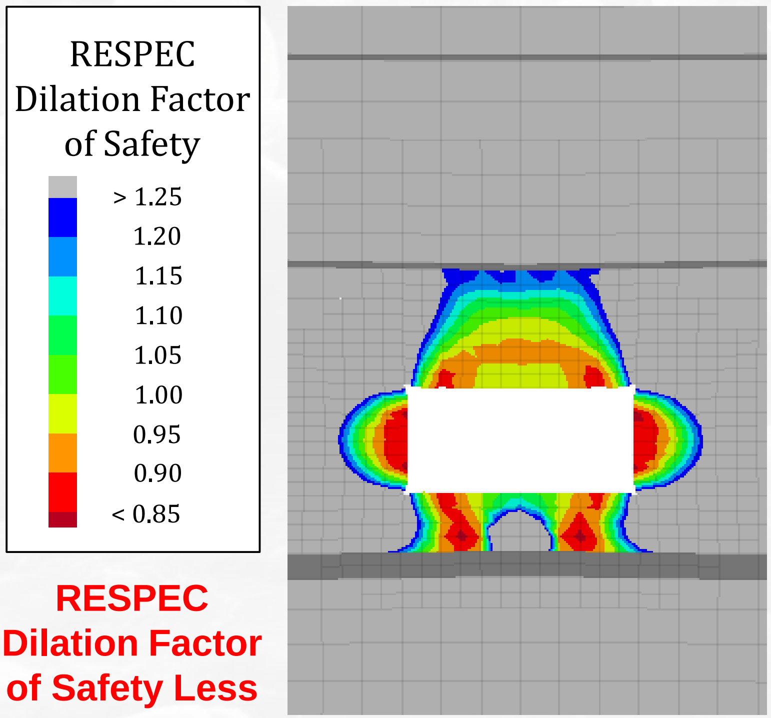
Horizontal Room Closure



Model Validation

- Agreement between mine observations and model predictions of salt damage

E140 S1775

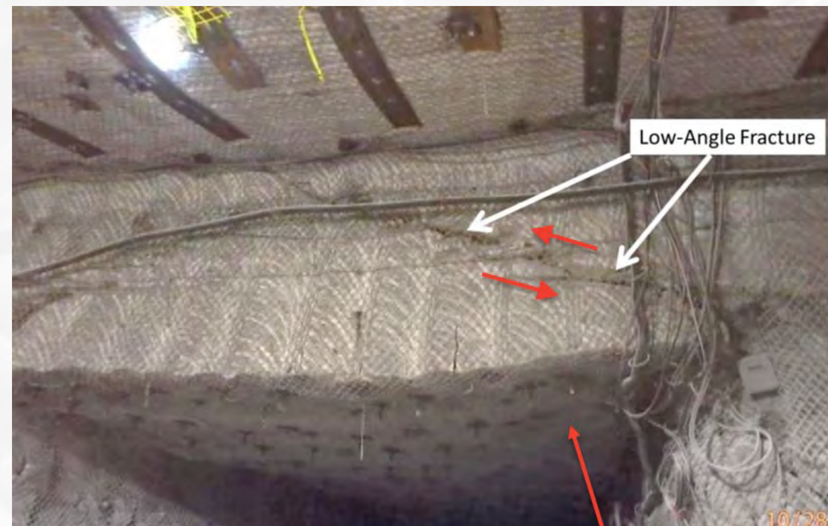


MB 138

Anhydrite "a"

MB 139

RESPEC Dilation Factor of Safety Less than 1.0 indicates damage (yellow/red)

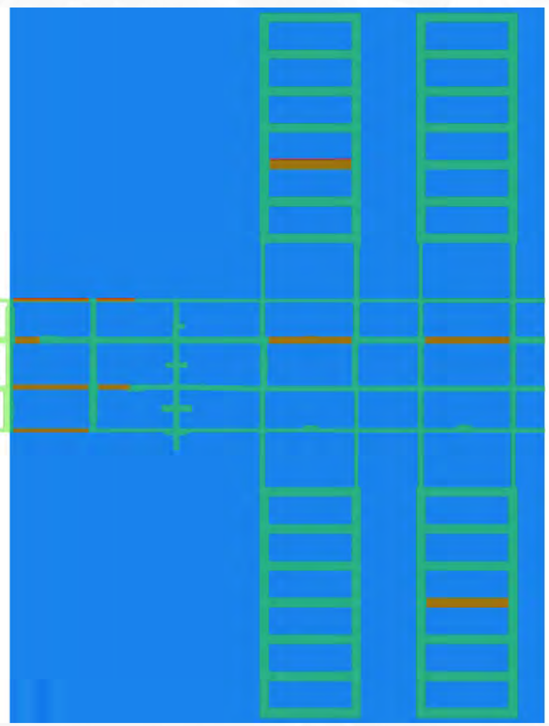


Roof Shear

Floor Shear

Development of Stability Metrics

- Stability Metrics
  - Conducted interviews with WIPP personnel to categorize 10 locations based on geotechnical ground conditions
  - Ground conditions were related to the time to first major ground control rehabilitation efforts and on-going maintenance requirements

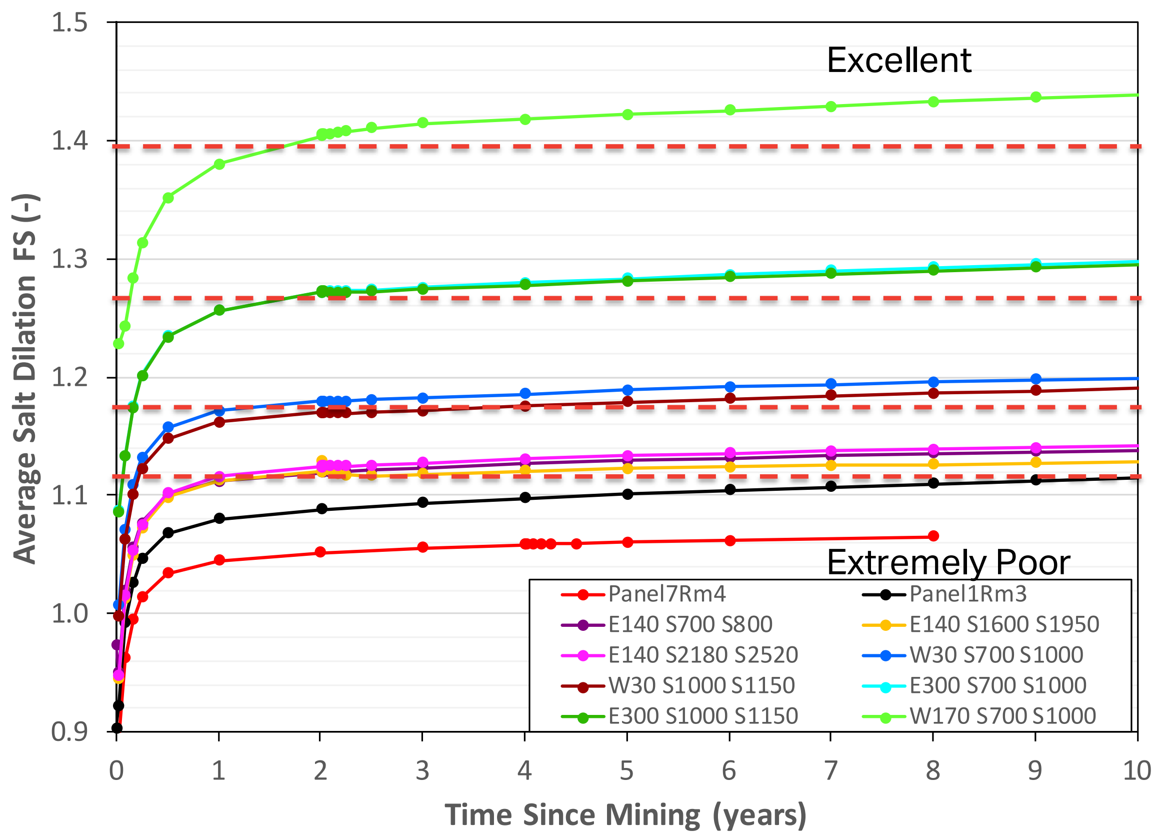


Location	Judged Conditions	Time to First Major Ground Control Rehab	On-Going Ground Control Maintenance
Panel 1 Room 3	Extremely Poor	5 - 8 years	Frequent scaling, Frequent Bolt Replacement
Panel 7 Room 4	Extremely Poor	5 - 8 years	Frequent scaling, Frequent Bolt Replacement
E140 S1600-S1950	Poor	10 - 15 years	Frequent scaling, Frequent Bolt Replacement
E140 S2180-S2520	Poor	10 - 15 years	Frequent scaling, Frequent Bolt Replacement
E140 S700-S800	Difficult	20 years	Frequent scaling, Frequent Bolt Replacement
W30 S700-S1000	Intermediate	20 - 30 years	Scaling, Occasional Bolt Replacement
W30 S1000-S1150	Intermediate	20 - 30 years	Scaling, Occasional Bolt Replacement
E300 S700-S1000	Good	30+ years	Occasional Scaling
E300 S1000-S1150	Good	30+ years	Occasional Scaling
W170 S700-S1000	Excellent	35+ years	Minimal Scaling

Development of Stability Metrics

- Stability Metrics
  - Quantitative (e.g. Volumetric Average RESPEC Salt Dilation Factor of Safety (RDFS) in Salt Back)
  - Qualitative (e.g. Do salt dilation factor of safety values less than 1.0 extend above Clay G?)

Performance of current rooms at WIPP



Thresholds

RDFS > 1.40 Excellent Conditions
(First Rehab > 35 years)

1.27 < RDFS < 1.40 Good Conditions
(First Rehab > 30 years)

1.17 < RDFS < 1.27 Intermediate Conditions
(First Rehab -20 to 30 years)

1.12 < RDFS < 1.17 Difficult to Poor Conditions
(First Rehab -10 to 20 years)

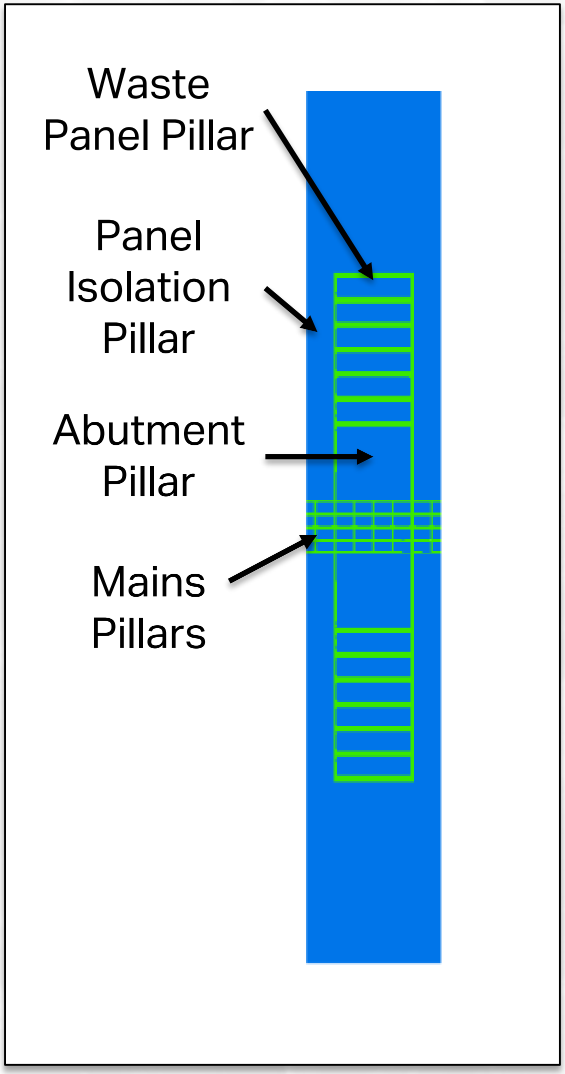
RDFS < 1.12 Extremely Poor Conditions
(First Rehab - 5 to 8 years)

Geomechanical Analysis of Conceptual Designs

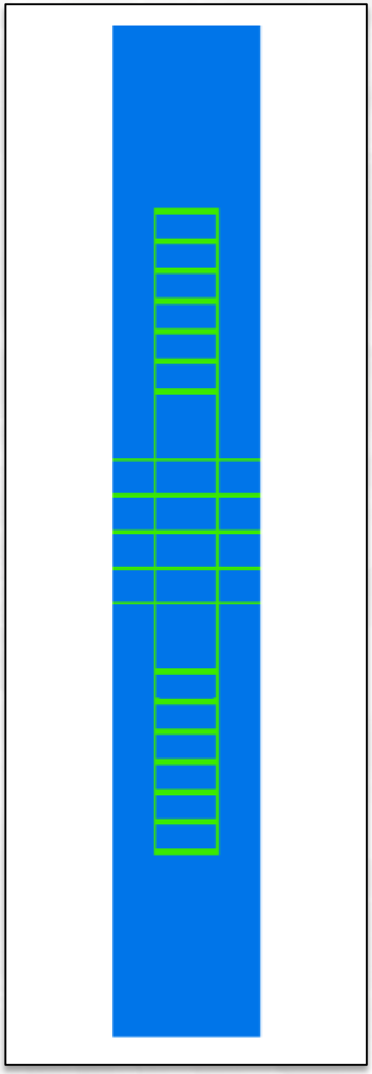
Mains design constraints

- 5-Entry Mains System
- 2 Waste Haulage Drifts (25-ft wide)
- Salt Haulage Drift (20-ft wide)
- 2 Ventilation Drifts (16-ft wide)

Small Pillar Design

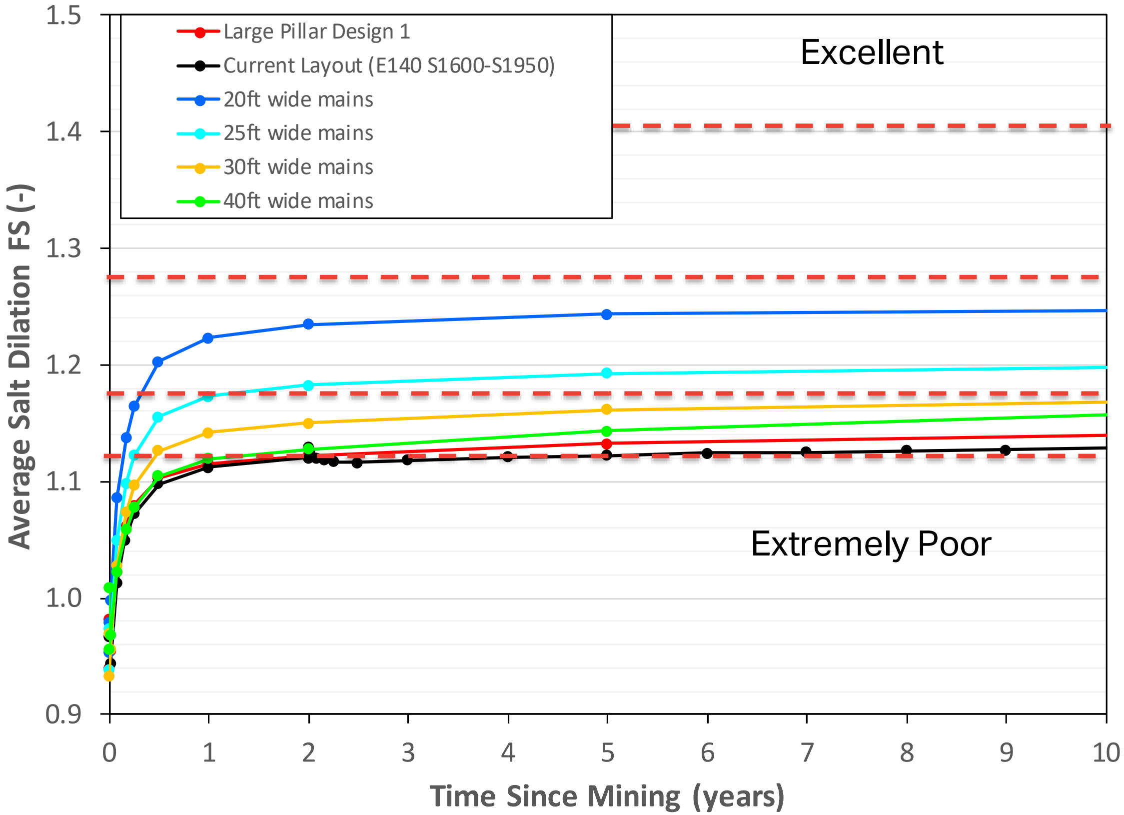


Large Pillar Design



Geomechanical Analysis of Conceptual Designs

Performance of the 25-ft wide waste haulage room



Thresholds

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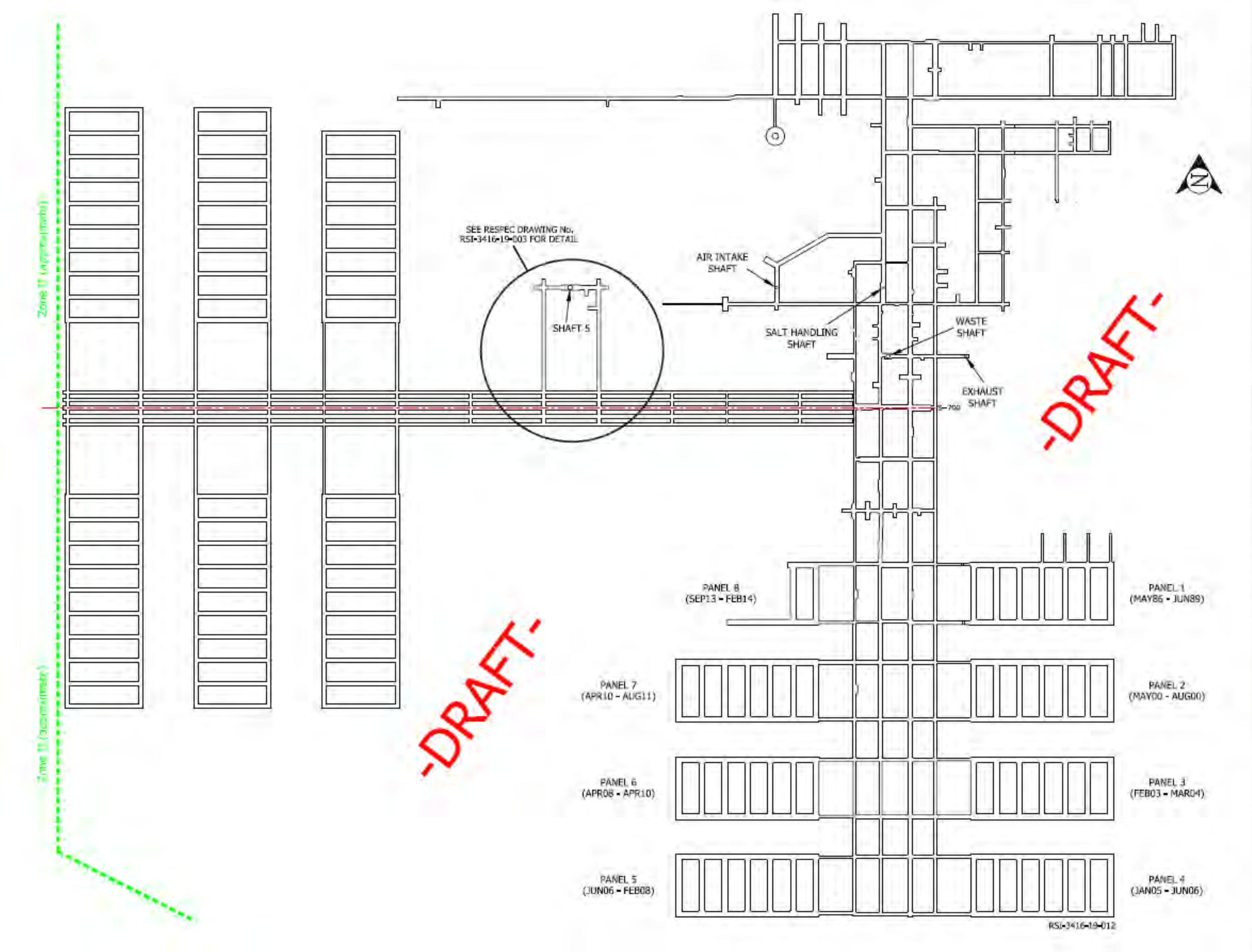
(First Rehab -20 to 30 years)

1.12 < RDFS < 1.17 Difficult to Poor Conditions
(First Rehab -10 to 20 years)

RDFS < 1.12 Extremely Poor Conditions
(First Rehab - 5 to 8 years)

Conceptual Design (DRAFT)

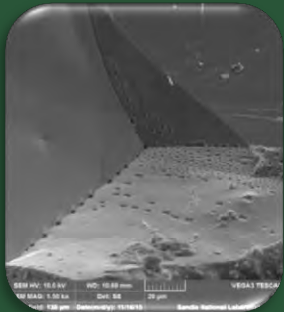


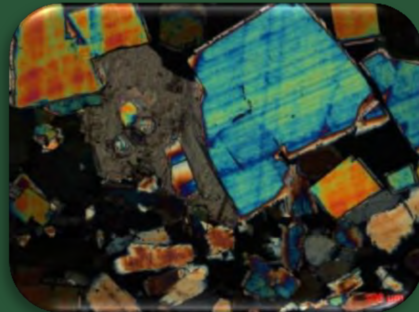
Conclusions

- Current layout
  - Some locations in the mains have excellent conditions and have not required major ground control rehabilitation
  - Other locations in the mains have required significant maintenance and ground control rehabilitation after 10 to 15 years and now require significant maintenance every couple of years

- Expected conditions in new mains system
  - Substantial reduction to the stresses that cause low angle shears to form and that distress the ground control system
  - Ventilation drifts and salt haulage drifts expect more than 30 years before first major ground-control rehabilitation and reduced maintenance efforts compared to current layout
  - Waste haulage drifts (25-ft wide) expect approximately 25 years before first major ground-control and reduced long-term maintenance efforts compared to current layout

Questions





Natural closure of salt openings

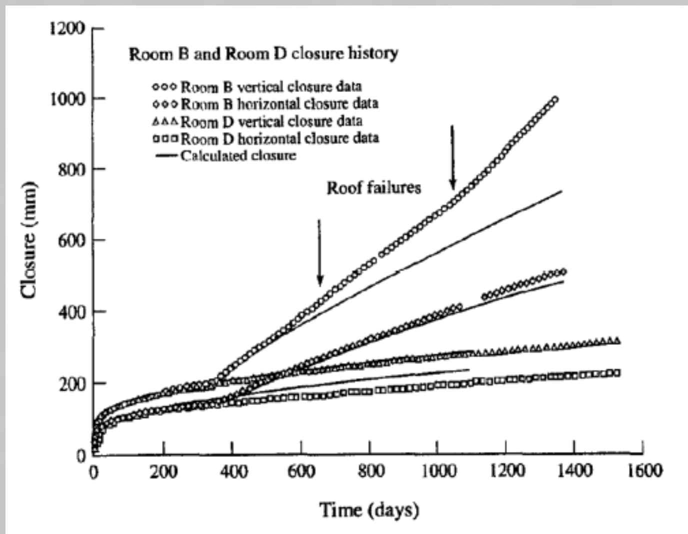
Till Popp
Institut für Gebirgsmechanik GmbH (IfG), Leipzig

Rapid City, SD, United States
May 28-30, 2019

Outline

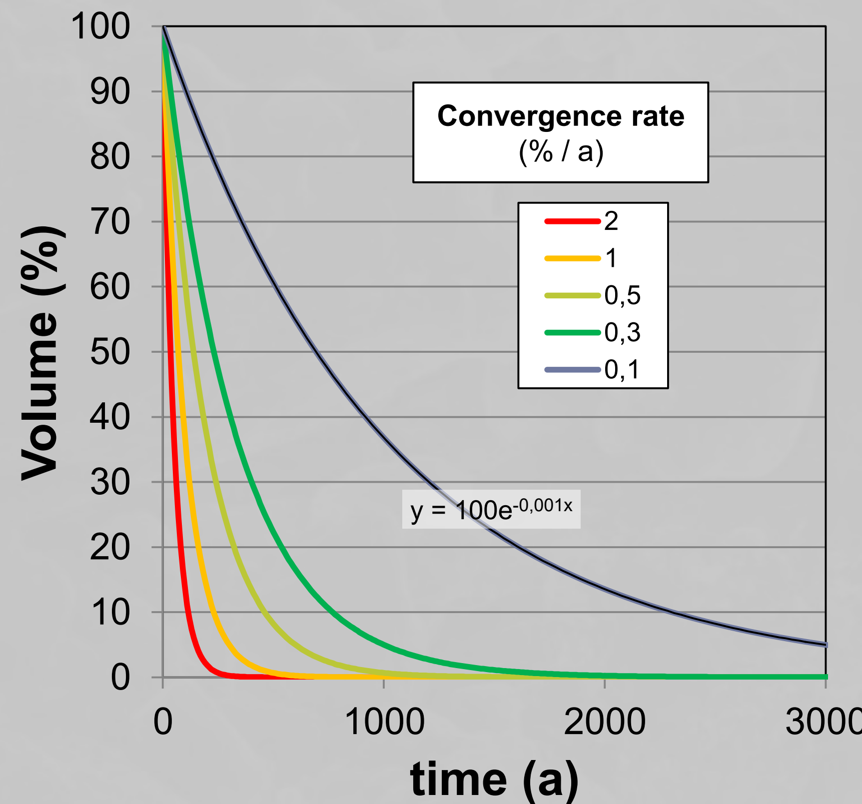
- Introduction
- Convergence – what it is ..
- Underlying processes of contour damage
- Natural backfill examples: in situ-observations
- Lab test results: dry / wet
- Personal summary

Convergence of underground openings



It‘s a fact: Salt creeps ➔ room closure, but:

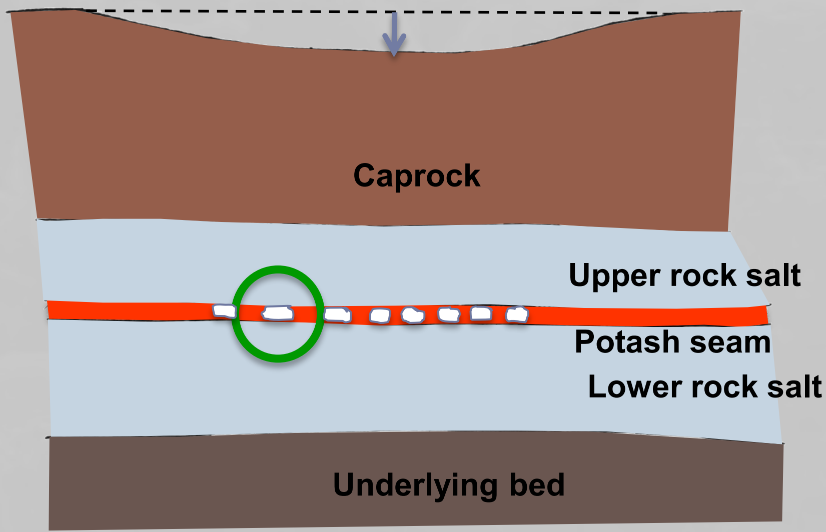
- **How it works?**
- **How long does it take?**
- **Is there a remaining porosity?**



The relative volume change $\dot{V}(t)$ / V(t) of any volume V(t) is related to as the convergence rate K:

$$\frac{\dot{V}(t)}{V(t)} = -\mathrm{K}\,(T_{rock}, p_{lith}, s_{backfill}, salt\ type)$$

Closure of underground openings

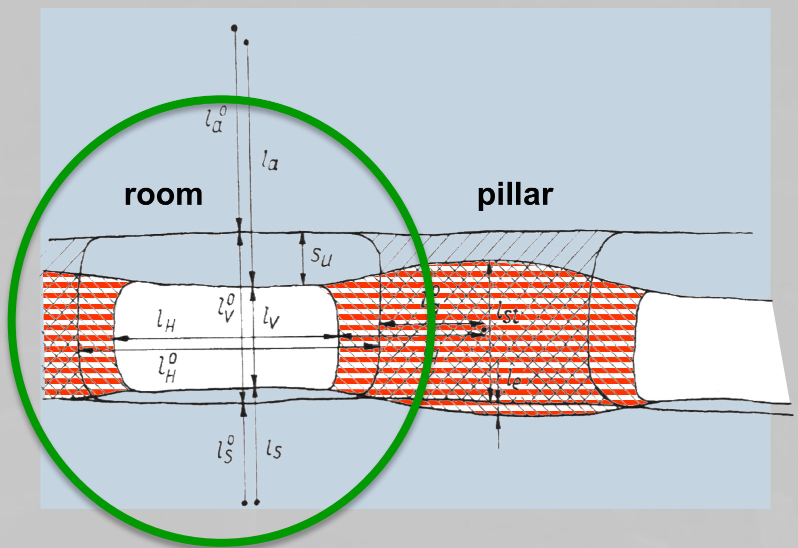


(1) Subsidence

lowering of the ground surface

(2) Room closure / Convergence

displacement between roof and floor of the underground opening / pillar deformation

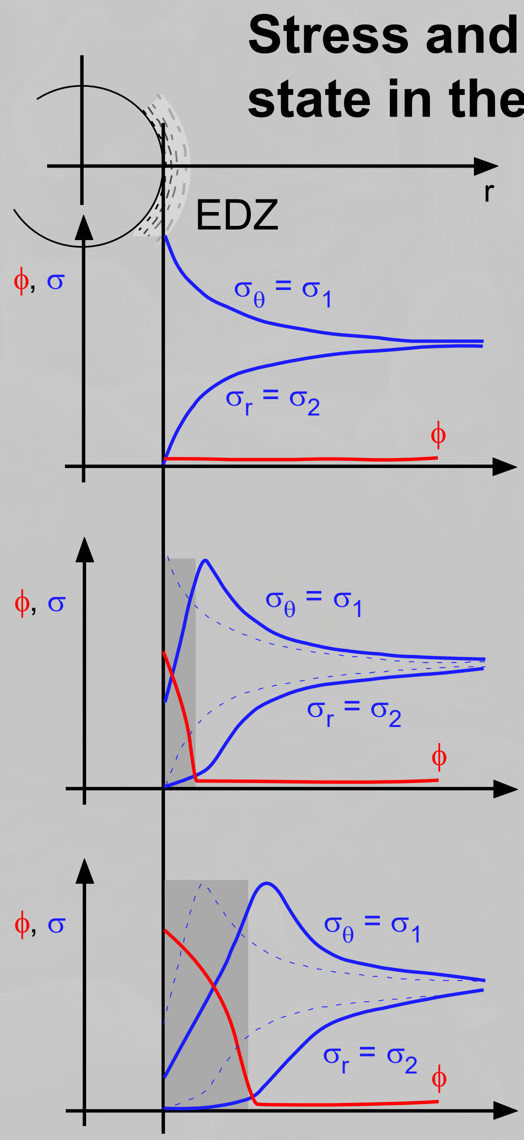


Thesis:

In the long-term underground openings will be completely closed.

$\rightarrow$ $Vol_{\text{Subsidence-trough}} \approx Vol_{\text{Room convergence}}$

Creation of underground openings in salt



(1) Excavation of the room

➔ *spontaneous development of the EDZ*

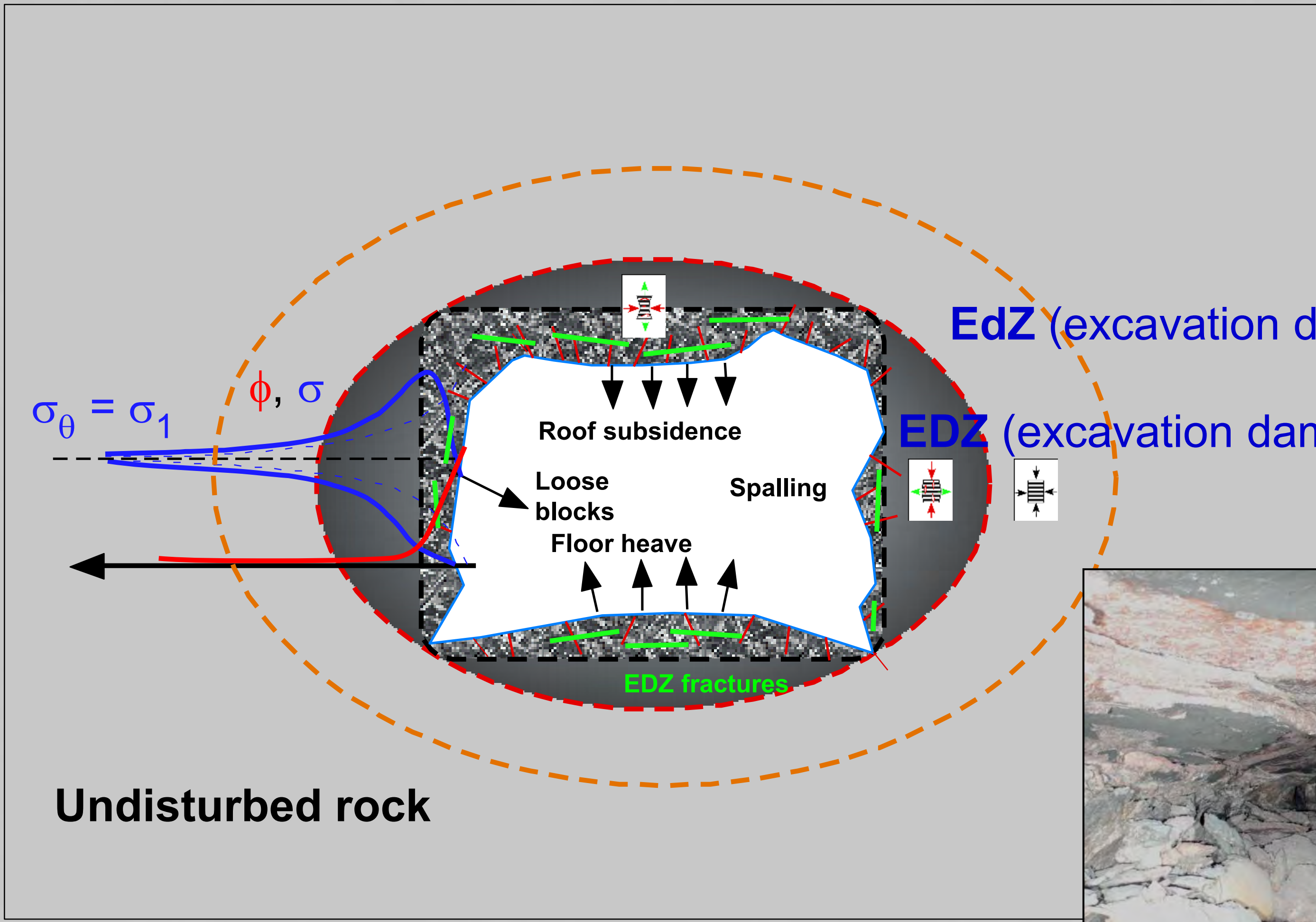
(2) Stress redistribution in the contour due to creep

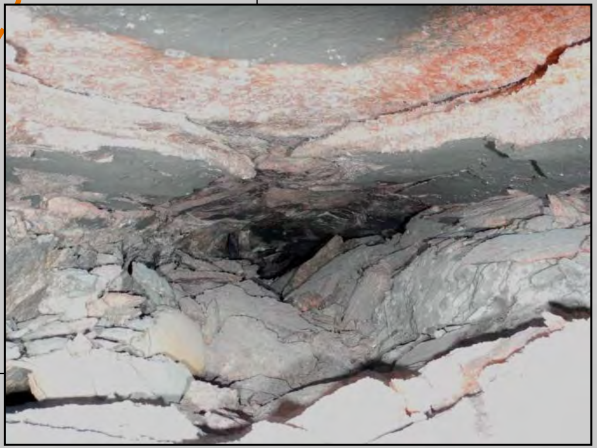
➔ *Extension of the EDZ*

➔ *Loading of the pillar*

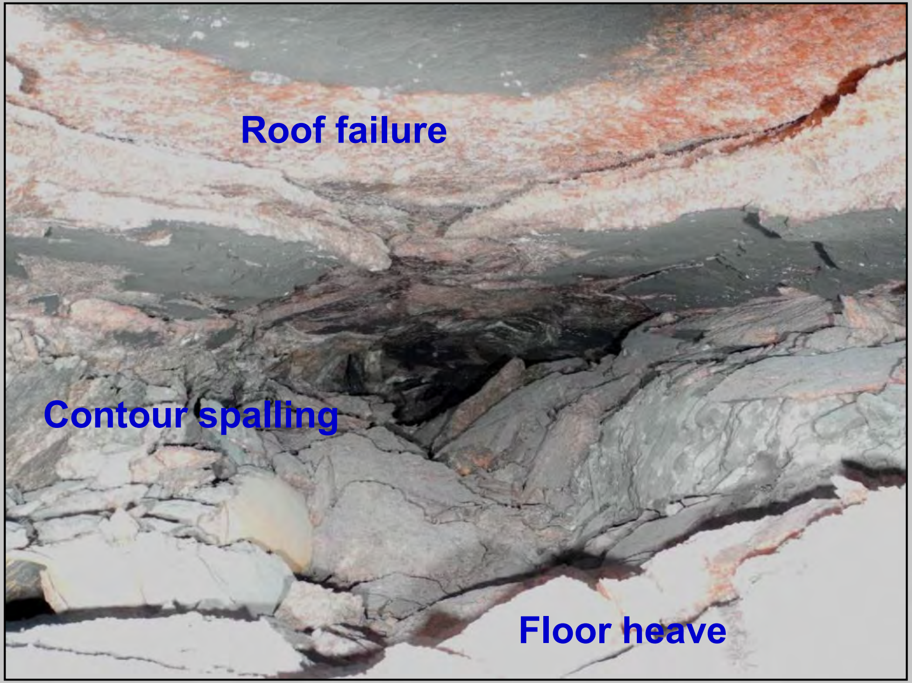
➔ *Development of damage in the contour with time*

Development of damage in the contour





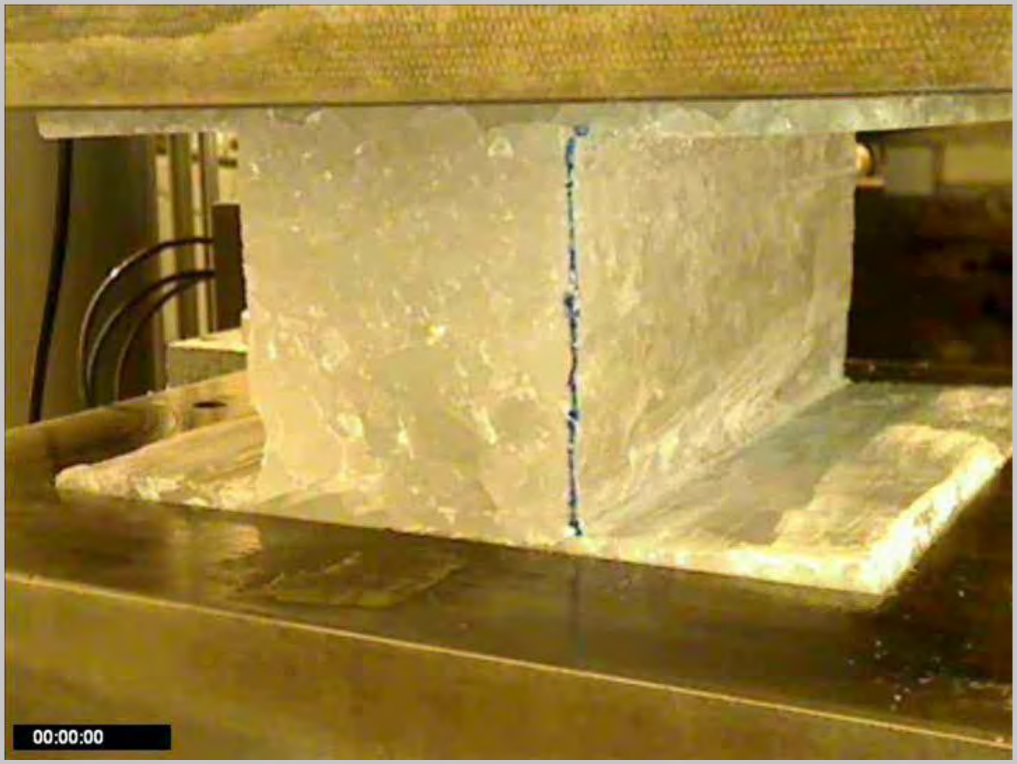
Underground observations



Different stages and mechanisms of room closure (Teutschenthal mine)

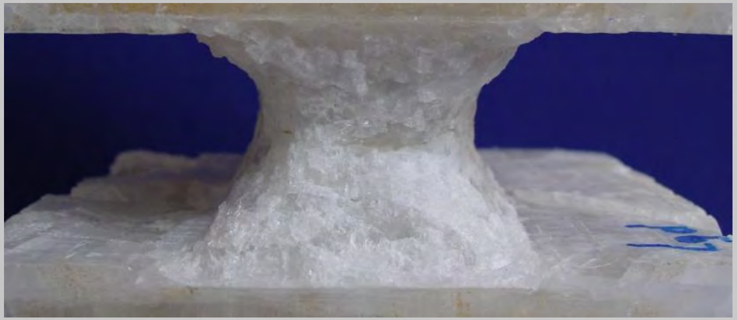
Photo source: K-UTEC (Dr. Stäubert)

Loading of salt – self backfill



- *How behaves the self backfill in the long term?*

Self-backfill due to contour failure



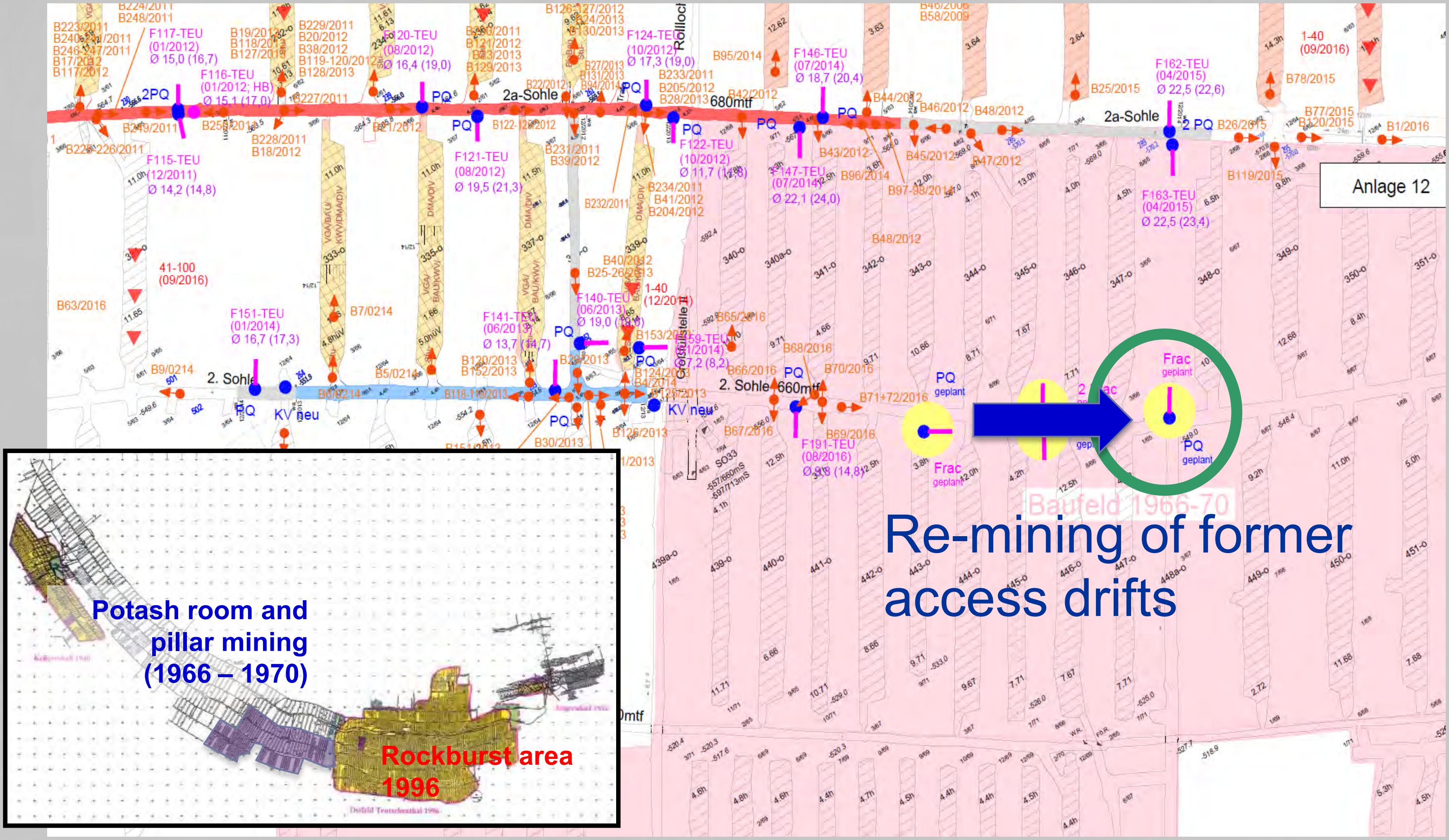
Remaining pillar contour

(**Note:** the remaining loaded pillar area is sufficient to carry the acting load due to high confinement in the loading area)

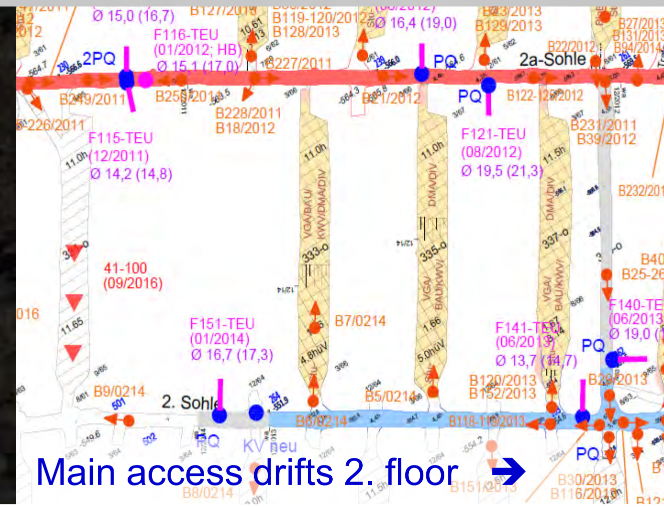
Natural reconsolidation of crushed salt in the Teutschenthal mine

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

Example Teutschenthal



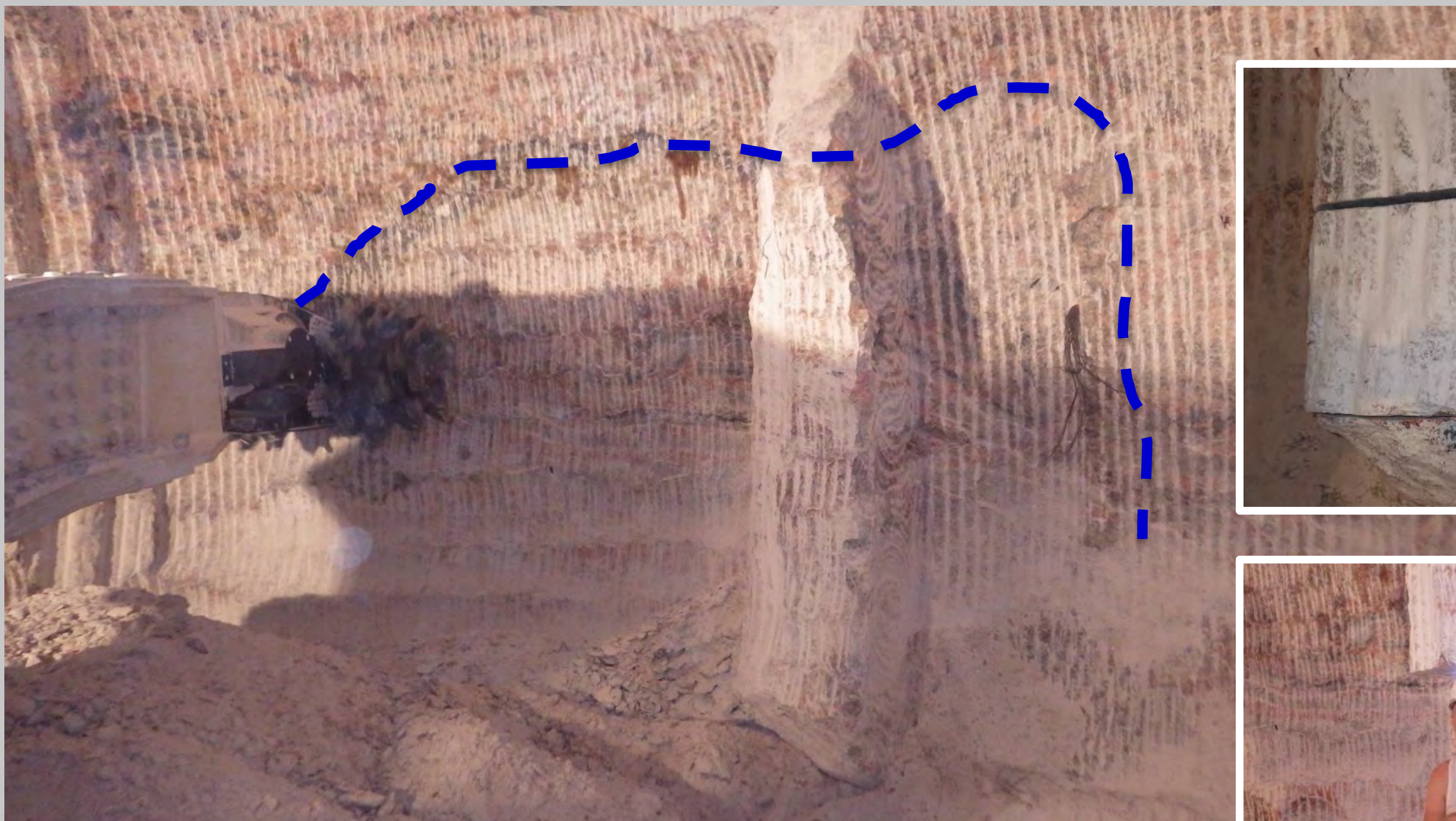
Re-mining of former access drifts



Natural reconsolidation of crushed salt in the Teutschenthal mine

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

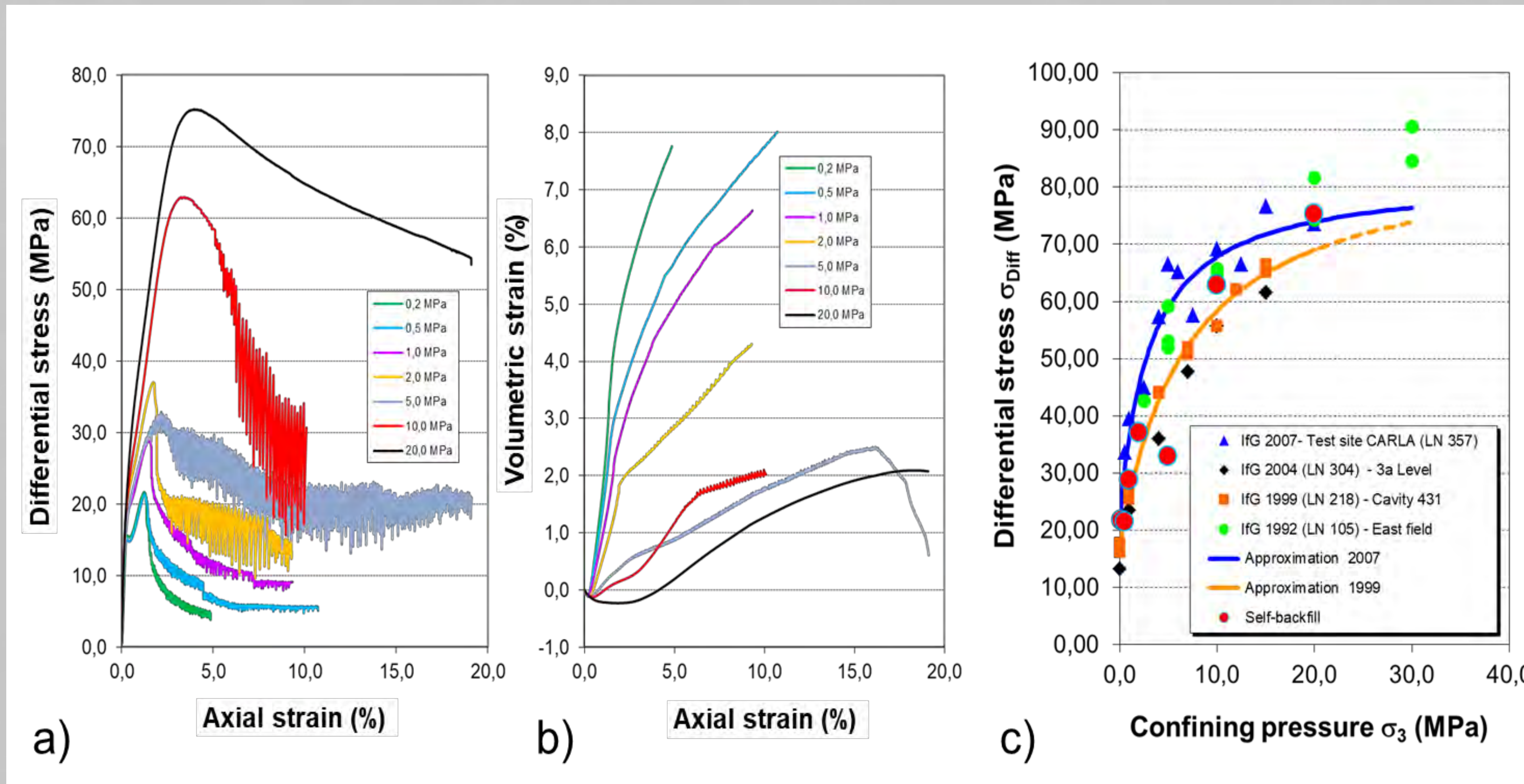
Block sampling

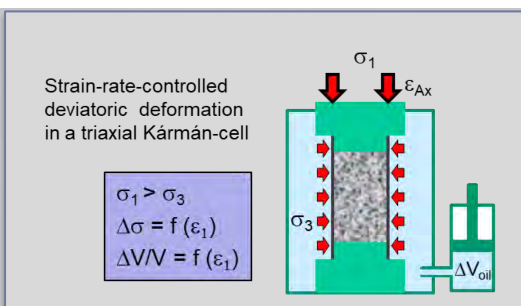


Triaxial strength testing

TC1:	TC2:	TC3:	TC4:	TC5:	TC6:	TC6:
σ_3 = 0,2 MPa	σ_3 = 1 MPa	σ_3 = 2 MPa	σ_3 = 5 MPa	σ_3 = 10 MPa	σ_3 = 20 MPa	σ_3 = 20 MPa
ε_{max} = 4,1%	ε_{max} = 11,4%	ε_{max} = 20,2%	ε_{max} = 20,1%	ε_{max} = 20,3%	ε_{max} = 20,2%	ε_{max} = 20,2%

Strength-dilatancy testing of reconsolidated crushed potash salt

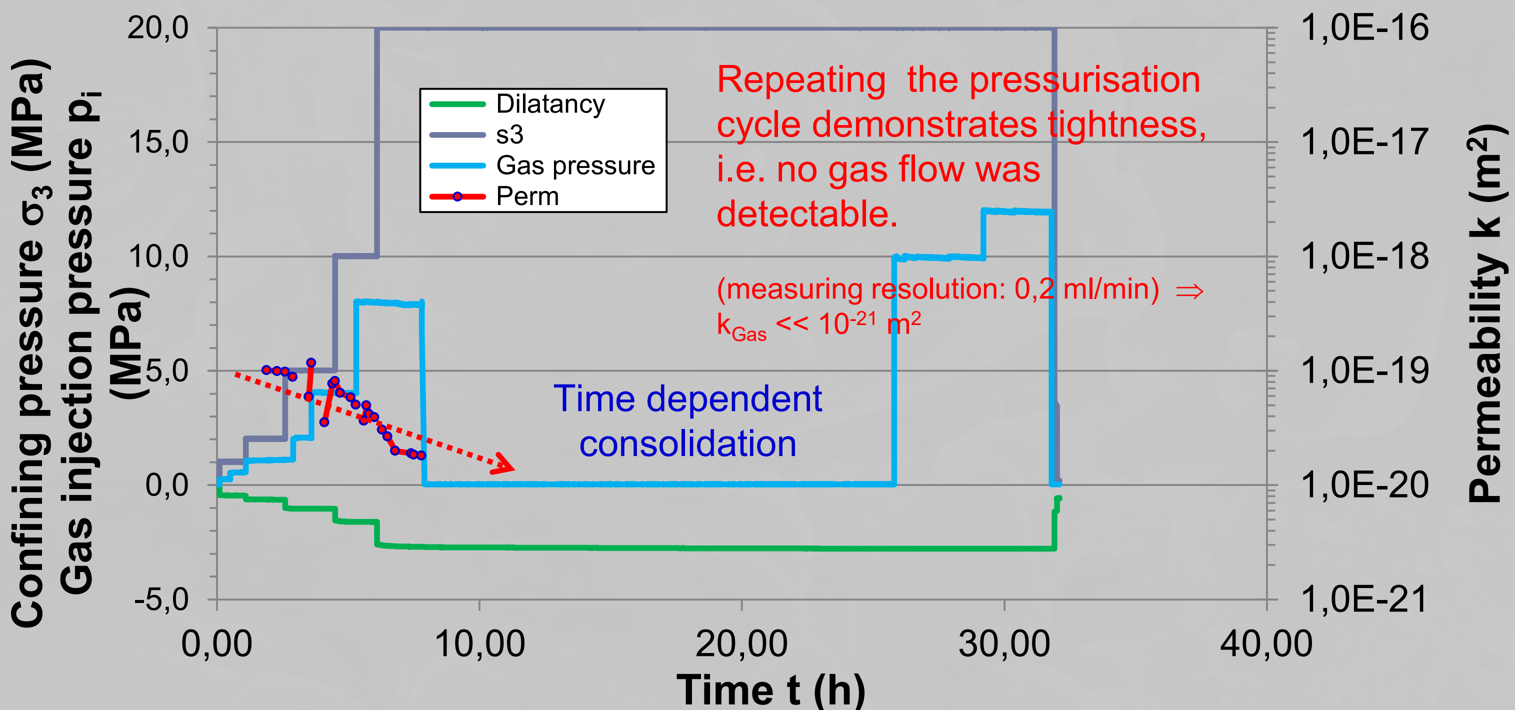


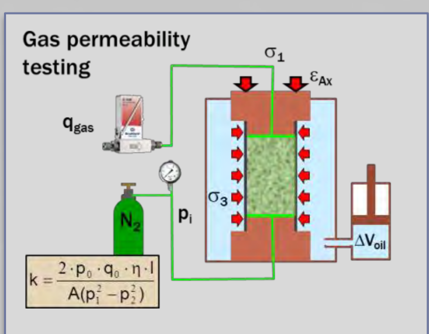


The reconsolidated material behaves like the virgin rock

☺ High strength

Permeability testing of reconsolidated crushed potash salt





The reconsolidated material behaves like the virgin rock

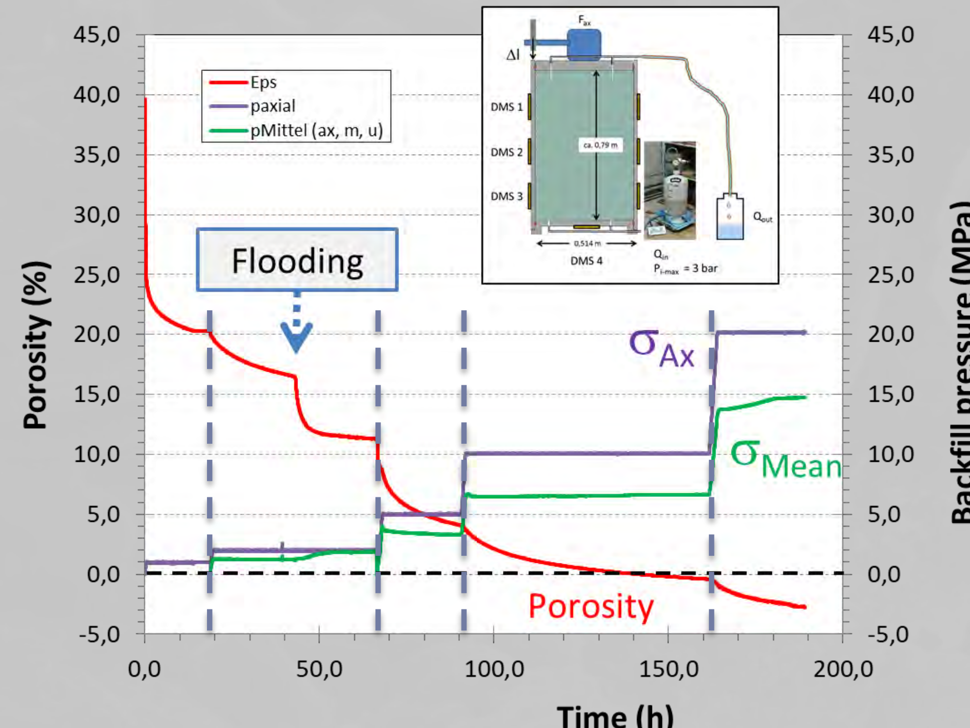
☺ Low permeability

Wetting of potash salt during consolidation

a)

b)

c)



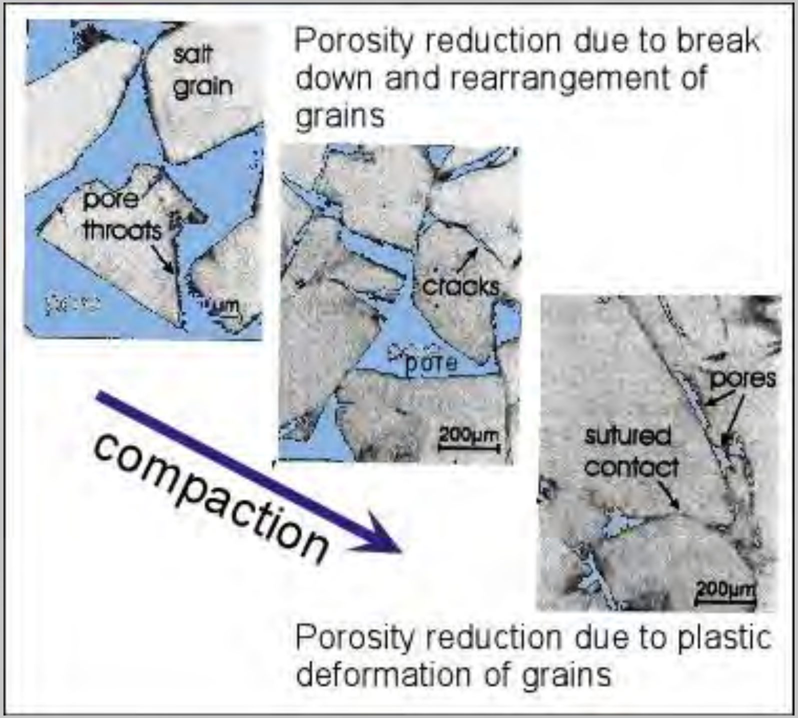
(1) Wetting of the natural backfill material accelerates (as a jump) the consolidation process

(2) The measured remaining porosity is < 0, that means dissolution processes took place.

Mechanisms of crushed salt consolidation

Stress dominated compaction

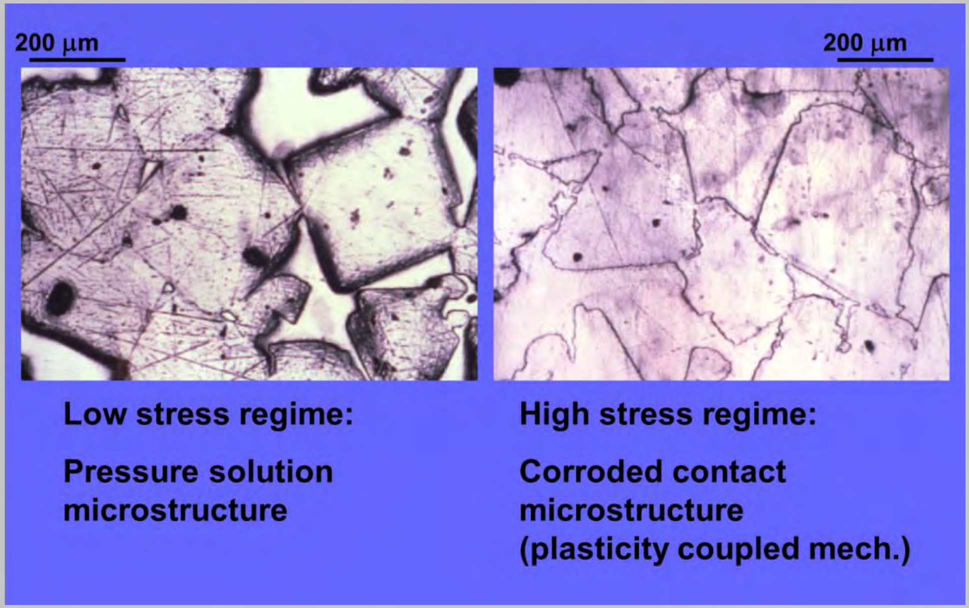
High porosity region → 10%



(Spangenberg et al., 1998)

Fluid-assisted deformation mechanisms and crystal plasticity

Wet samples or in the low porosity region < 10%

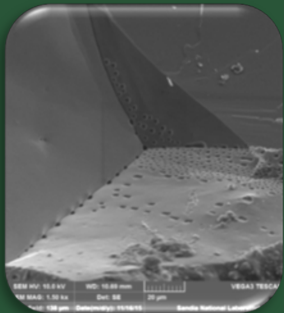
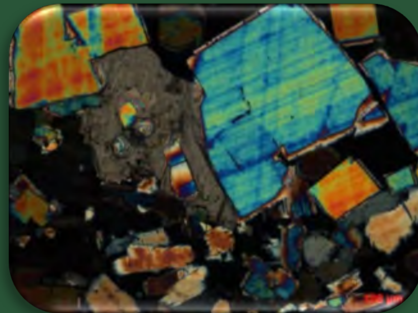


(Spiers et al. 2005)

Summary / personal opinion

- **Industrial analogues (conventional salt mines) give valuable input for assessment of radioactive waste repositories**
- **Lessons learned at the Teutschenthal site:**
  - Natural closure of underground openings due to salt creep is a fact.
  - Despite room closure of underground openings is a long-lasting process, it will happen within periods of up to 1000 years depending on, e.g. the salt type, repository depth …
  - During re-consolidation the natural salt properties (e.g. strength, tightness) of the crushed salt will be restored
  - Humidity will accelerate this process,

    but note: if the openings are completely flooded the developing fluid pressure will reduce the convergence (stabilization of underground openings)

Addressing Drift Closure with Roof Fall and Related Uncertainties in WIPP PA

Tom Peake
U.S. Environmental Protection Agency

Rapid City, SD, United States
May 28-30, 2019

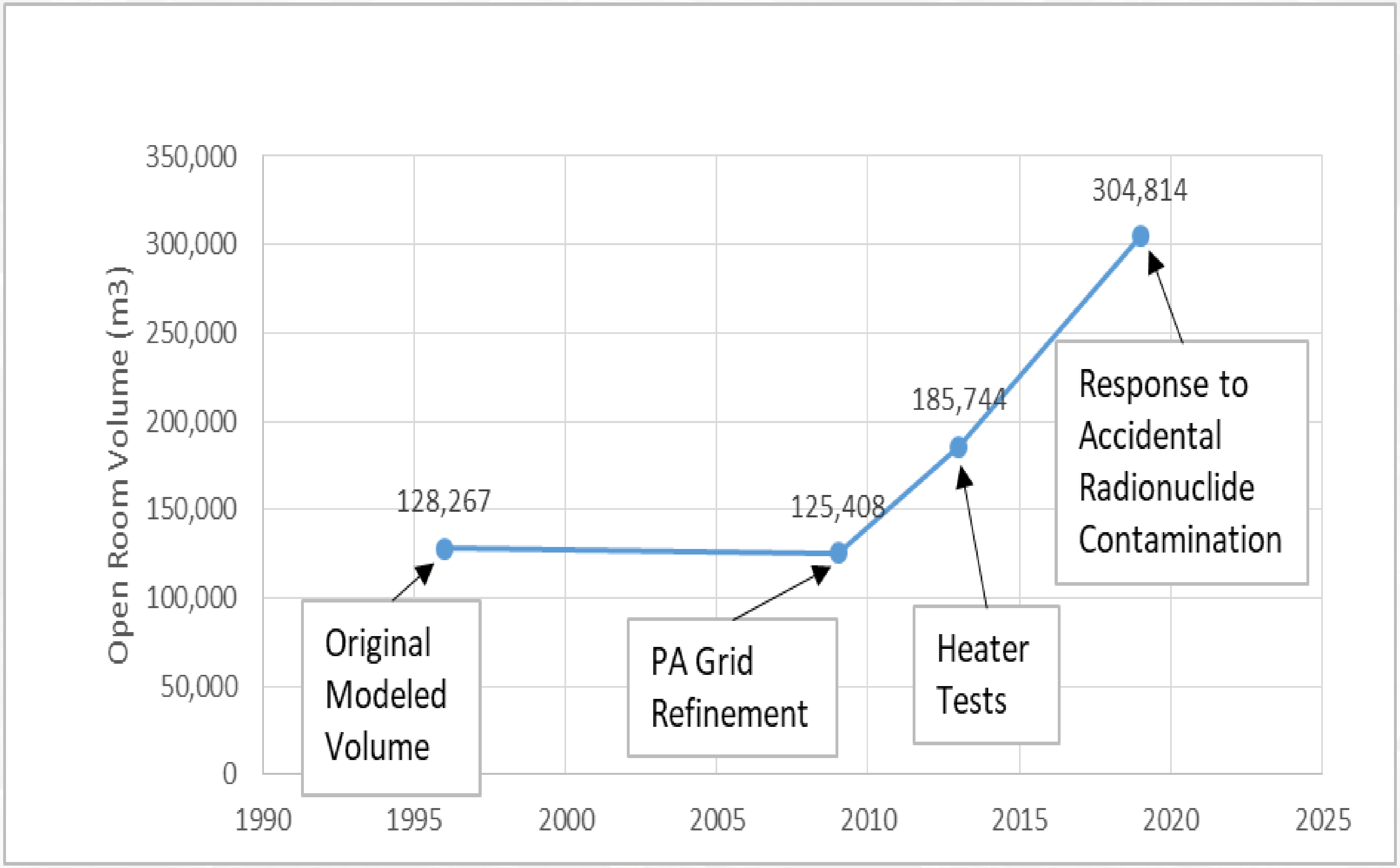
Background

- WIPP Halite (Salado) is subject to significant creep closure and healing
- DOE/SNL has modeled the halite as fairly static
  - WIPP PA assumes permeabilities of open rooms are 10 orders of magnitude higher than intact halite for 10,000 years with a porosity similar to sandstone
  - Intent with this approach is to bound the analysis
- Current PA modeling does not explicitly model healing of open areas with no backfill:
  - Salt healing in open rooms with roof fall is not well understood and has not been modeled in PA

US EPA Questions

- Does the WIPP PA representation of open areas closure adequately represent future performance?
  - Changing initial modeling conditions:
    - Facility closure will be delayed by decades
    - Increase in the open area expected compared to mid-1990s and no plans to backfill much of it (e.g., experimental area, abandoned Panel 9 and affected panels)
  - Uncertainty in closure rates
  - Uncertainty in end-state conditions
- How should the physical characteristics of the disposal system be expressed in the modeling?
- How is site experience with ground control getting incorporated into the modeling or how should it get incorporated?

Volume of Open Rooms Increasing

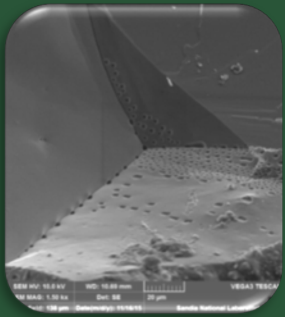
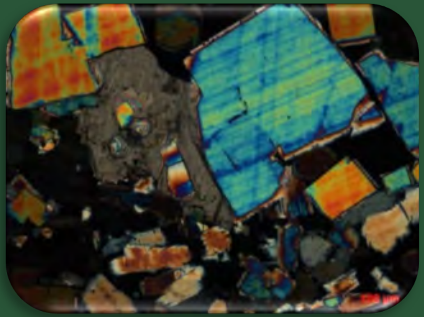


Uncertainties in Closure Rates & Properties

- Closure and healing of open drifts is less understood than backfilled drifts, particularly if roof falls have occurred
- Substantial closure of open areas may occur before gas generation becomes significant
  - Repository releases are strongly influenced by high gas pressures
  - Uncertainty in closure rates was not addressed in WIPP PA as it was believed to be bounding but assumptions have changed
- End-state permeability and porosity are expected to approach intact halite within the 10,000-year regulatory period but the timing is uncertain and variable

Modeling Issues

- Creep closure rates and porosity/permeability reduction processes in open drifts with roof falls take on more importance in the PA modeling with more open areas expected in the repository
- How should the physical characteristics of the disposal system be expressed in the modeling?
  - Initial conditions
  - Uncertainties in closure rates & halite properties
  - How best should site experience be used?

10th US/German Workshop on Salt Repository Research, Design, and Operation

Evan Keffeler
RESPEC

Rapid City, SD, United States
May 28-30, 2019

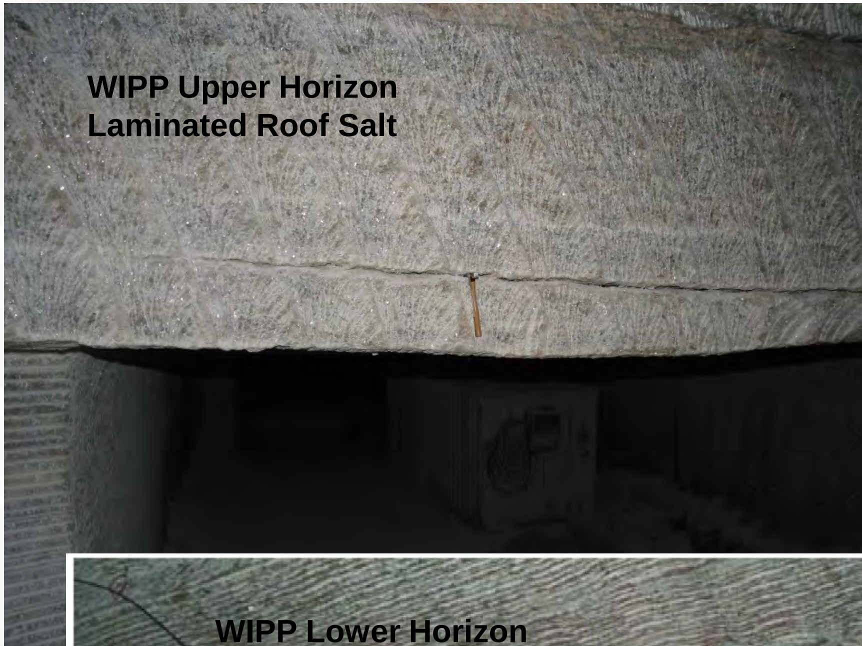
Breakout Session:
Natural Closure of Salt Openings

Alternatively: Mechanical Evolution of Mined Excavations in Salt

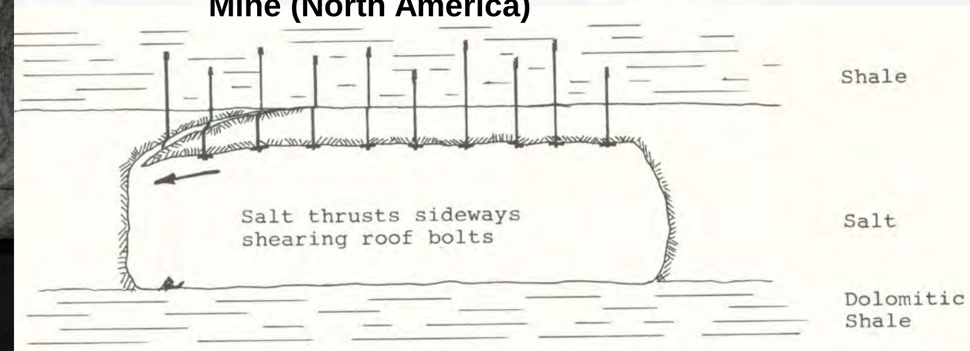
What happens when opening created in salt?

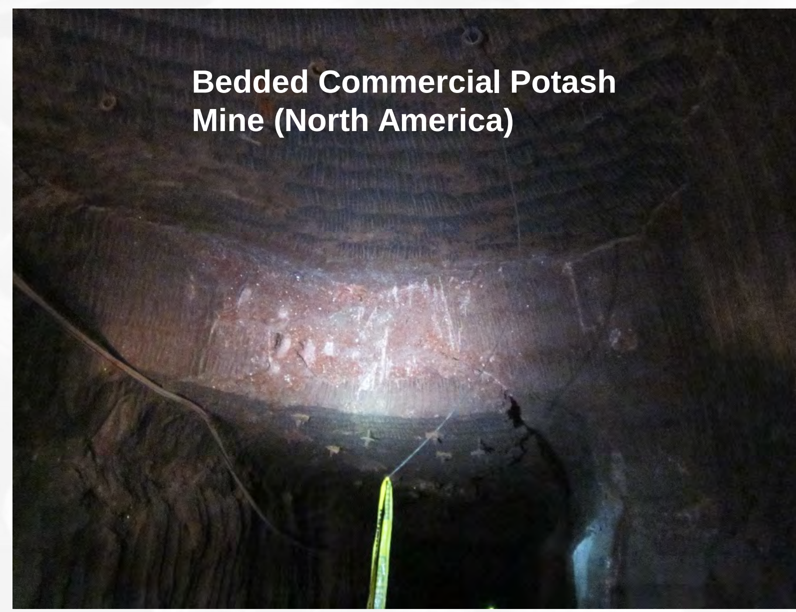
- For conventional excavations
  - Creep deformation
    - Continual deformation in response to shear stress
  - Near surface damage (“Damaged Rock Zone”)
    - Large shear stresses with little confinement around opening
- Excavation closure combination of
  - Creep deformation
  - Volume increase from damage (dilation, separations, and fracturing)
- Contributing factors
  - Stress
  - Geology
  - Geometry

Roof Damage



Bedded Commercial Salt Mine (North America)





Floor Damage

Rib Damage

Case Study

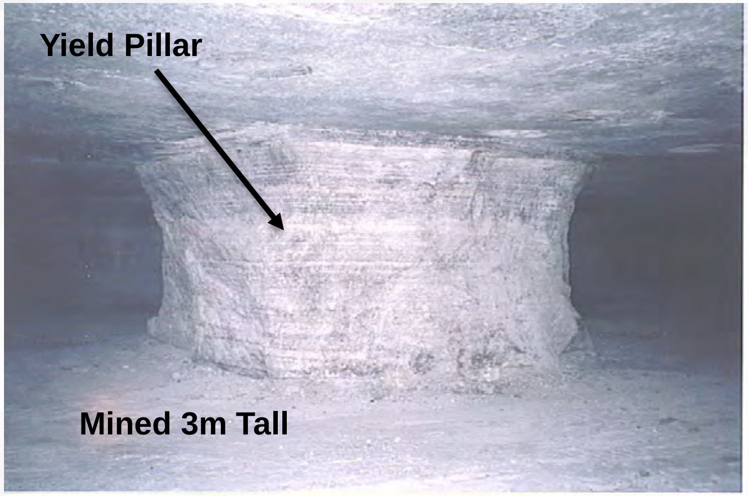
Commercial Bedded Salt Mine (North America)

- Main entries with 40 year design life
  - 550m deep
  - Designed to reduce stress concentration and minimize effects of creep
  - Mined approximately 20 years ago
- Ribs
  - Minor scale on surface
  - <1m: hairline fractures
  - ~1m to ~2m: Cloudy (dilated) salt
  - >2m: translucent salt, effectively impermeable
- Roof
  - Composed of salt and dolomite
  - No visible roof shears
  - Fractures in first ~2m
  - Effectively impermeable >3m
- Floor
  - Composed of salt
  - Hairline fractures and cloudy salt in first ~0.5m
  - Effectively impermeable >0.5m into floor

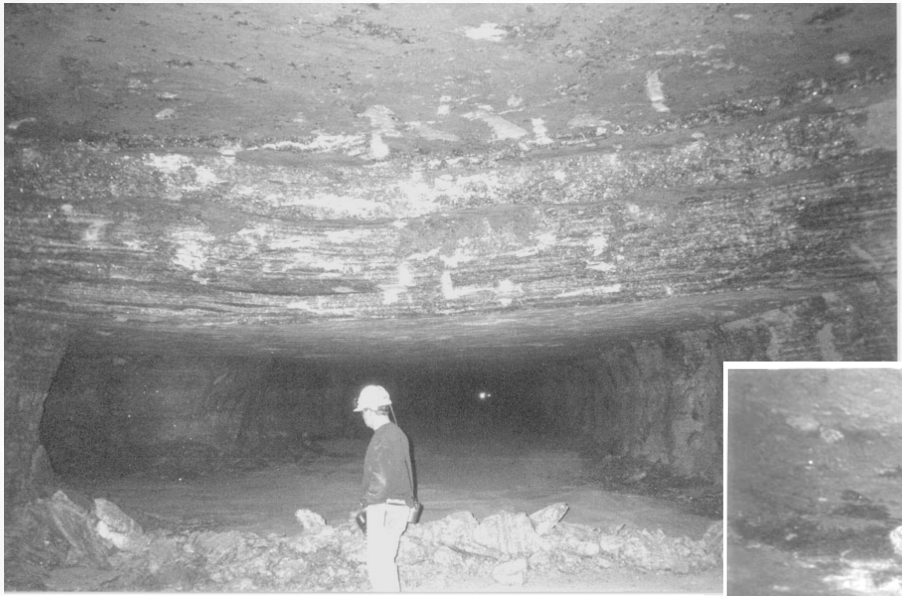
Case Study
Commercial Bedded Potash Mine North America

- "Stress room" in production panel
  - 900m deep
  - Highly stress room that protects the beltway
  - Deteriorates within weeks after mining
  - Designed to fail within month after mining
- Ribs
  - Large rib scales develop soon after mining
- Roof
  - Low angle shear fractures form soon after mining
  - Roof falls within month after mining

Creep Closure over Wide Panel



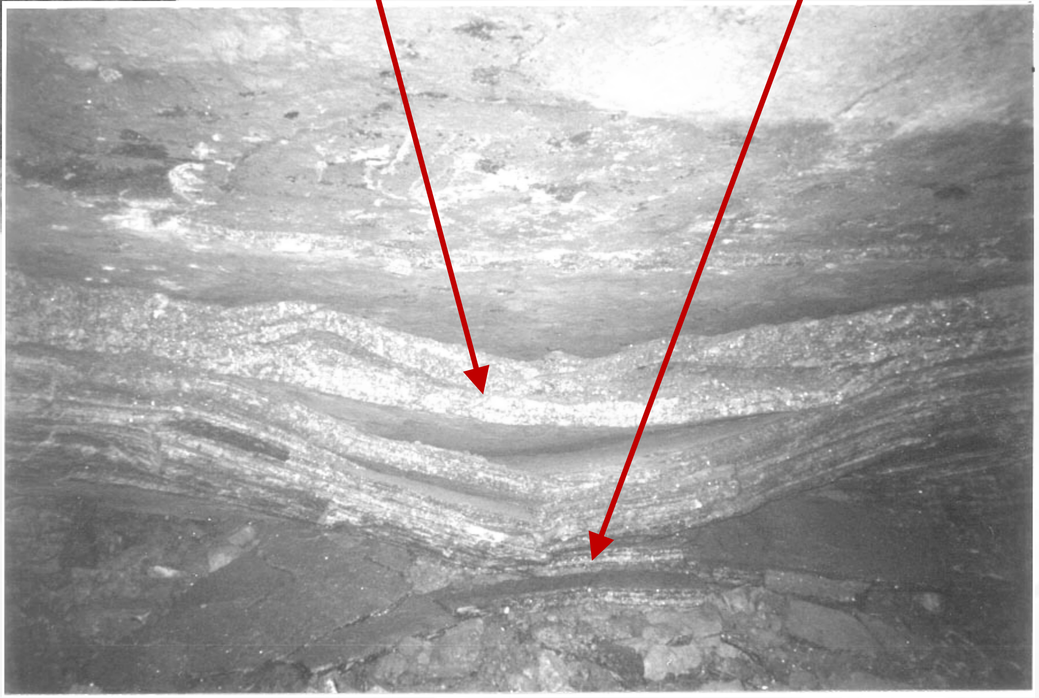
Combined Creep and Damage



Originally a 3m tall opening

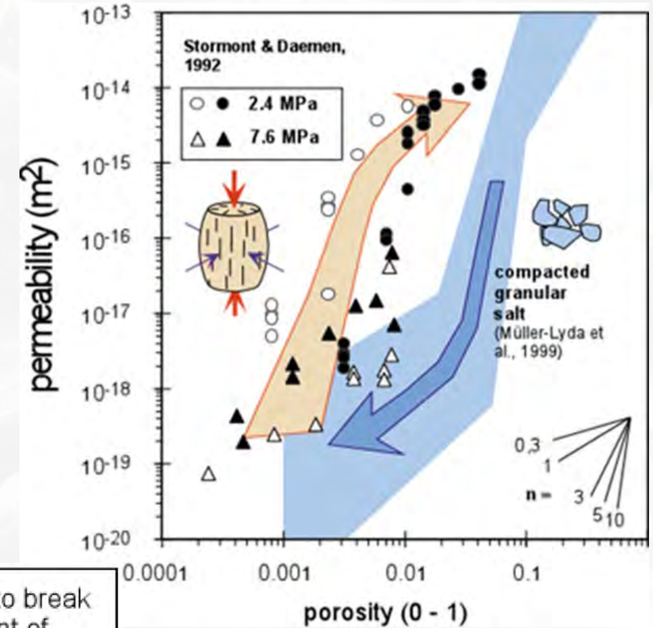
Roof Sag over 10m wide room

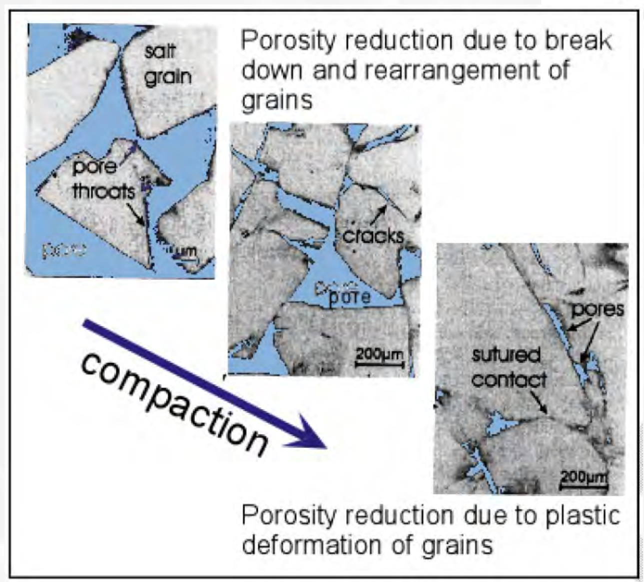
Severe roof sag and floor heave now touching



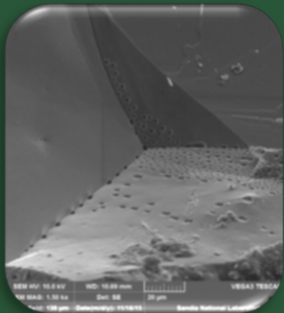
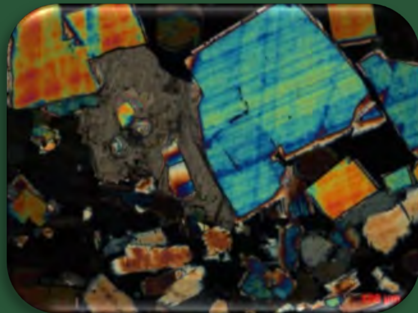
After Excavation has Closed

- Creep rates reduce as shear stresses reduce
- Interconnected porosity reduces
  - Brittle failure of grains
  - Grain reorientation
  - Pressure solution/redoposition
  - Crystal plasticity
- Permeability trends toward native formation





Thank You

BEN VASIM

Introduction to a Benchmarking of TH²M Simulators and First Results

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

Sandia National Laboratories
BGE TEC BGE TECHNOLOGY GmbH
PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology
RESPEC
SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY
U.S. DEPARTMENT OF ENERGY
Federal Ministry for Economic Affairs and Energy

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Rapid City, SD, United States
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Confederaziun svizra

Swiss Confederation

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GRS
(2 teams: BS and K)

BERKELEY LAB

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Service Sismologique Suisse
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- Oliver Czaikowski, Larissa Friedenberg
- Stephan Hotzel, Ingo Kock
- Jonny Rutqvist, Mengsu Hu
- Antonio P. Rinaldi

Contents

- Introduction to the BenVaSim project
- Some simulation results for a H^1M-coupled model
  (H^1: single-phase flow)
- Some simulation results for a H^2M-coupled model
  (H^2: two-phase flow – liquid and gaseous phases with water and air)
- Conclusions of the work so far

Introduction to the Project

→ Motivations for the project – observations and conclusion

- existing benchmarkings:
  sometimes large spreading widths within the results of the different teams *(especially for mechanical quantities)*
- possible reasons:
  constitutive models, considered processes
  ...and simulators?
- quality assurance necessary, especially for application on real repository designs
- only a few (special-case) analytical solutions available
- national availability of >1 quality-assured simulator

→ ***simulator benchmarking***

Introduction to the Project

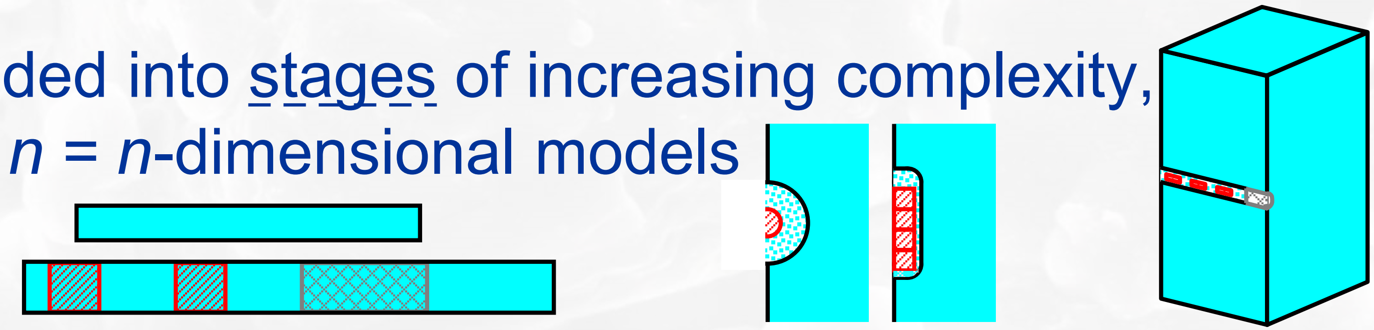
→ Participants – partner organizations and their simulators

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

Introduction to the Project

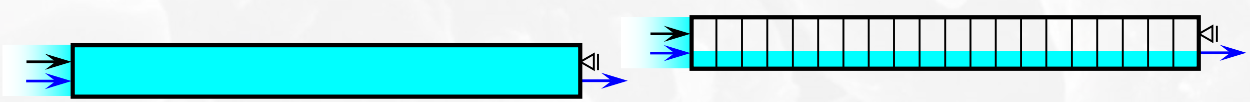
→ Work program setup – stages, models, and scenarios

- project divided into stages of increasing complexity, i.e.: stage *n* = *n*-dimensional models



- models stem from parts of generic repository systems, idealized and simplified → numerical test cases

- scenarios for assessing effects of changing parameters, boundary conditions, physical processes or the like



alterations of

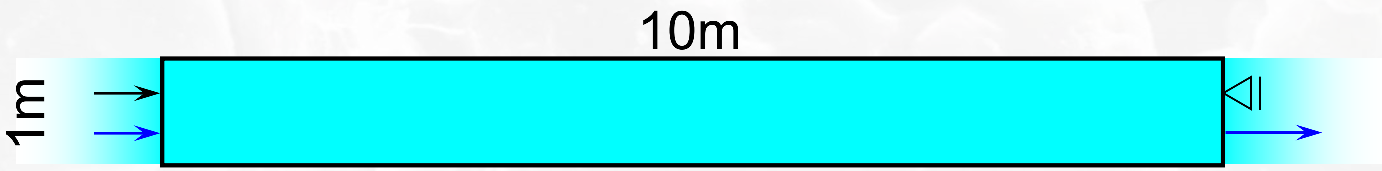
$S_{l0},\ \alpha,\ p_{cap},\ \hat{Q}_{m;g;lhs}\ \ldots$

Simulation Results

→ HM processes – models and equations

- mechanical process:
  equation of motion *(no gravity, small strains)*, Hooke's model
- hydrological processes:
  mass-balance equation *(for each phase φ)*, Darcy's model
- H→M coupling:
  Biot's effective-stress definition $\sigma_{eff} = \sigma_{tot} - \alpha p_{eq} I$
  with $p_{eq} = \sum_\varphi S_\varphi p_\varphi$
- M→H coupling: $\frac{1}{\breve{M}_\varphi}\dot{p}_\varphi + \frac{\phi}{S_\varphi}\dot{S}_\varphi = \frac{1}{S_\varphi}\dot{\zeta}_{V/V;\varphi} + \alpha\dot{\varepsilon}_{vol}$

H^{1}M Model: Basic Scenario



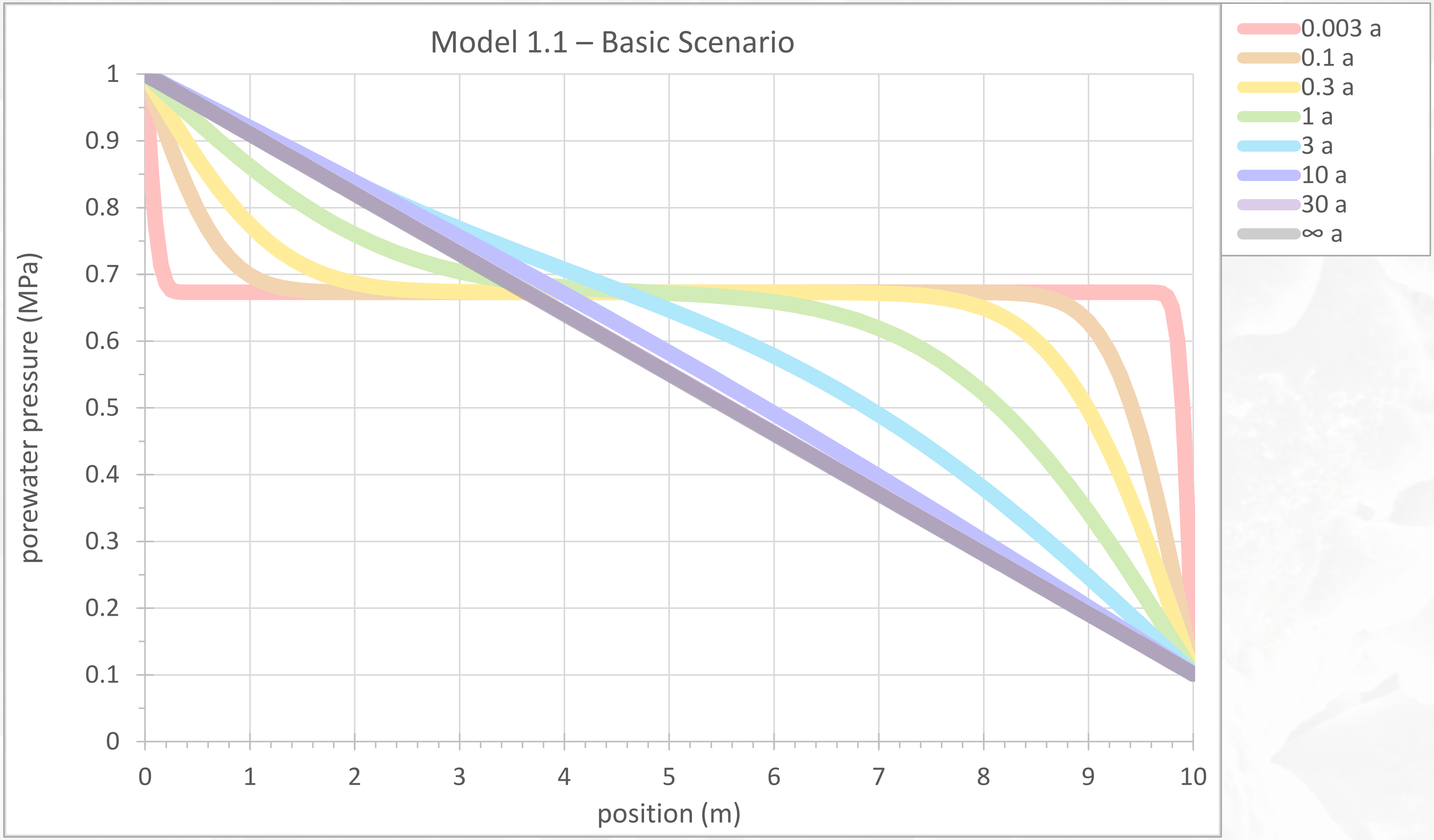
$$\sigma_{tot;lhs} = 1\,MPa \quad p_{l;lhs} = 1\,MPa \quad S_{l;lhs} = 1$$

$$\sigma_{tot0} = 0.1013\,MPa \quad p_{l0} = 0.1013\,MPa \quad S_{l0} = 1$$

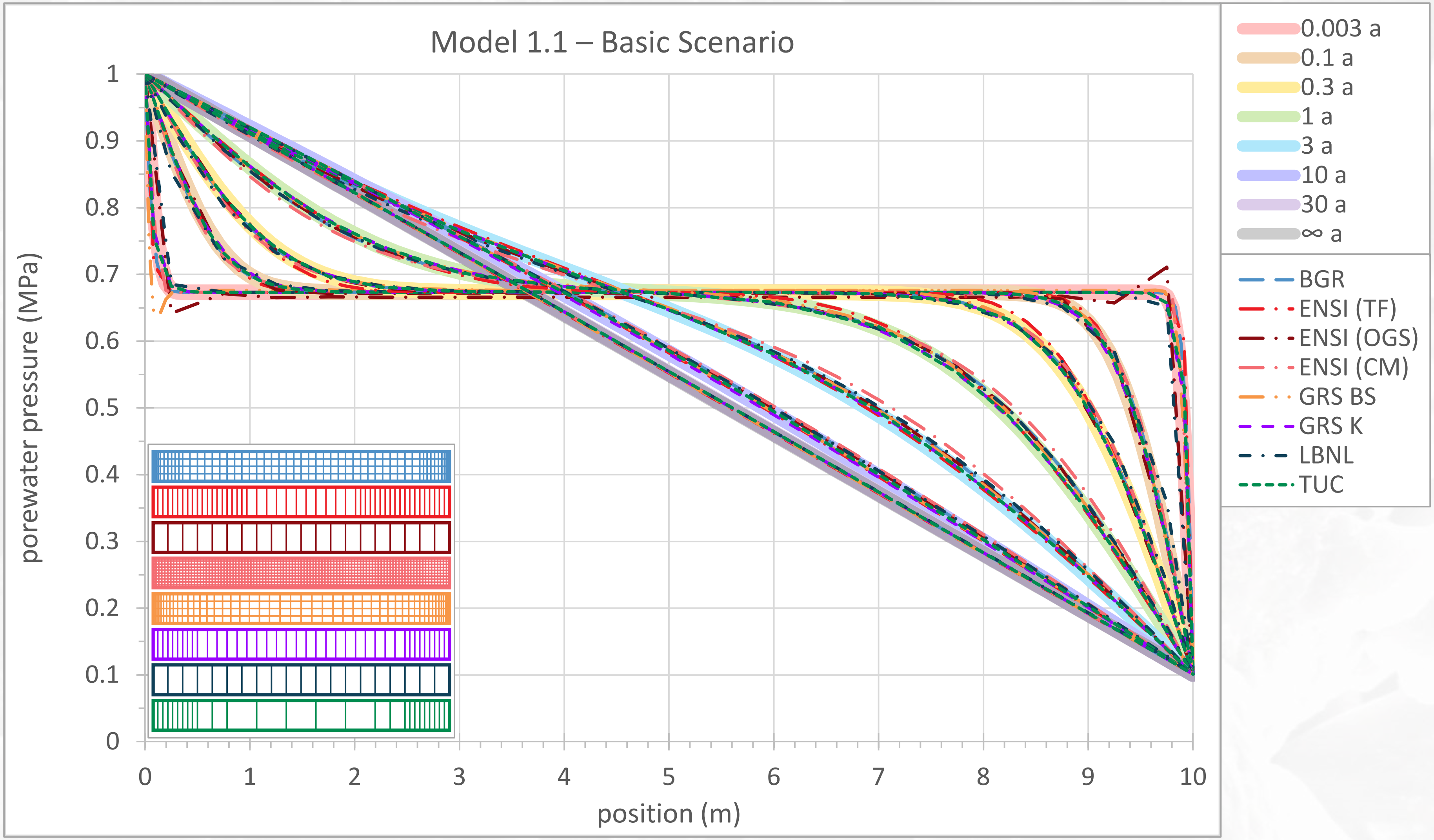
$$u_{rhs} = 0\,m \quad p_{l;rhs} = 0.1013\,MPa \quad S_{l;rhs} = 1$$

parameters			
Young's modulus	E	$8{,}000$	MPa
Poisson's ratio	ν	0	
Biot's coefficient	α	1	
porosity	ϕ	0.15	
intrinsic permeability	K	10^{-20}	m^2
liquid viscosity	η_l	10^{-9}	$MPa \cdot s$
liquid bulk modulus	$\breve{K}_l$	$2{,}100$	MPa

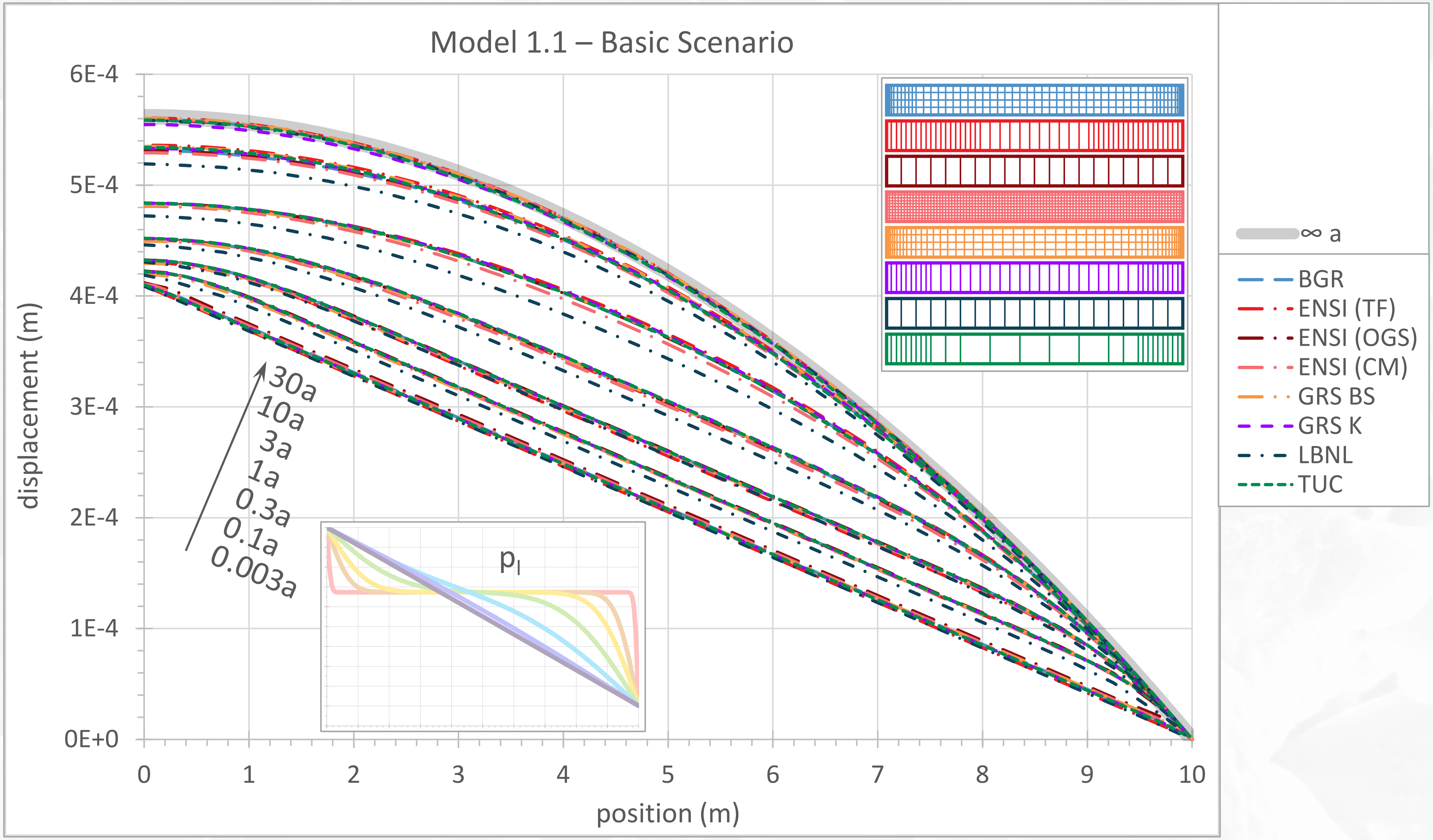
H¹M Model: Basic Scenario



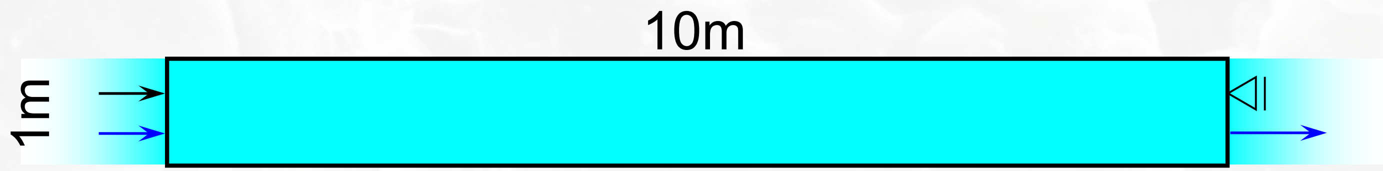
H¹M Model: Basic Scenario



H¹M Model: Basic Scenario



H^1M With Compressible Grains



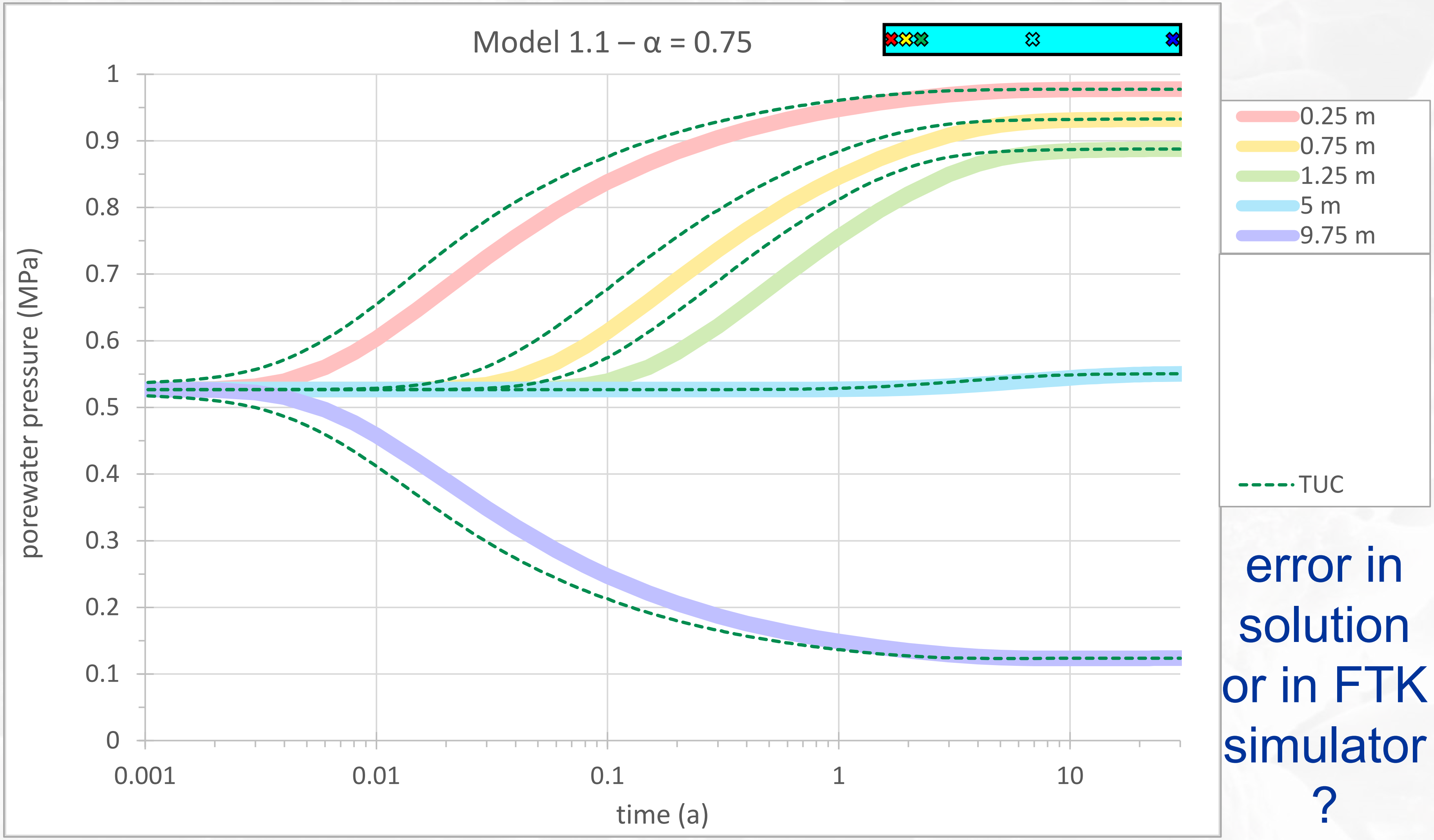
$$\sigma_{tot;lhs} = 1\ MPa \qquad \sigma_{tot0} = 0.1013\ MPa \qquad u_{rhs} = 0\ m$$

$$p_{l;lhs} = 1\ MPa \qquad p_{l0} = 0.1013\ MPa \qquad p_{l;rhs} = 0.1013\ MPa$$

$$S_{l;lhs} = 1 \qquad S_{l0} = 1 \qquad S_{l;rhs} = 1$$

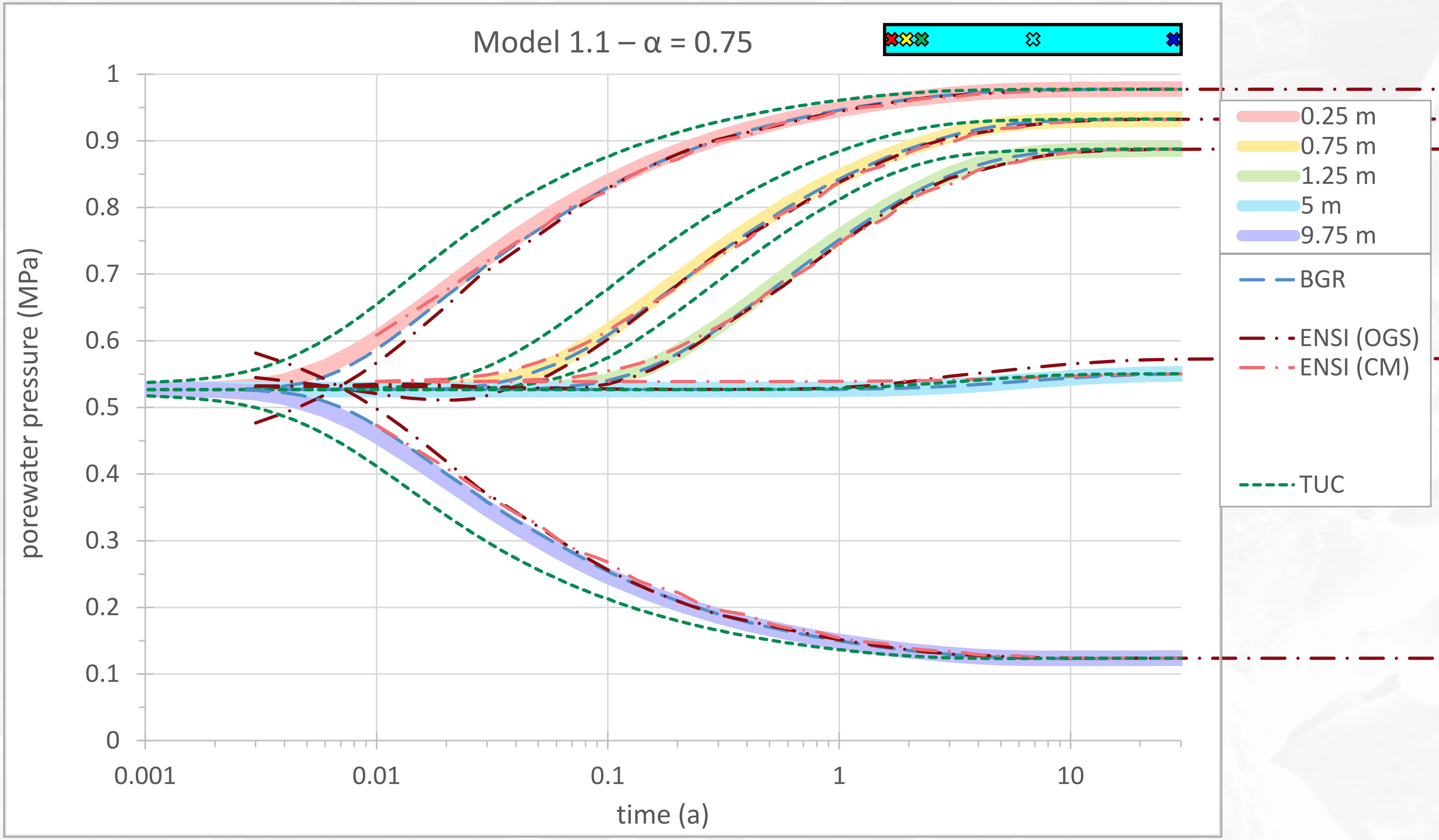
parameters			
Young's modulus	E	8,000	MPa
Poisson's ratio	ν	0	
Biot's coefficient	α	0.75	
porosity	ϕ	0.15	
intrinsic permeability	K	10^{-20}	m^2
liquid viscosity	η_l	10^{-9}	$MPa \cdot s$
liquid bulk modulus	$\breve{K}_l$	2,100	MPa

H¹M With Compressible Grains



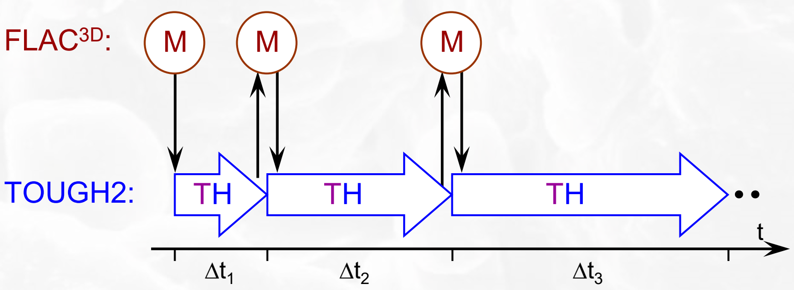
error in solution or in FTK simulator ?

H^1M With Compressible Grains

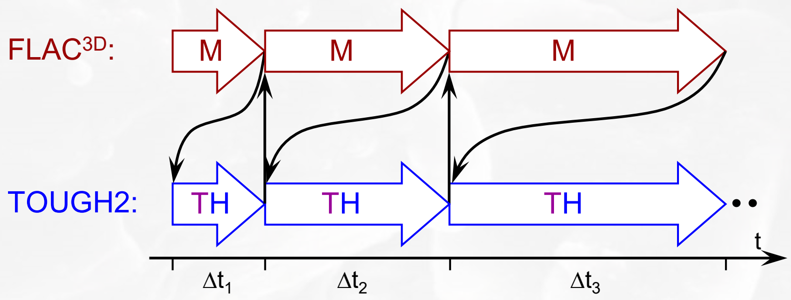


H¹M With Compressible Grains

time-independent constitutive model:



time-dependent constitutive model:

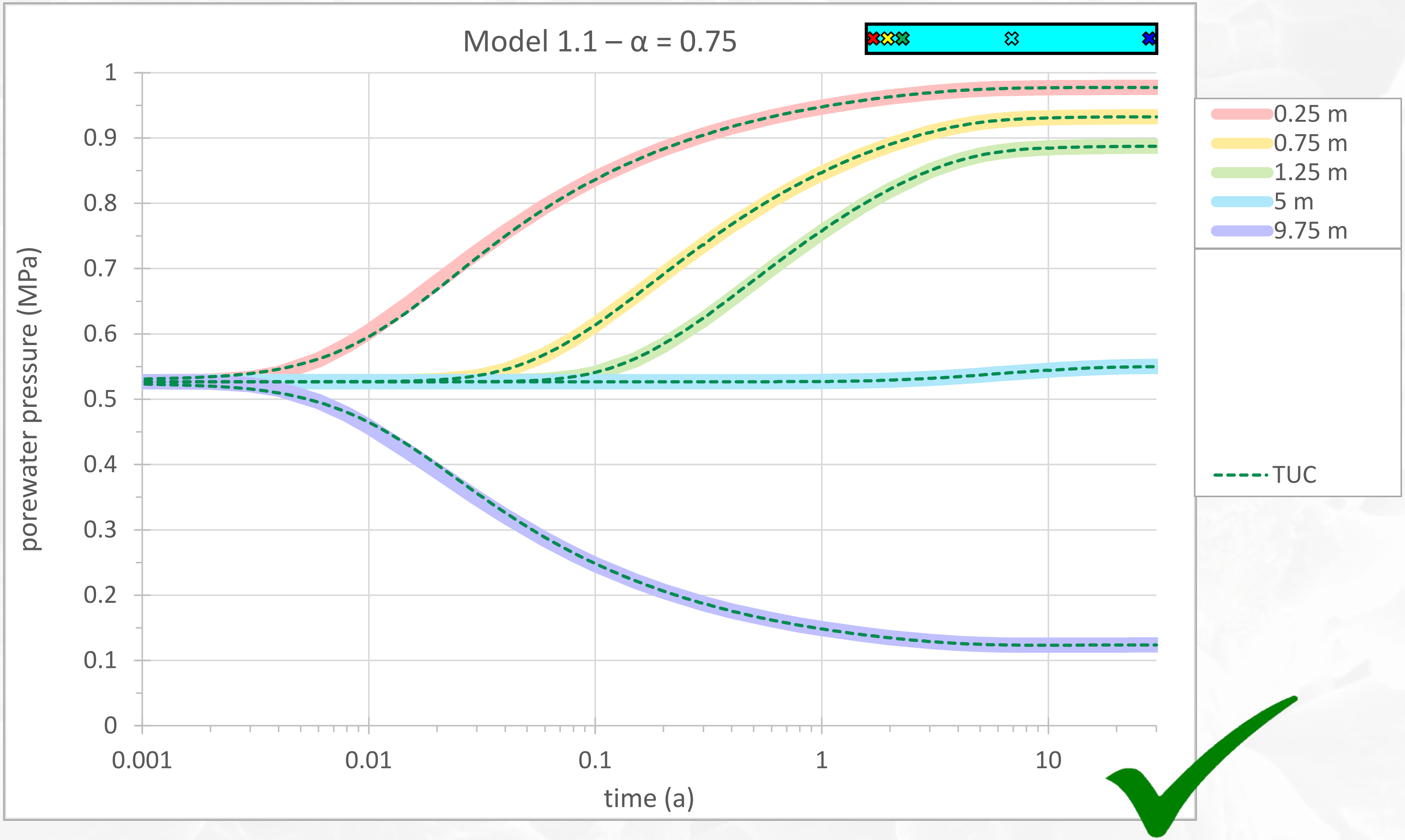


- FLAC^{3D} accounts for grain compressibility (Biot theory)
- FLAC^{3D} formula for HM coupling (isothermal, $S_l \equiv 1$):

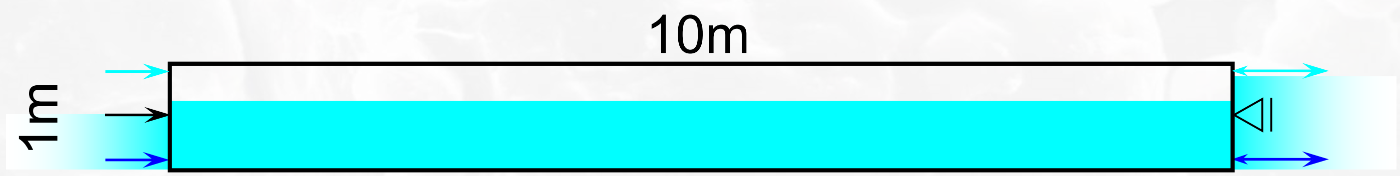
$$\frac{1}{\breve{M}}\dot{p} = \alpha\dot{\varepsilon}_{vol} + \dot{\zeta}_{V/V}$$

- in FTK, grain compressibility parameters had not been transferred to TOUGH2 → bug has been fixed

H¹M With Compressible Grains



H²M Model: Basic Scenario



$$\sigma_{tot;lhs} = 4\,MPa \quad p_{g;lhs} = 3\,MPa \quad S_{l;lhs} = 0.5$$

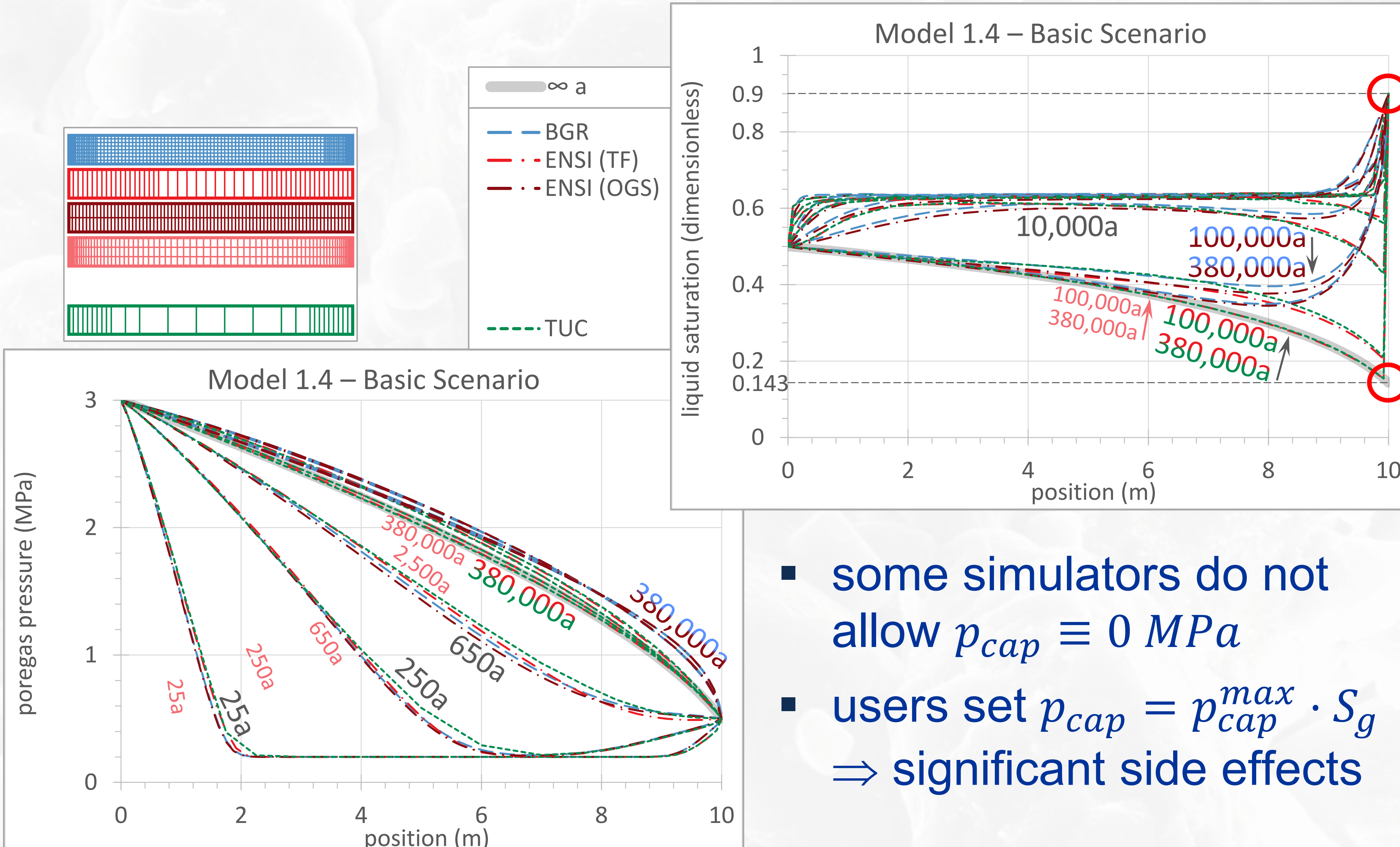
$$\sigma_{tot0} = 4\,MPa \quad p_{g0} = 0.2\,MPa \quad S_{l0} = 0.63$$

$$u_{rhs} = 0\,m \quad p_{g;rhs} = 0.5\,MPa \quad S_{l;rhs} = 0.9$$

parameters			
Young's modulus	E	650	MPa
Poisson's ratio	ν	0	
Biot's coefficient	α	1	
porosity	ϕ	0.33	
intrinsic permeability	K	$2.5 \cdot 10^{-21}$	m^2
gas viscosity	η_g	$1.8 \cdot 10^{-11}$	$MPa \cdot s$
liquid viscosity	η_l	10^{-9}	$MPa \cdot s$
liquid bulk modulus	$\breve{K}_l$	2,220	MPa

$$p_{cap} \equiv 0\,MPa$$
$$K_{rel;\varphi} = S_\varphi$$

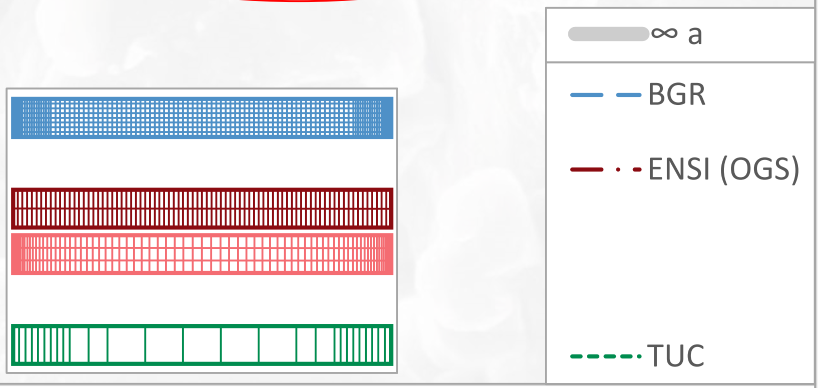
H^2M Model: Basic Scenario

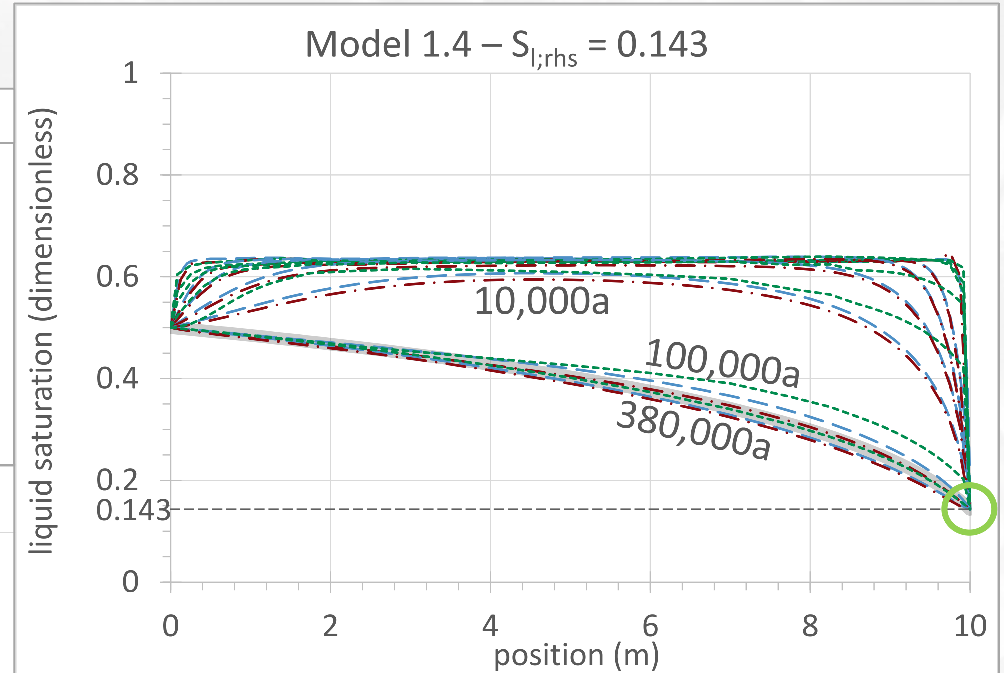


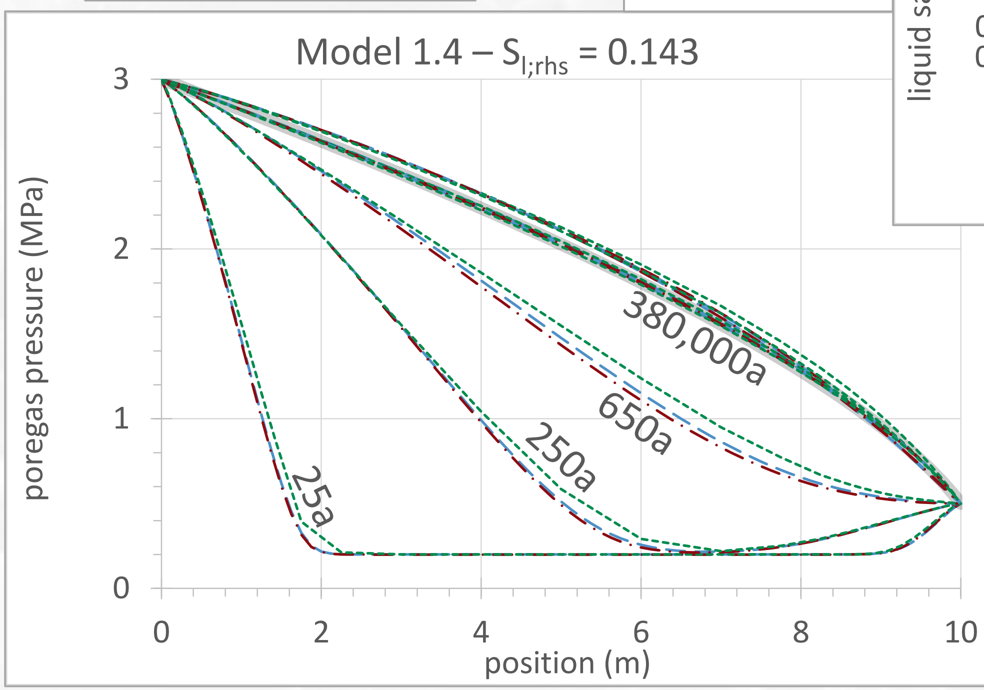
- some simulators do not allow $p_{cap} \equiv 0\ MPa$
- users set $p_{cap} = p_{cap}^{max} \cdot S_g$ $\Rightarrow$ significant side effects

H²M With Matching Boundary

$S_{l;rhs} = 0.143$







- right boundary condition matches analytical value $\Rightarrow$ continuous curves
- minor effect of difference in p_{cap} functions

Conclusions

- models look simple at a first glance...
  but simulating is not necessarily straightforward
- BenVaSim was also initiated to show potential for improvement of the involved simulators
  → purpose has been served
- comprehension for H^2M processes and for simulators could be promoted and intensified by this project
- results can be used as benchmarks by third parties

Thank you for your attention!

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

MANAGED BY

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

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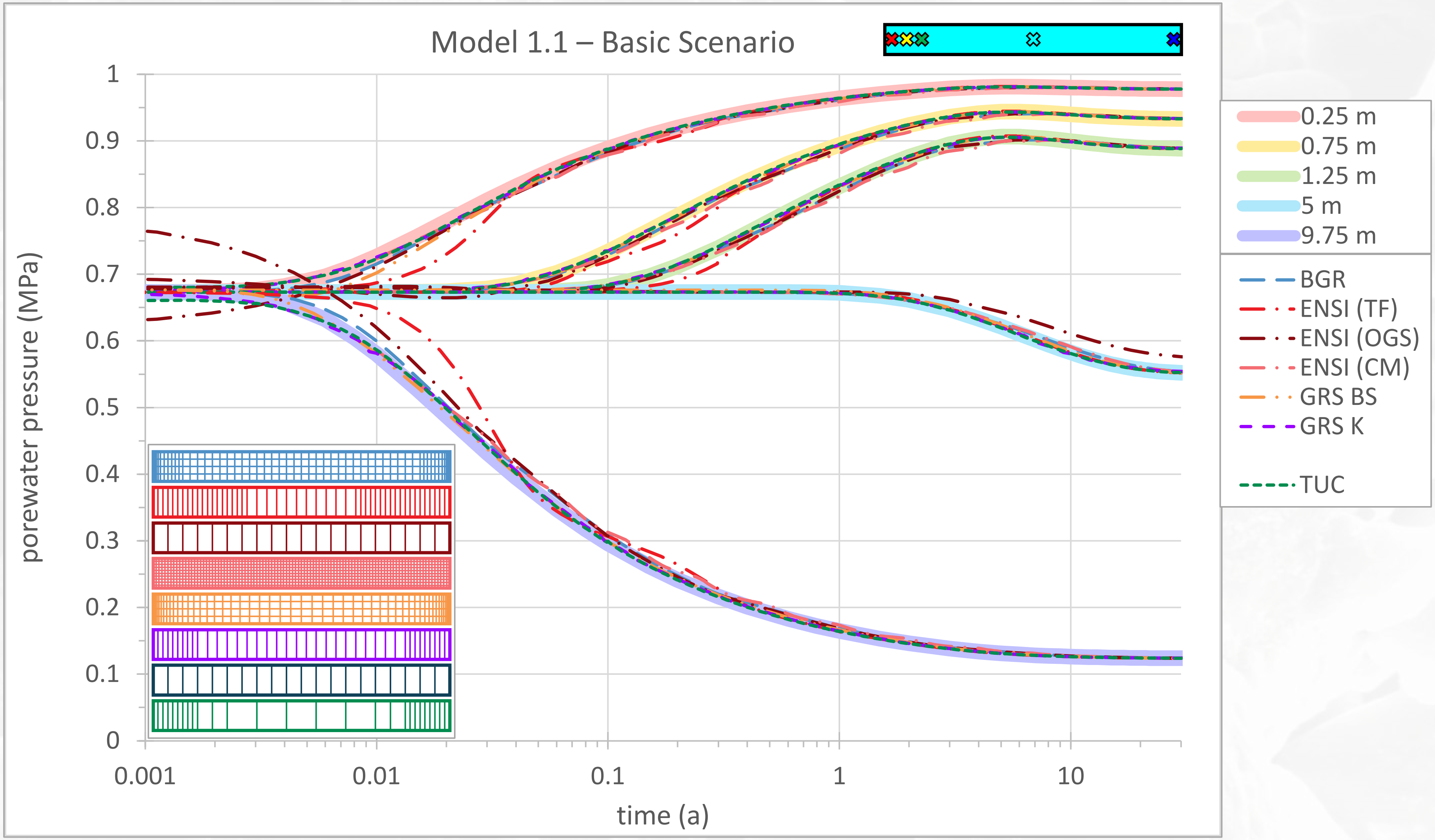
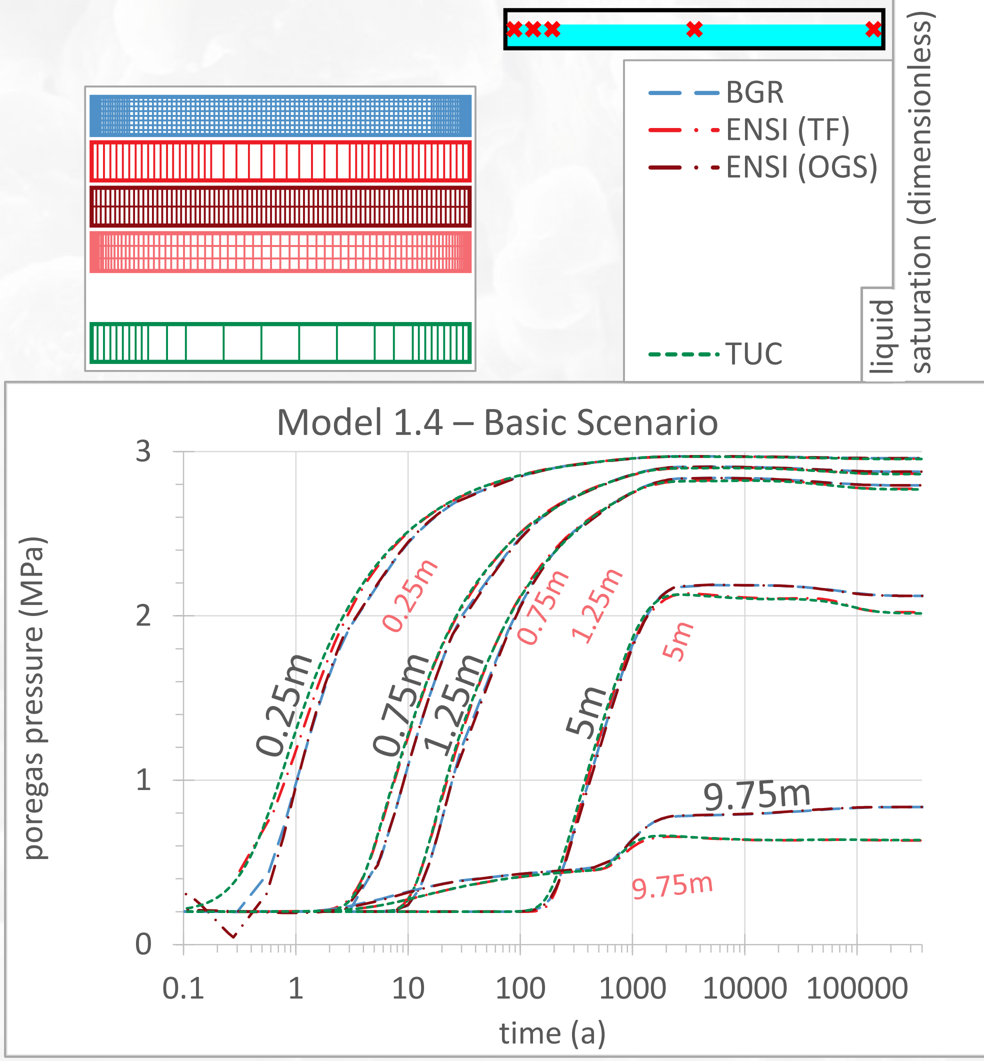
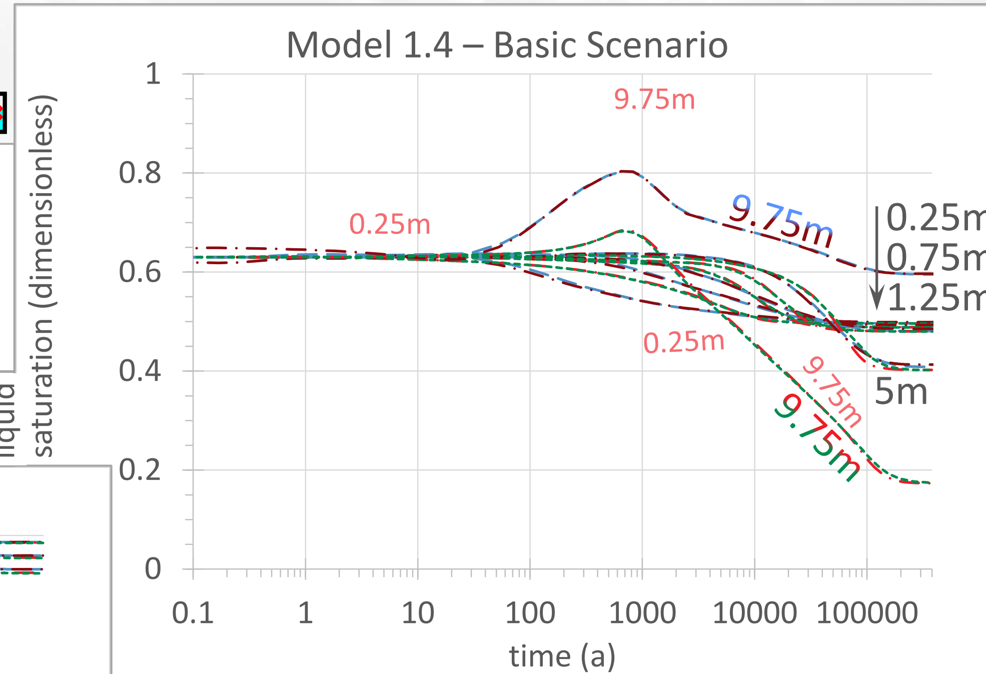
H¹M Model: Basic Scenario



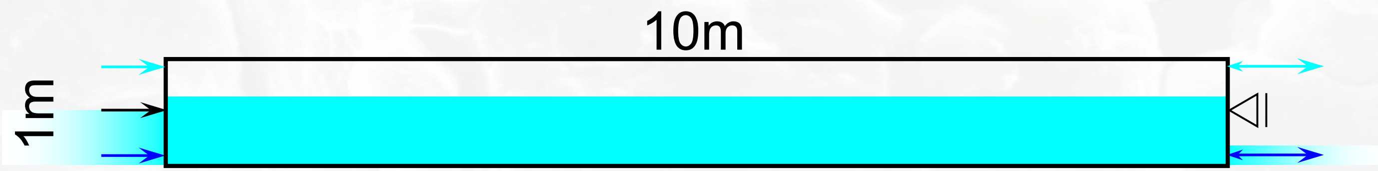
H²M Model: Basic Scenario





- gas phase balances out significantly faster than liquid phase

H²M With Matching Boundary

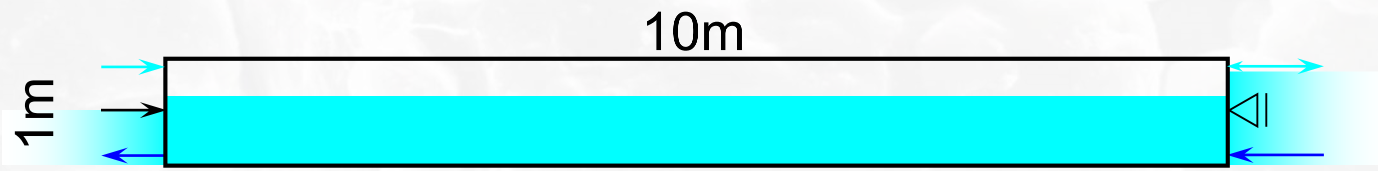


$$\sigma_{tot;lhs} = 4\ MPa \qquad \sigma_{tot0} = 4\ MPa \qquad u_{rhs} = 0\ m$$
$$p_{g;lhs} = 3\ MPa \qquad p_{g0} = 0.2\ MPa \qquad p_{g;rhs} = 0.5\ MPa$$
$$S_{l;lhs} = 0.5 \qquad S_{l0} = 0.63 \qquad S_{l;rhs} = 0.143$$

parameters			
Young's modulus	E	650	MPa
Poisson's ratio	ν	0	
Biot's coefficient	α	1	
porosity	ϕ	0.33	
intrinsic permeability	K	$2.5 \cdot 10^{-21}$	m^2
gas viscosity	η_g	$1.8 \cdot 10^{-11}$	$MPa \cdot s$
liquid viscosity	η_l	10^{-9}	$MPa \cdot s$
liquid bulk modulus	$\breve{K}_l$	2,220	MPa

$$p_{cap} \equiv 0\ MPa$$
$$K_{rel;\varphi} = S_{\varphi}$$

H²M With Phase Interactions



$$\sigma_{tot;lhs} = 4\ MPa \qquad \sigma_{tot0} = 4\ MPa \qquad u_{rhs} = 0\ m$$

$$p_{g;lhs} = 3\ MPa \qquad p_{g0} = 0.2\ MPa \qquad p_{g;rhs} = 0.5\ MPa$$

$$S_{l;lhs} = 0.5 \qquad S_{l0} = 0.63 \qquad S_{l;rhs} = 0.9$$

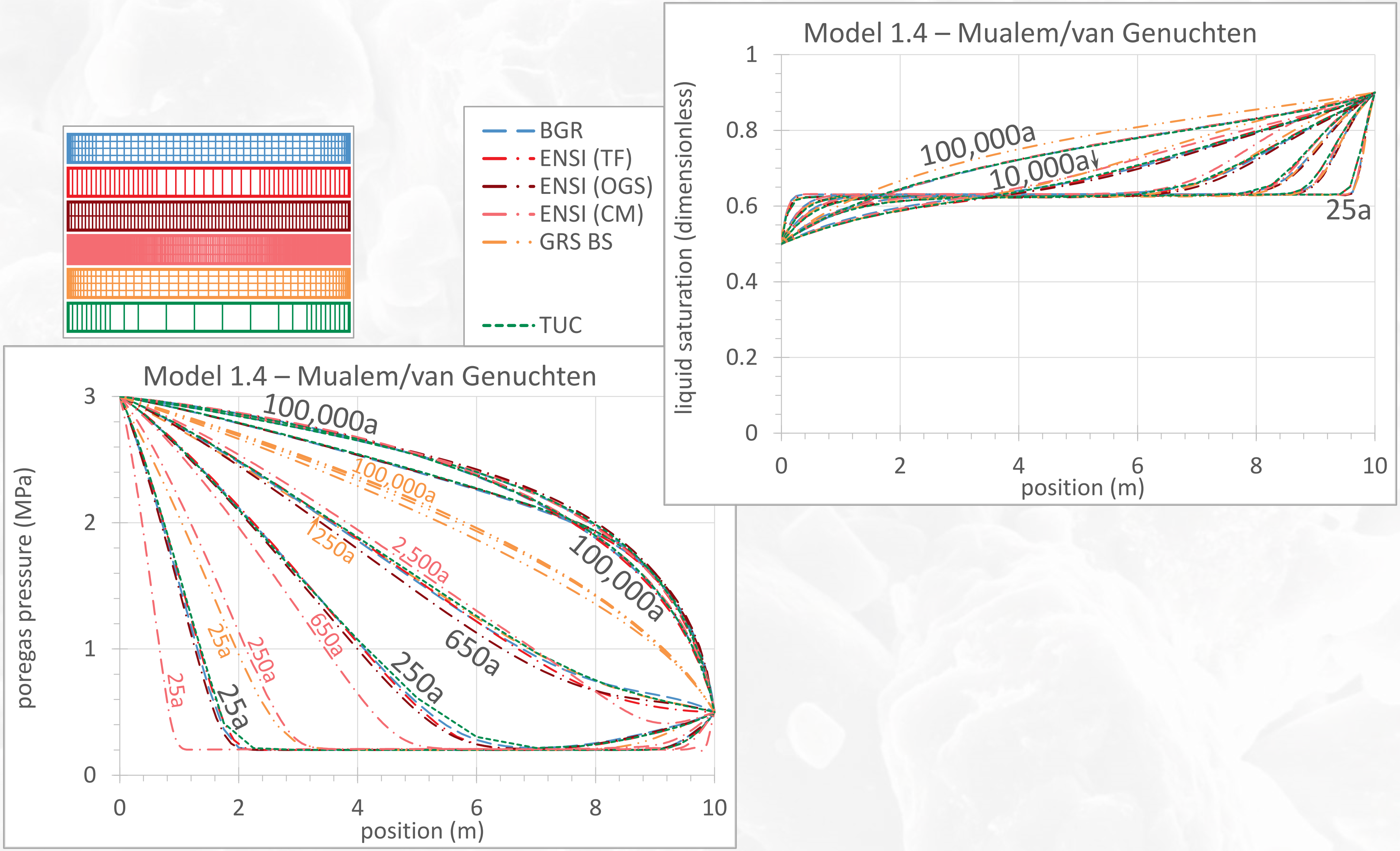
$$p_{cap} = p_{cap0}\left(S_{l;eff}^{-1/m} - 1\right)^{1-m} \qquad K_{rel;l} = S_{l;eff}^{\tilde{\varepsilon}} \cdot \left(1 - \left(1 - S_{l;eff}^{1/m}\right)^{m}\right)^{2}$$

$$K_{rel;g} = \left(1 - S_{l;eff}\right)^{\tilde{\gamma}} \left(1 - S_{l;eff}^{1/m}\right)^{2m}$$

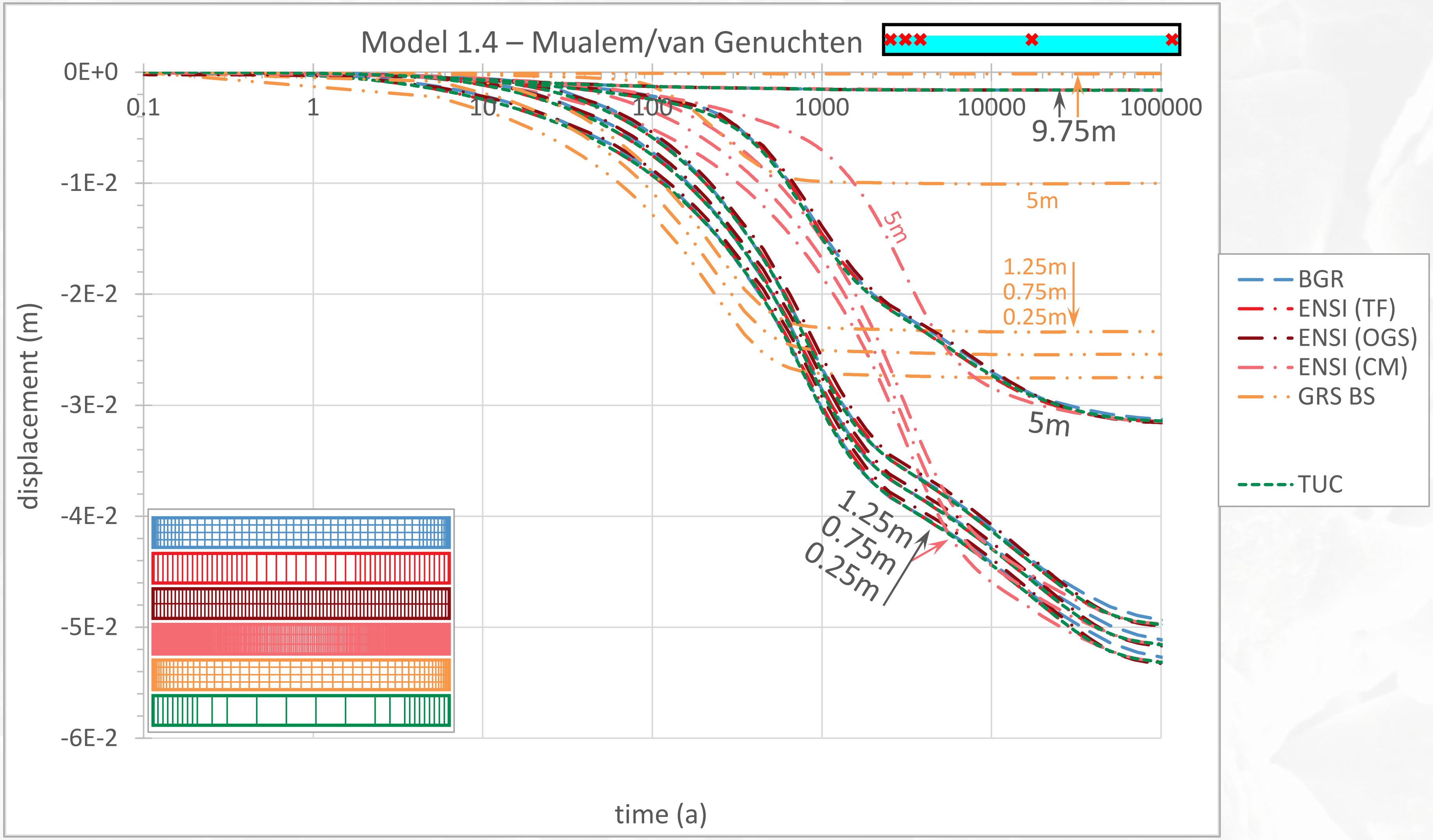
parameters as before plus			
residual liquid saturation	S_{lr}	0.02	
residual gas saturation	S_{gr}	0	
van Genuchten parameter	m	0.5	
van Genuchten pre-factor	p_{cap0}	11	MPa
pore connectivity parameters	$\tilde{\varepsilon} \mid \tilde{\gamma}$	0.5	

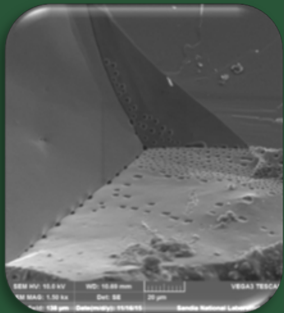
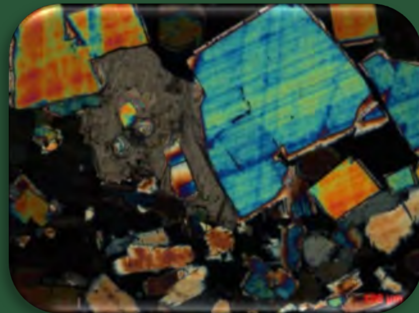
Mualem/ van Genuchten

H²M With Phase Interactions



H²M With Phase Interactions



Two-phase fluid flow calculations for a complex nuclear repository in a rock salt host formation

Ingo Kock, Martin Navarro, Guido Bracke

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH

Rapid City, SD, United States

May 28-30, 2019

Outline

A complex nuclear repository

Methods & Models

Results

Conclusions

A complex nuclear repository:

Case Study: Endlager für radioaktive Abfälle Morsleben (ERAM)

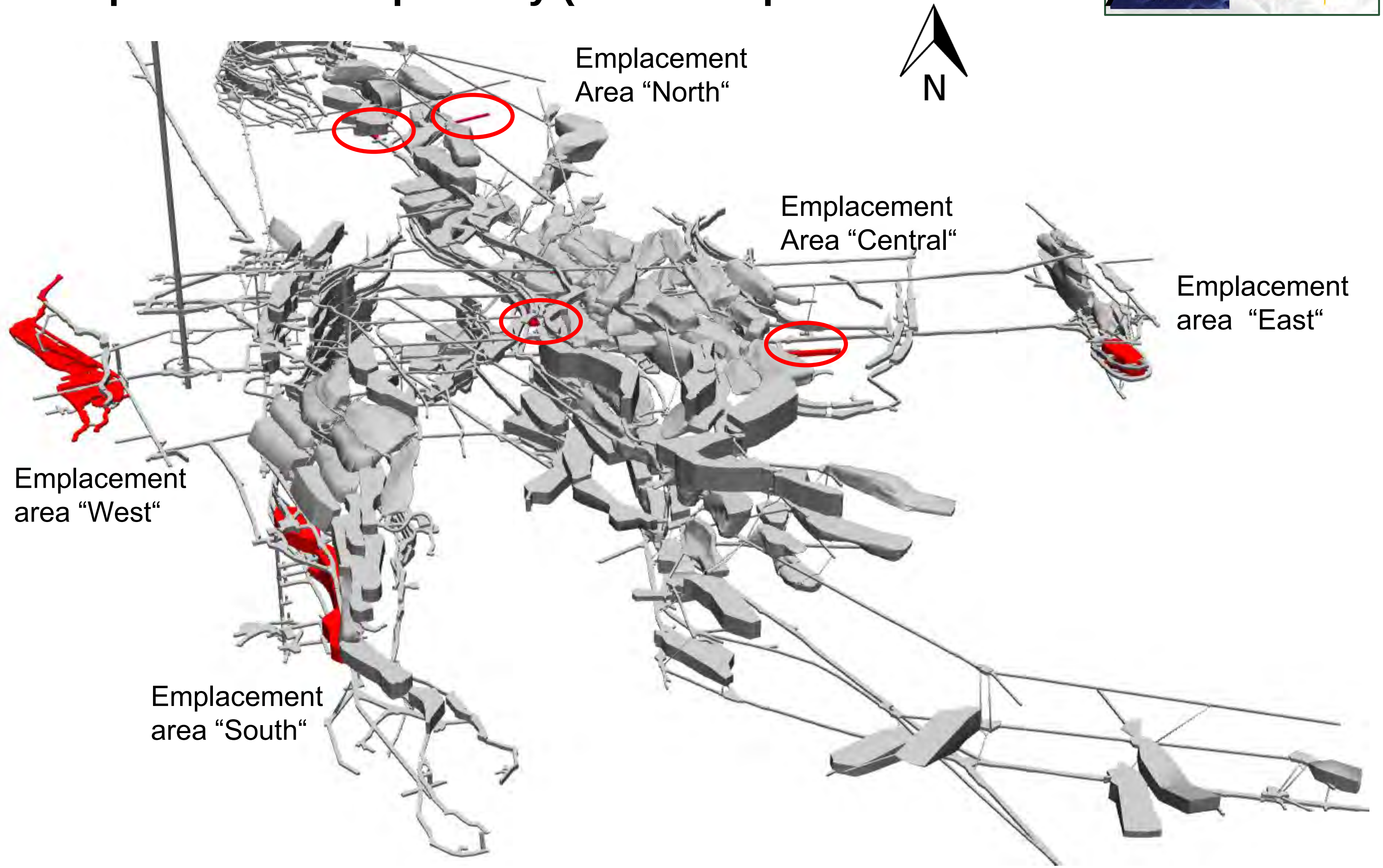
- Shallow (~400 m) LLW/ILW waste repository
- Complex mine layout/geometry: Salt mine from 1897/1910 to 1969
- Emplacement of waste started in 1971 and (with interruptions) finished in 1998
- From 1971 to 1998: emplacement of approx. 37 000 m³ LLW und ILW
- Activity: approx. $6x10^{14}$ Bq (as of 30.06.2005)

Detailed information available:

- Decommissioning concept and plan
- Radionuclide inventory
- Gas generation
- Mine layout
- Scenarios
- Calculations for long-term safety

➔ Focus on 3D Two-Phase Fluid Flow calculations

A complex nuclear repository (Southern part Bartensleben)



Modified from Kock et al. 2016

Model assumptions (based on existing long-term safety analysis)

- Most of the mine is accessible for fluids (liquid & gas)

  ➔ two emplacement areas with radioactive waste: “North“ & “Central“

- Other emplacement areas are isolated with 16 engineered barriers with a permeability of $1x10^{-18}$ m²: “South”, “West” & “East”
- Repository planned to be backfilled with salt concrete
- Salt rock convergence is slow, but will eventually close gaps between backfill and the tunnel roof
- 2 scenarios: “**dry**” and “**significant** brine inflow”
- The inflowing brine may corrode / alter barriers, permeability increases to $1x10^{-14}$ m²
- The host rock (rock salt) is considered to be impermeable (except for potential inflow locations)

Code and calculations

<u>TOUGH2 (LBNL) with GRS extensions</u>

- Porosity & permeability decrease with time und pressure
- Canisters can be gas source: corrosion by water/brine consumption
- Barrier alteration

<u>3D two phase flow calculations</u>

3 different meshes: “basic”, “enhanced”, “complex”

Complex mesh incorporates the mine’s

- volume, depth, length
- multi-floor pillar and room structure

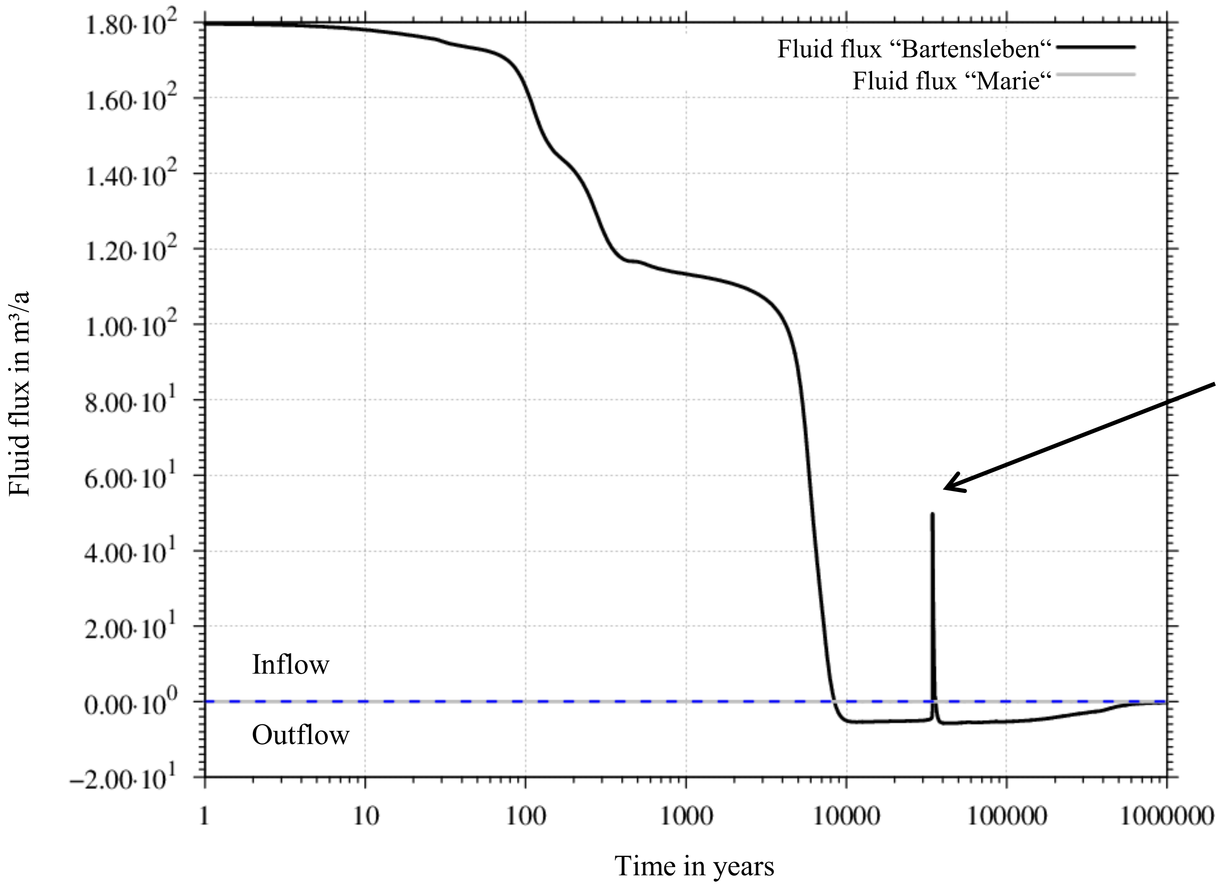
- ^{14}C in CH_4 as gaseous nuclide (half-life: 5730 ys)
- 34 other nuclides with a half-life > 500 a are considered.
- 2 scenarios with deterministic parameter variations ➔ 700 deterministic model runs
- 400 probabilistic model runs

Basic model

Enhanced model

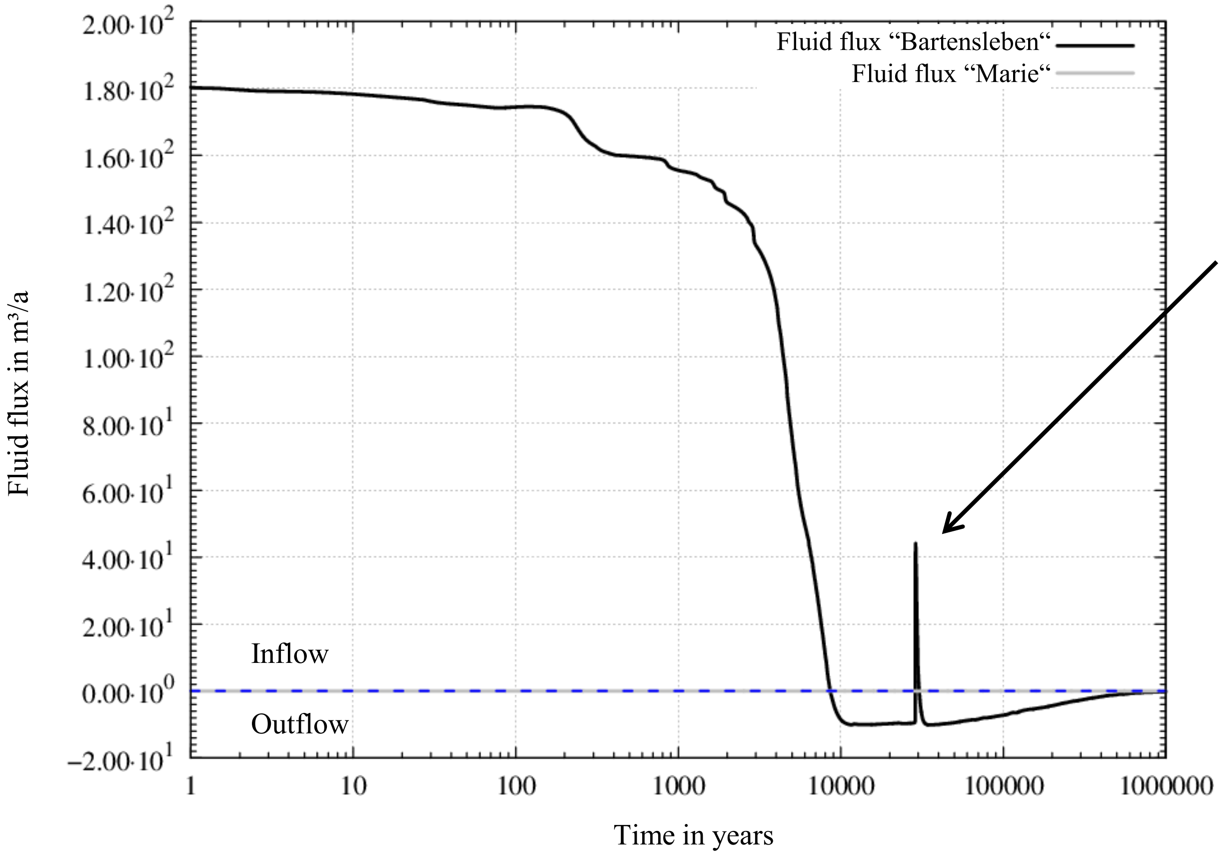
Complex model

Basic model with fluid inflow scenario



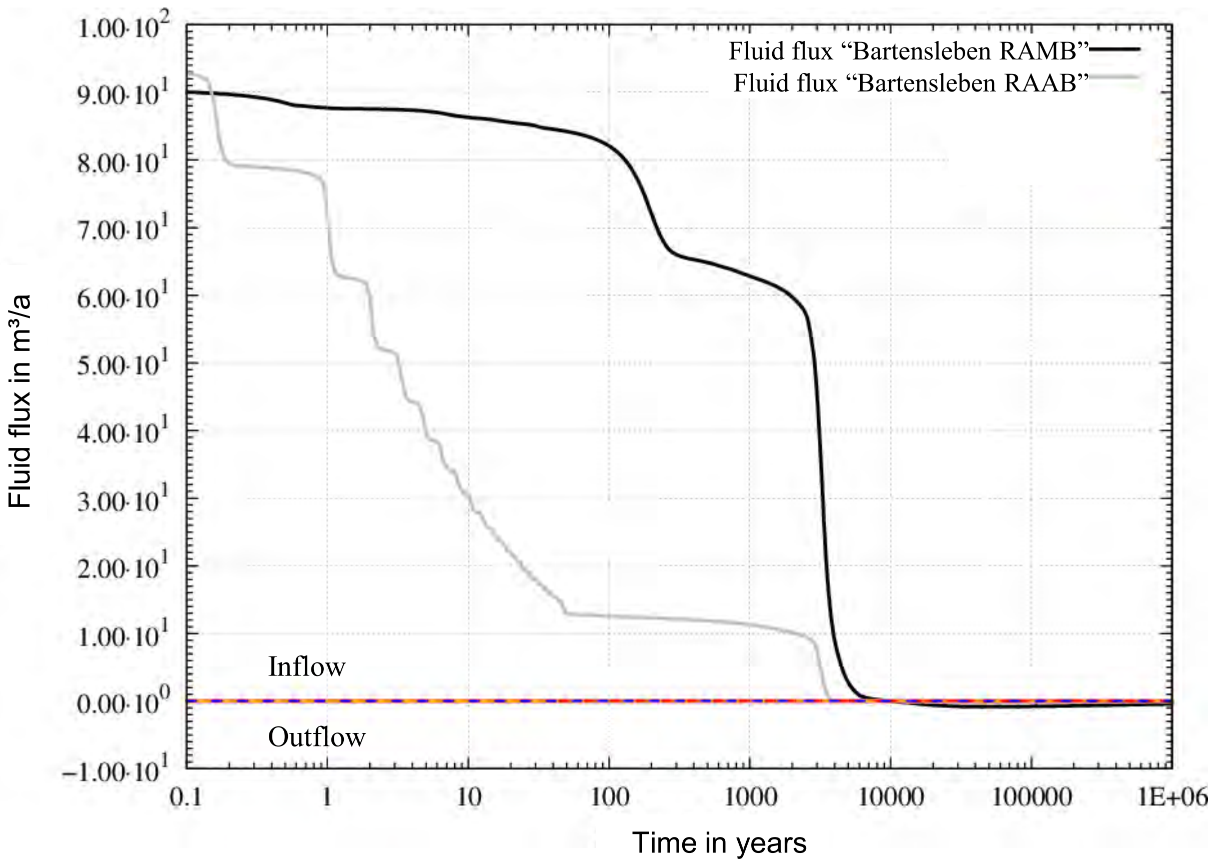
- Only inflow for "Bartensleben" part active
- In less than 10 000 ys the open mine areas are filled with brine.
- After ~34 000 ys barrier to repository area „South" is corroded ➔ short but strong inflow event.
- After ~45 000 ys radionuclides are transported out of „South"

Enhanced model with fluid inflow scenario



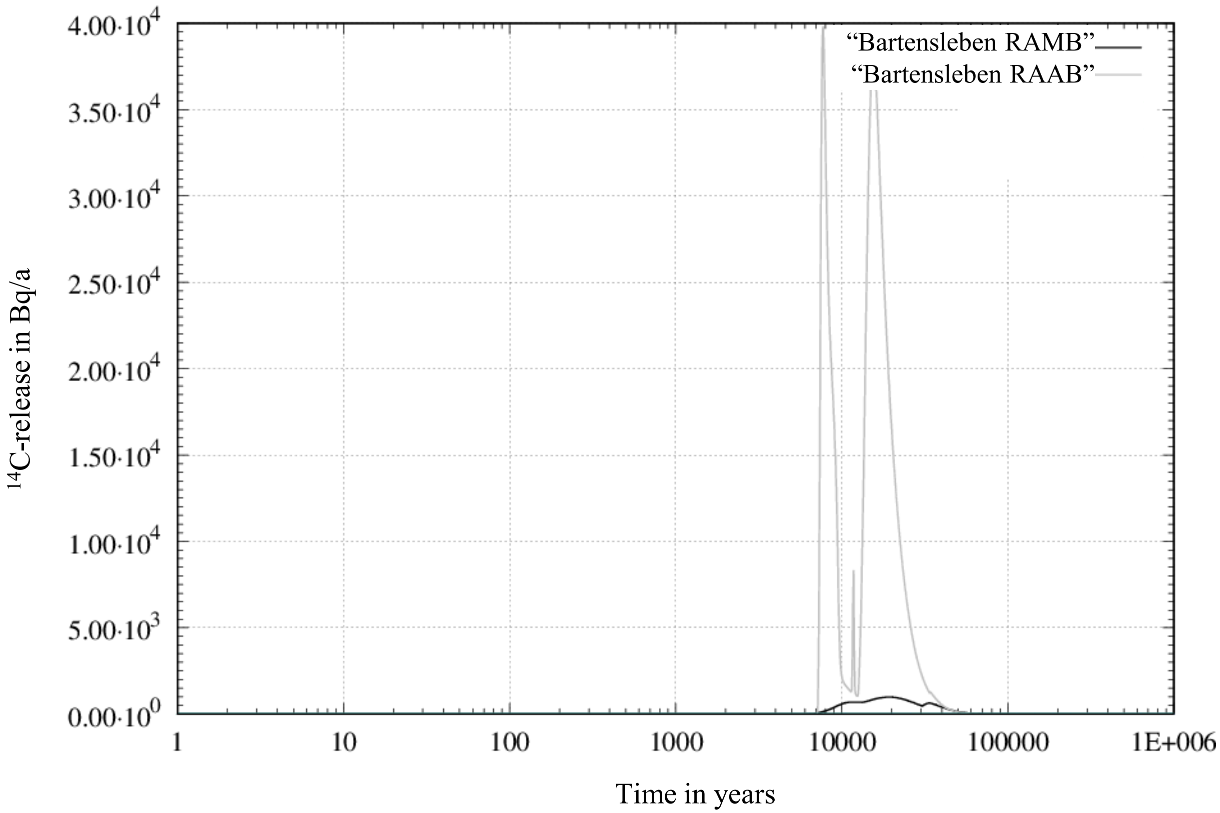
- Almost identical results compared to basic model
- Barrier corrosions finishes a bit earlier after ~30 000 ys
- Short but strong inflow event therefore occurs earlier (compared to basic model)

Complex model with fluid inflow scenario



- Only inflow for "Bartensleben" part active, but for both locations
- In about 10 000 ys the open mine areas are filled with brine.
- Low but constant outflow
- Corrosion of barriers takes a long time: ~389 000 ys.
- Also:
  - gas flow out of the repository
  - ~ 2 m³/a (but peak at 17 m³/a)

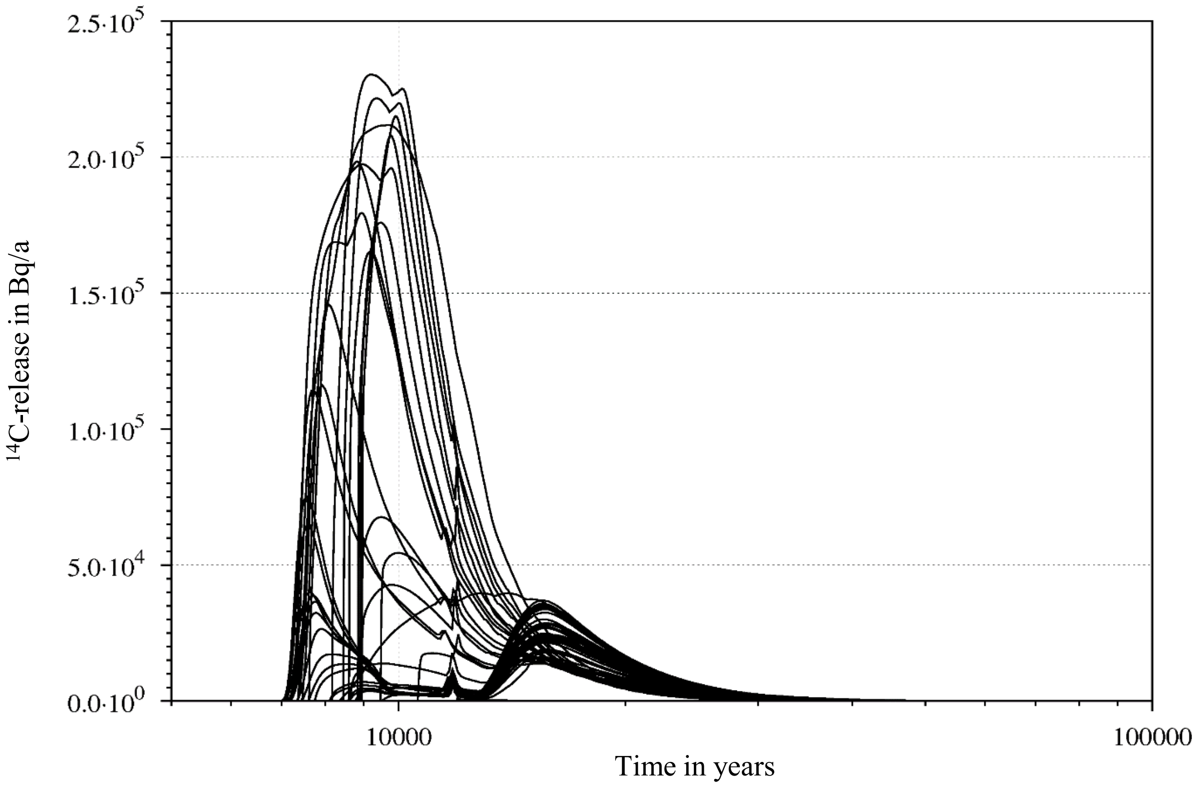
Complex model: 14C-release (gas & liq.)



- Release occurs at two postulated inflow locations of "Bartensleben"
- Release differs strongly between these two locations
- Reason is that "RAAB" is directly located 4 floors above emplacement area "North"

Complex Model, Inflow scenario

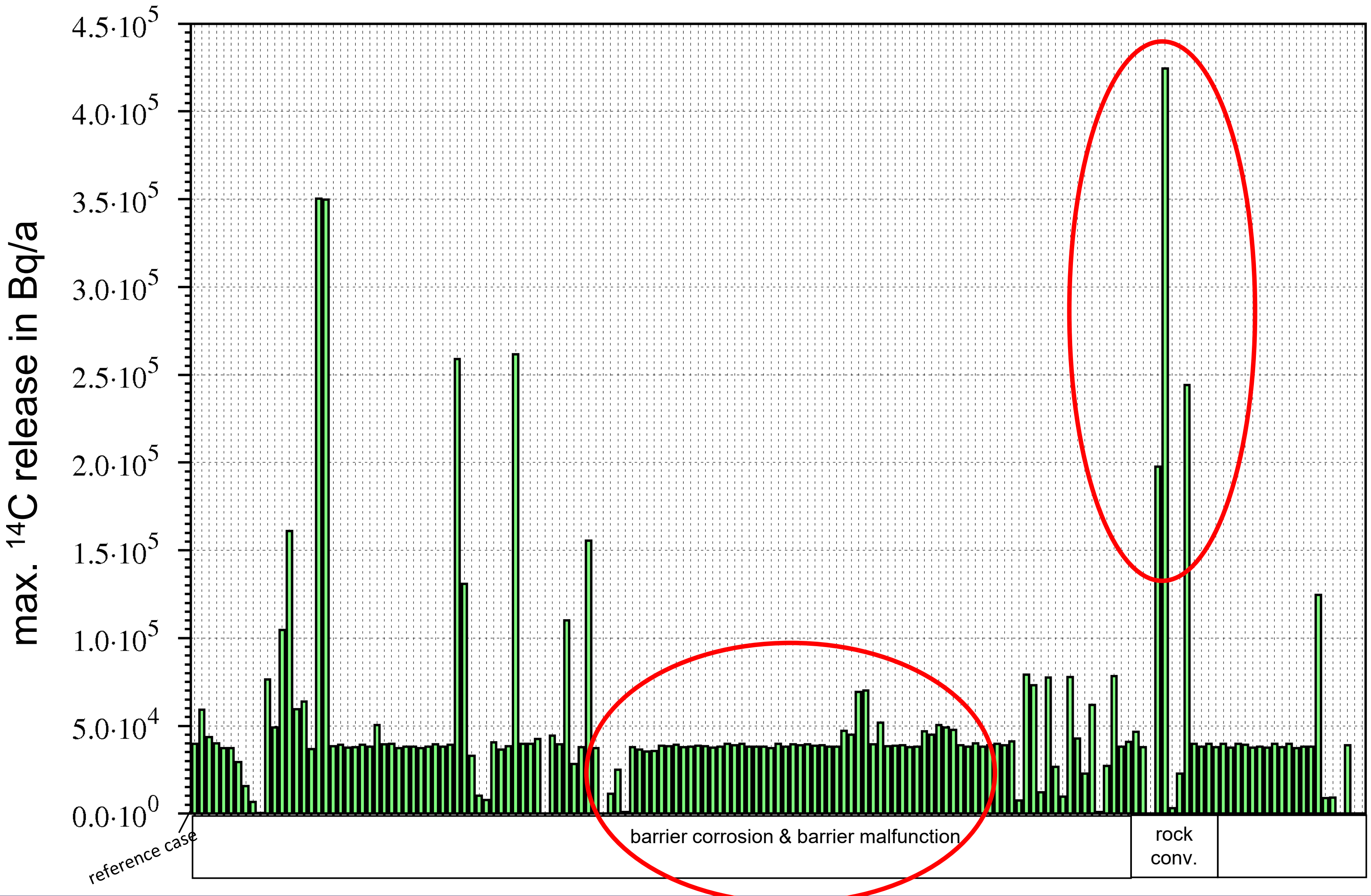
Probabilistic variations of Two-Phase Flow parameters (van-Genuchten)



- 100 model runs
- Release at “Bartensleben RAAB”
- Parameter variations:
  - Residual gas saturation
  - entry pressure (P_0) of Backfill / Barriers
  - “m” parameter
- Significant (sensitivity analysis) parameters:
  - Gas entry pressure of backfill
  - Residual gas saturation

All deterministic parameter variations (max 14C release)

Bartensleben RAAB



Conclusions

- In a complex repository geotechnical barriers do not necessarily govern the repository’s behavior completely throughout its lifetime

- In our case, the backfill and salt rock convergence show a significant influence on the repository’s behavior.

Why?

- Even if a barrier has malfunctioned from the beginning:
  - the (backfilled) pathway to the potential outflow location is far away
  - the permeability decreases in the backfill

➔ radionuclides (^{14}C) decay before they reach the outflow location

Thank you for your attention!

Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (for financial support; No: UM13A03400)

BfS (partly now Bundesgesellschaft für Endlagerung, BGE) and its subcontractors for answering many questions regarding the ERAM

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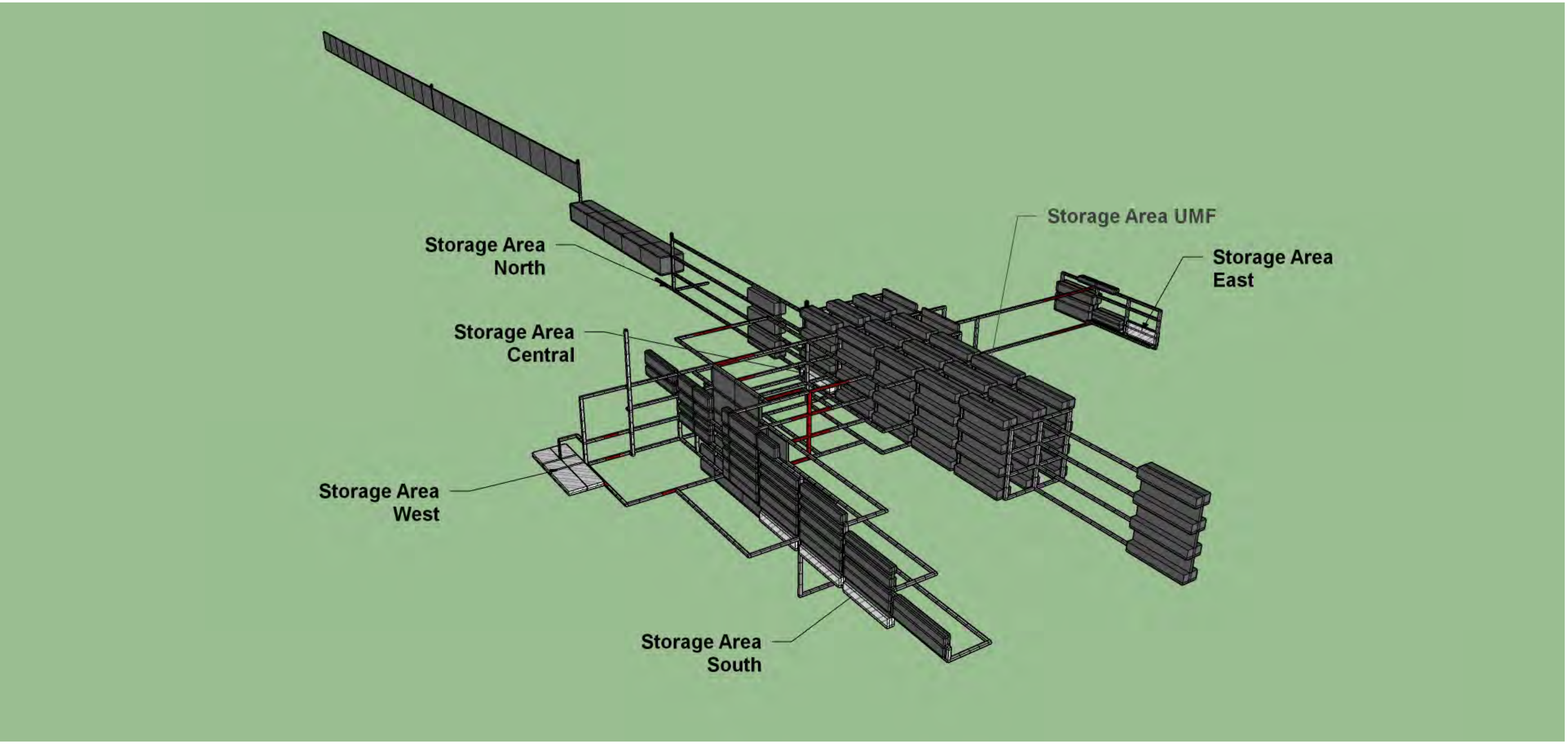
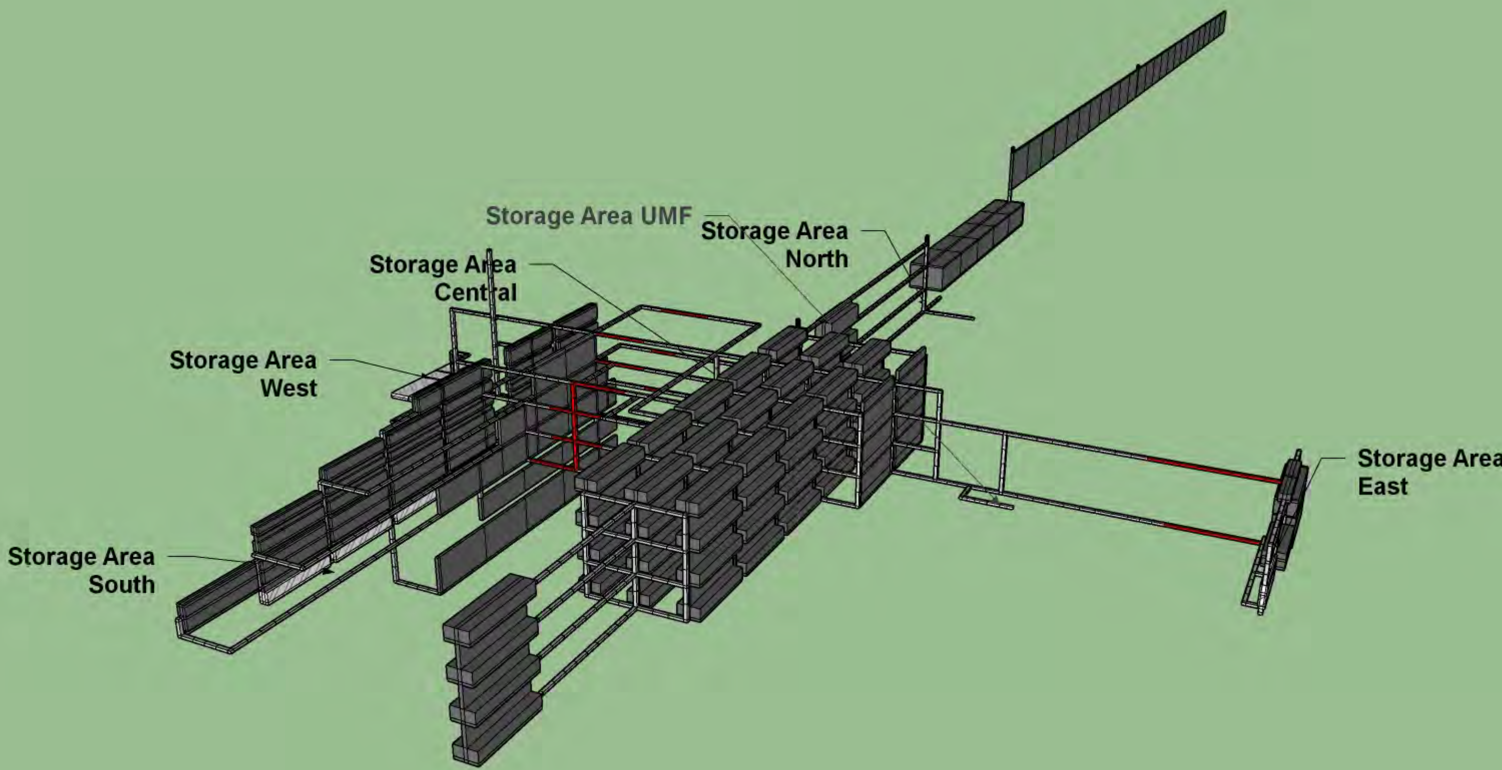
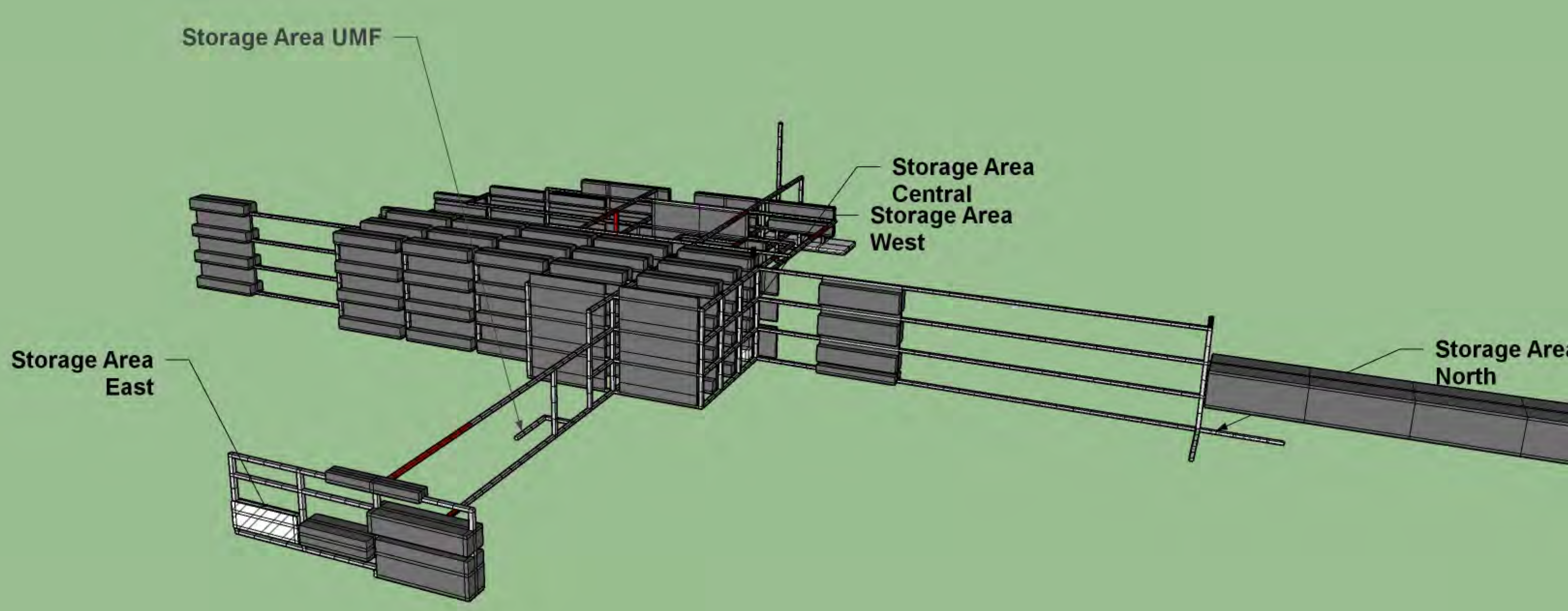
Kock I, Frieling G, Navarro M (2016) Fluidströmung und Radionuklidtransport in komplexen Endlagerbergwerken: Synthesebericht Teil 1/2. Zweiphasenfluss in einem salinaren Endlager am Beispiel des ERAM, GRS-399. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln

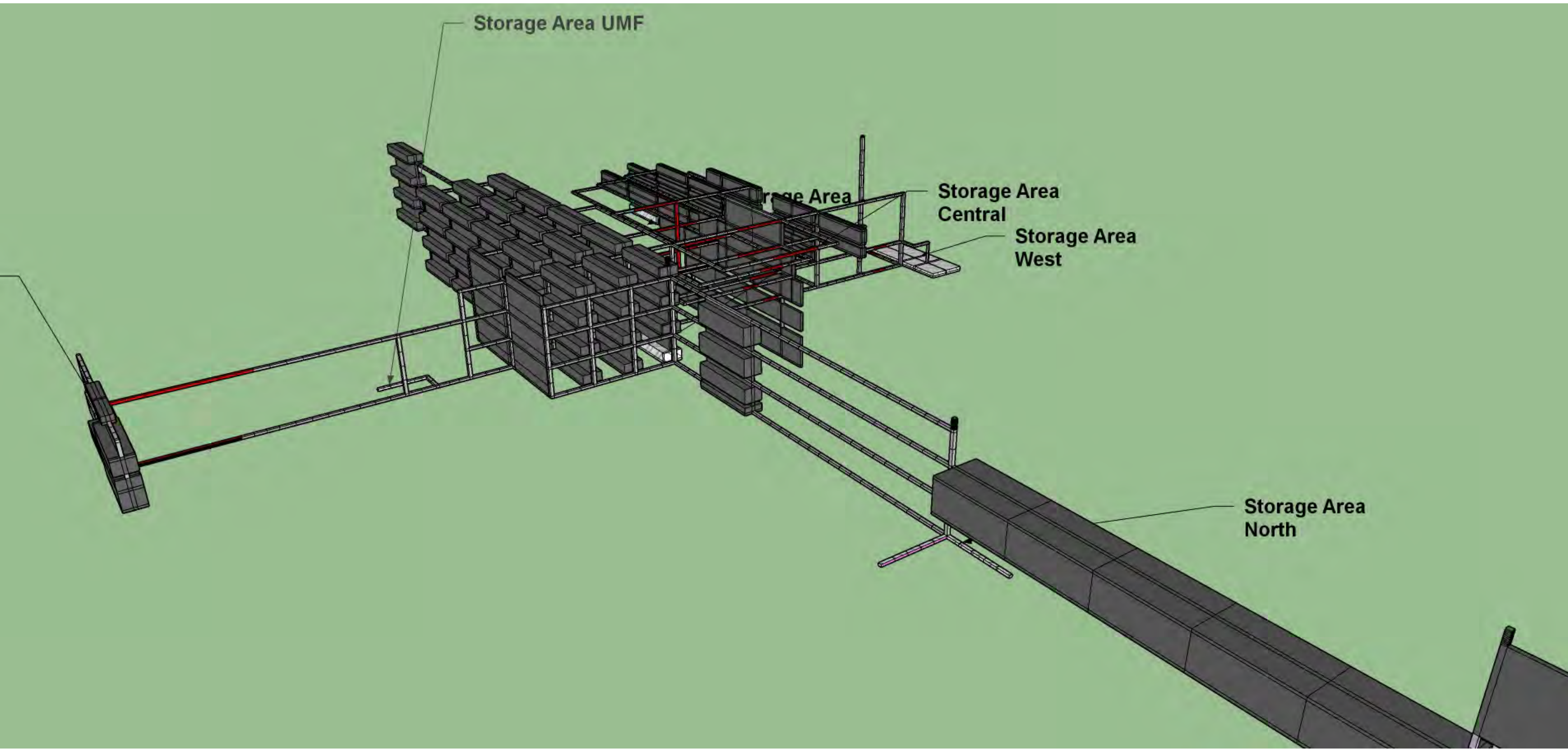

Storage Area UMF
Storage Area North
Storage Area East
Storage Area Central
Storage Area West
Storage Area South

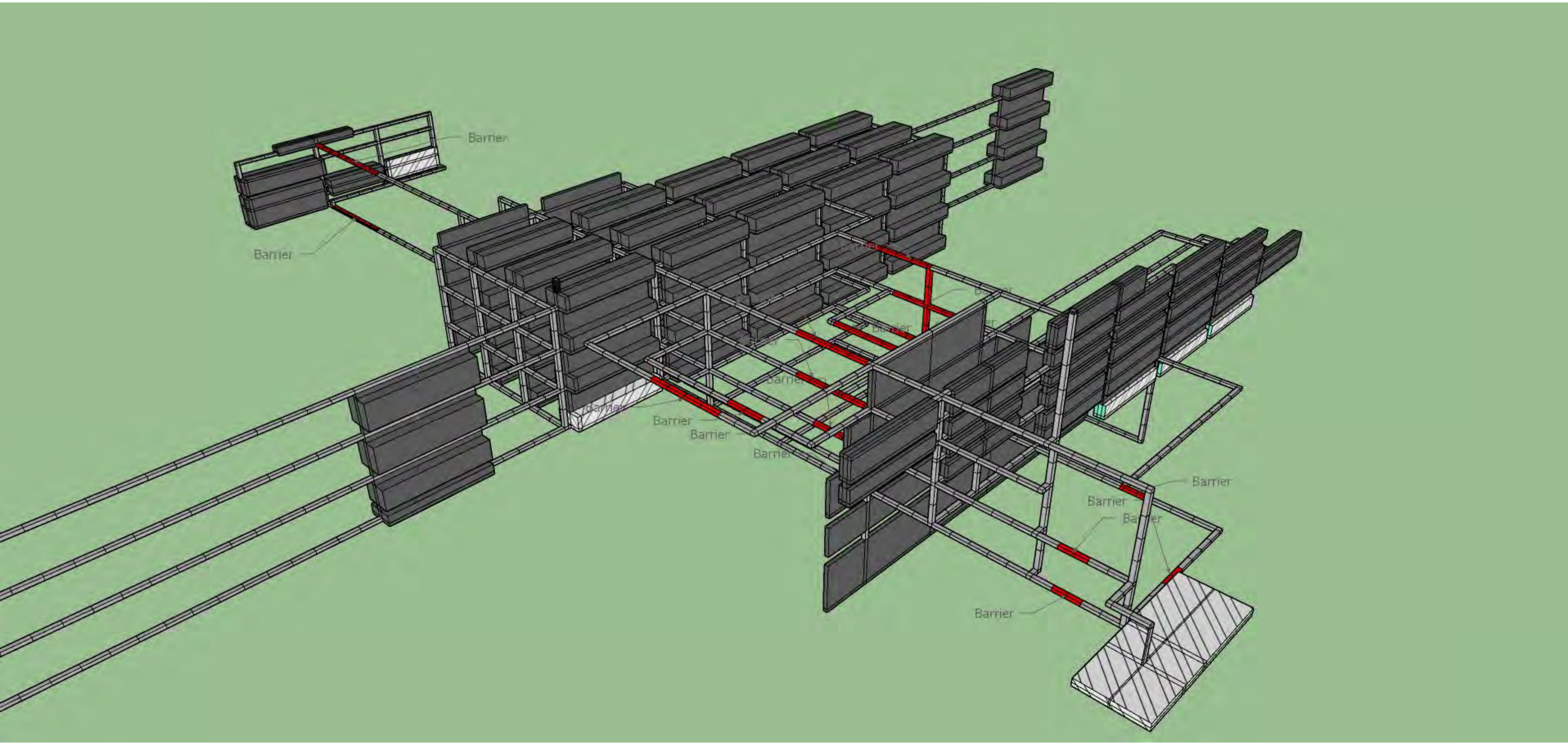


Storage Area UMF
Storage Area North
Storage Area Central
Storage Area West
Storage Area South
Storage Area East



Storage Area UMF
Storage Area Central
Storage Area West
Storage Area East
Storage Area North


Storage Area UMF
Storage Area
Central
Storage Area
West
Storage Area
North


Barrier
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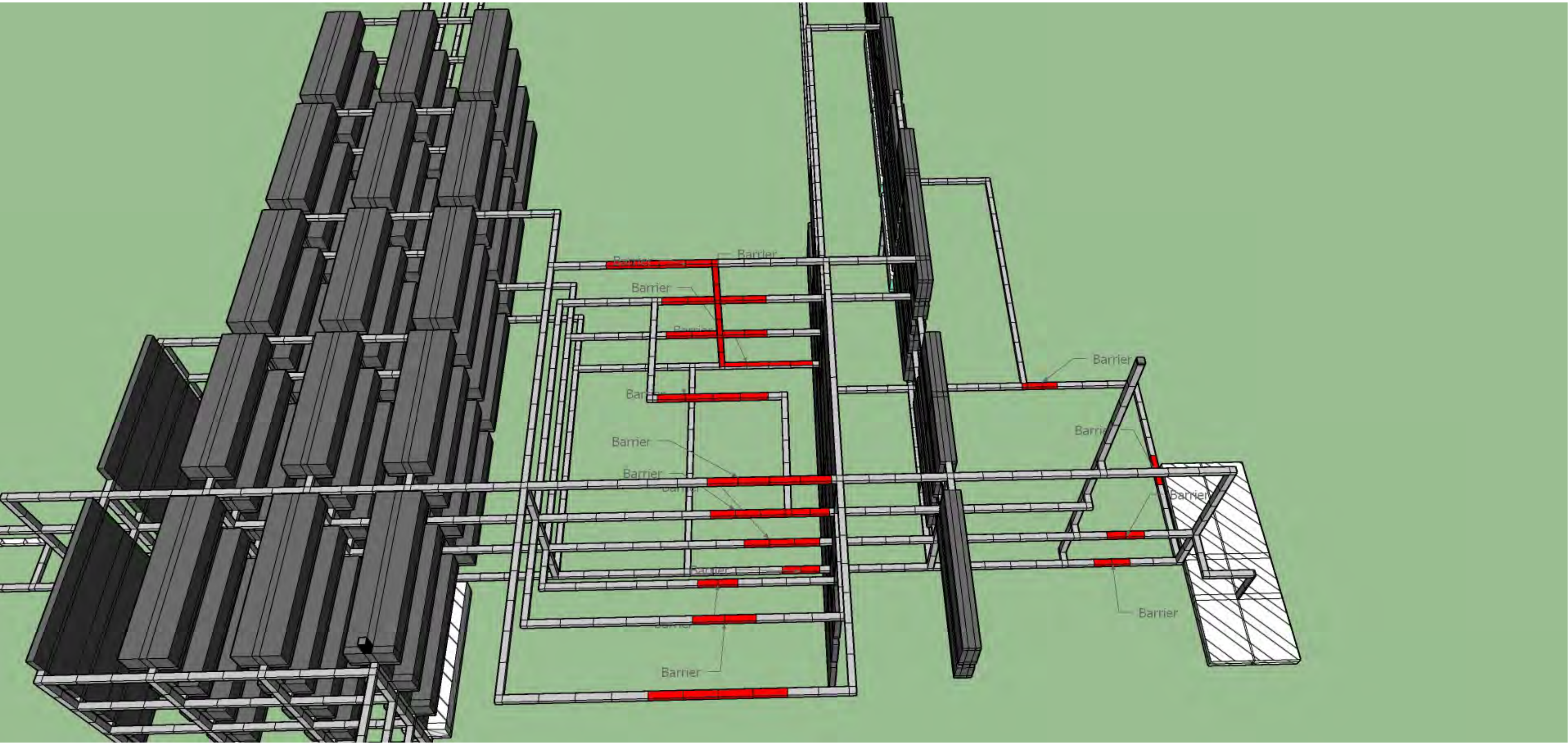
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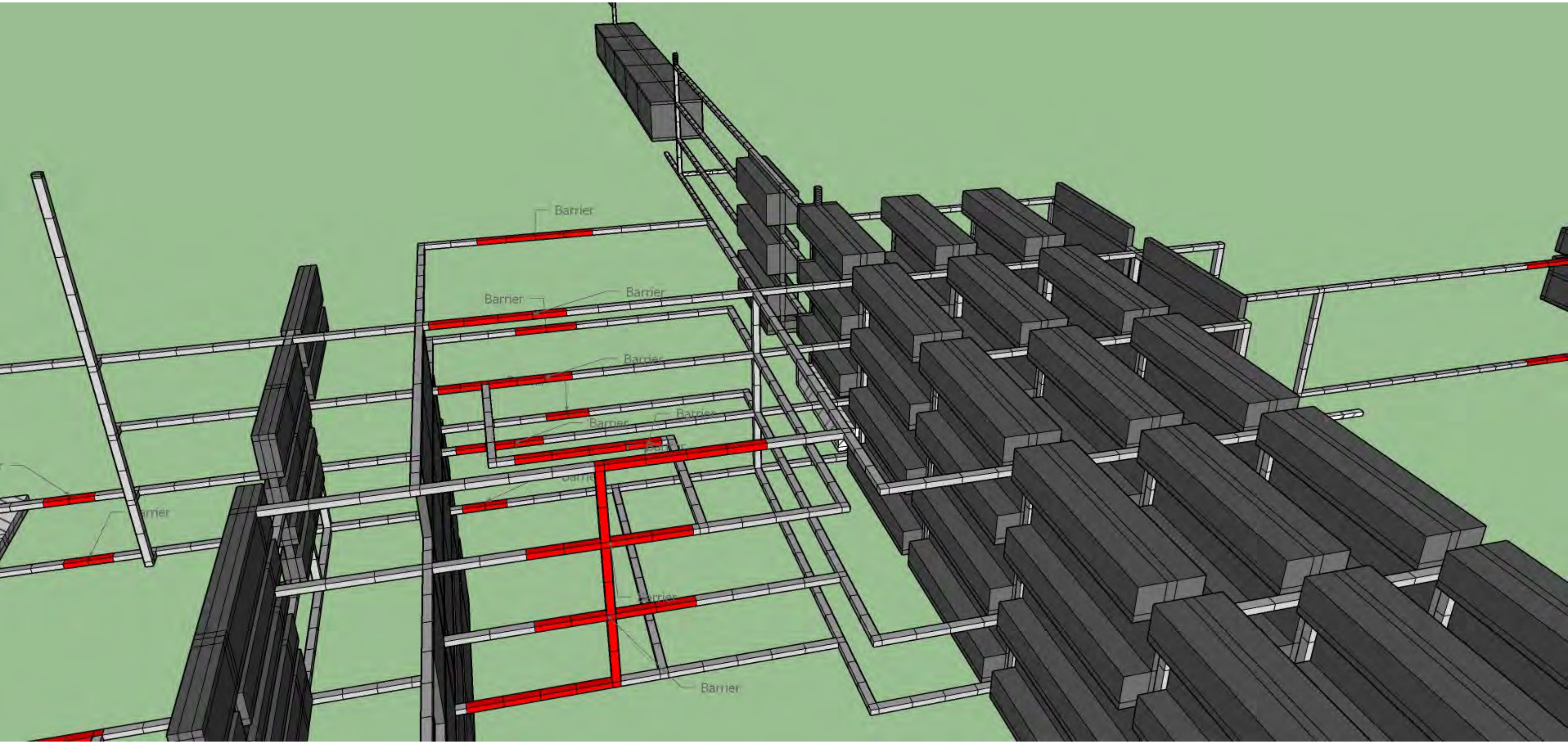
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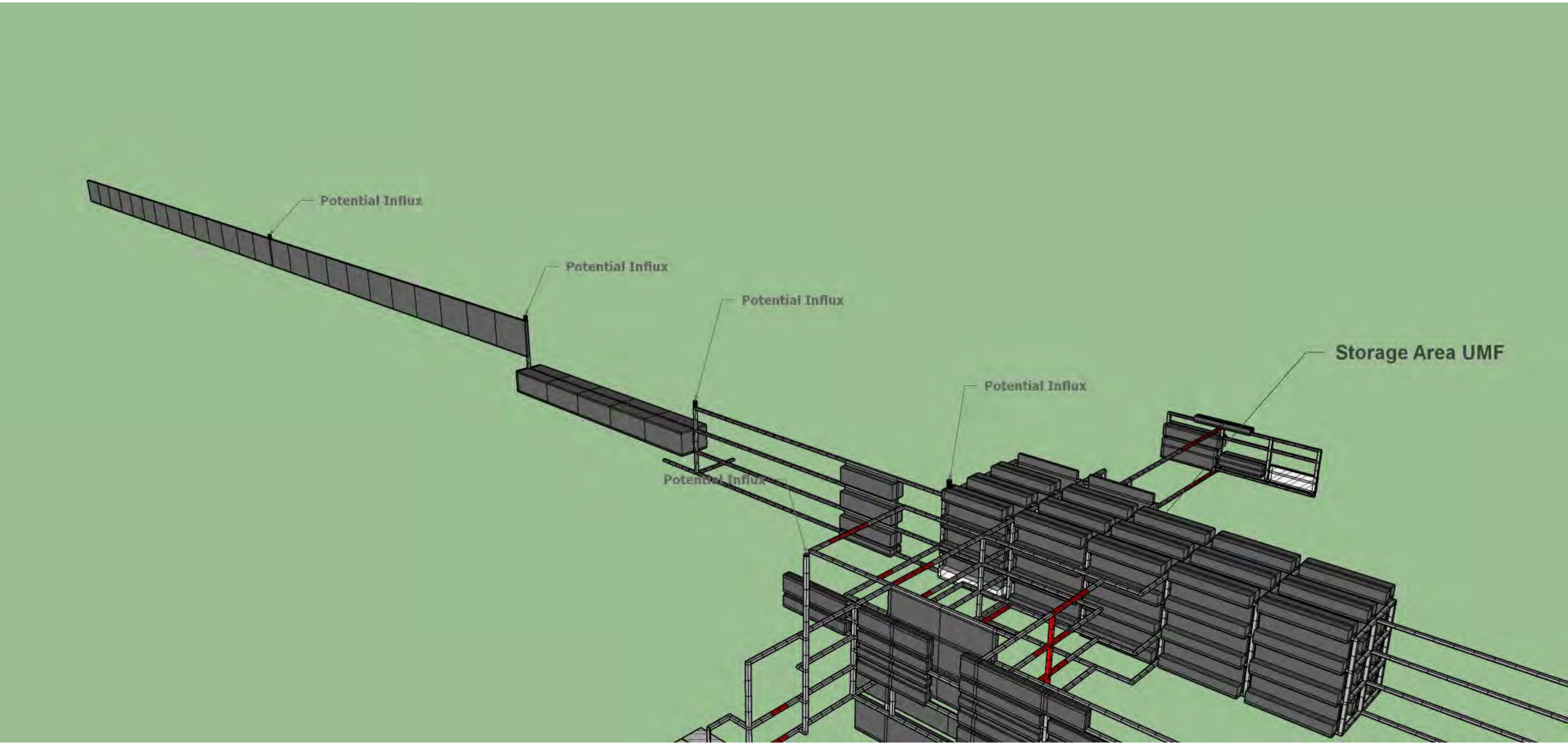
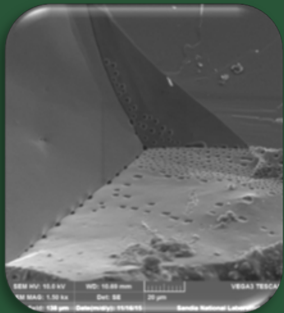
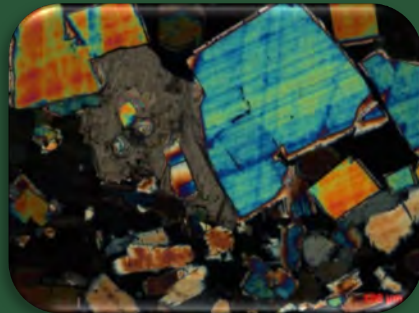


Potential Influx
Potential Influx
Potential Influx
Storage Area UMF
Potential Influx
Potential Influx

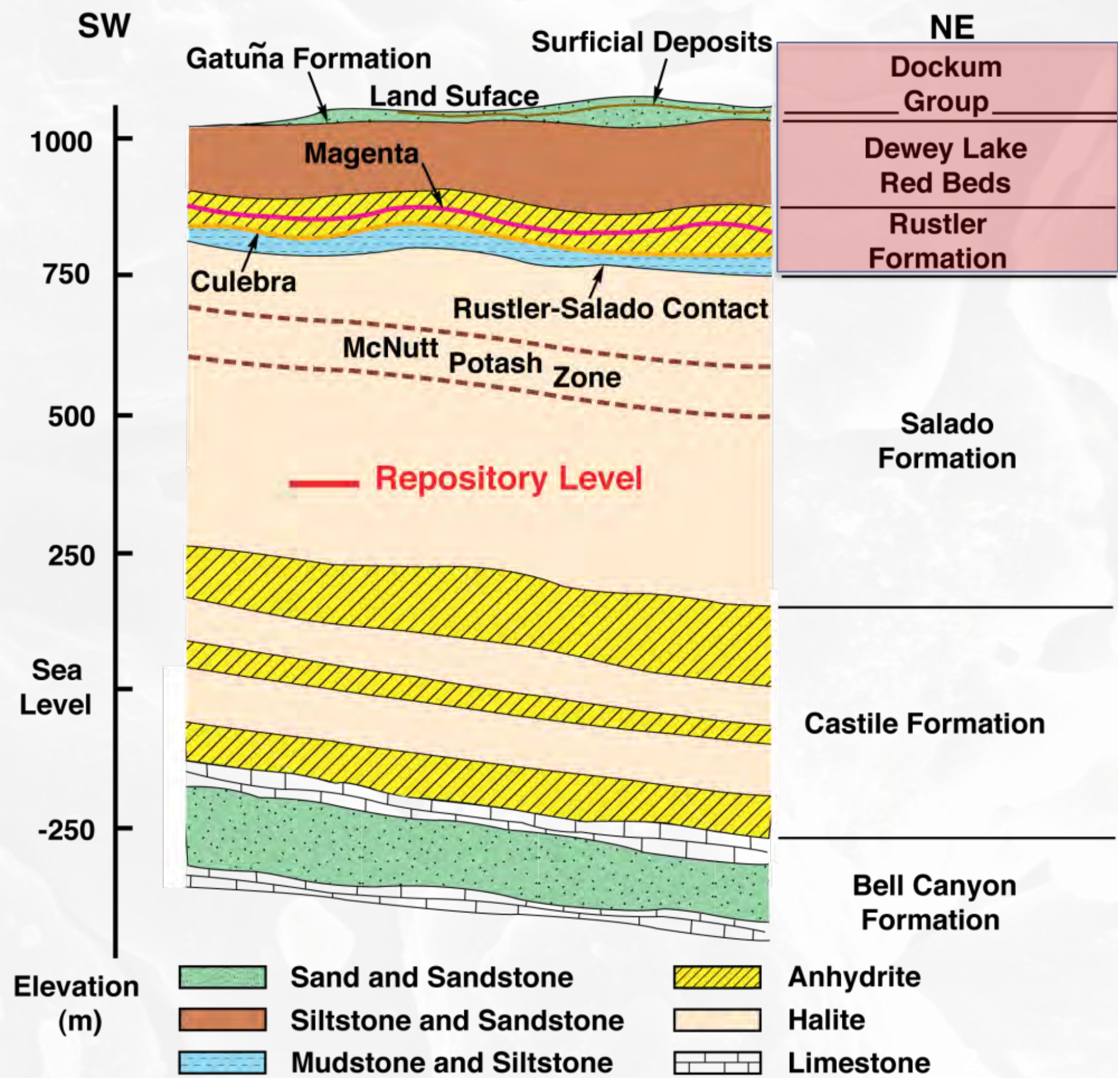
Basin-Scale Density-Dependent Groundwater Flow

Jens Wolf, Anke Schneider
Gesellschaft für Anlagen- und Reaktorsicherheit
Kristopher L. Kuhlman
Sandia National Laboratories

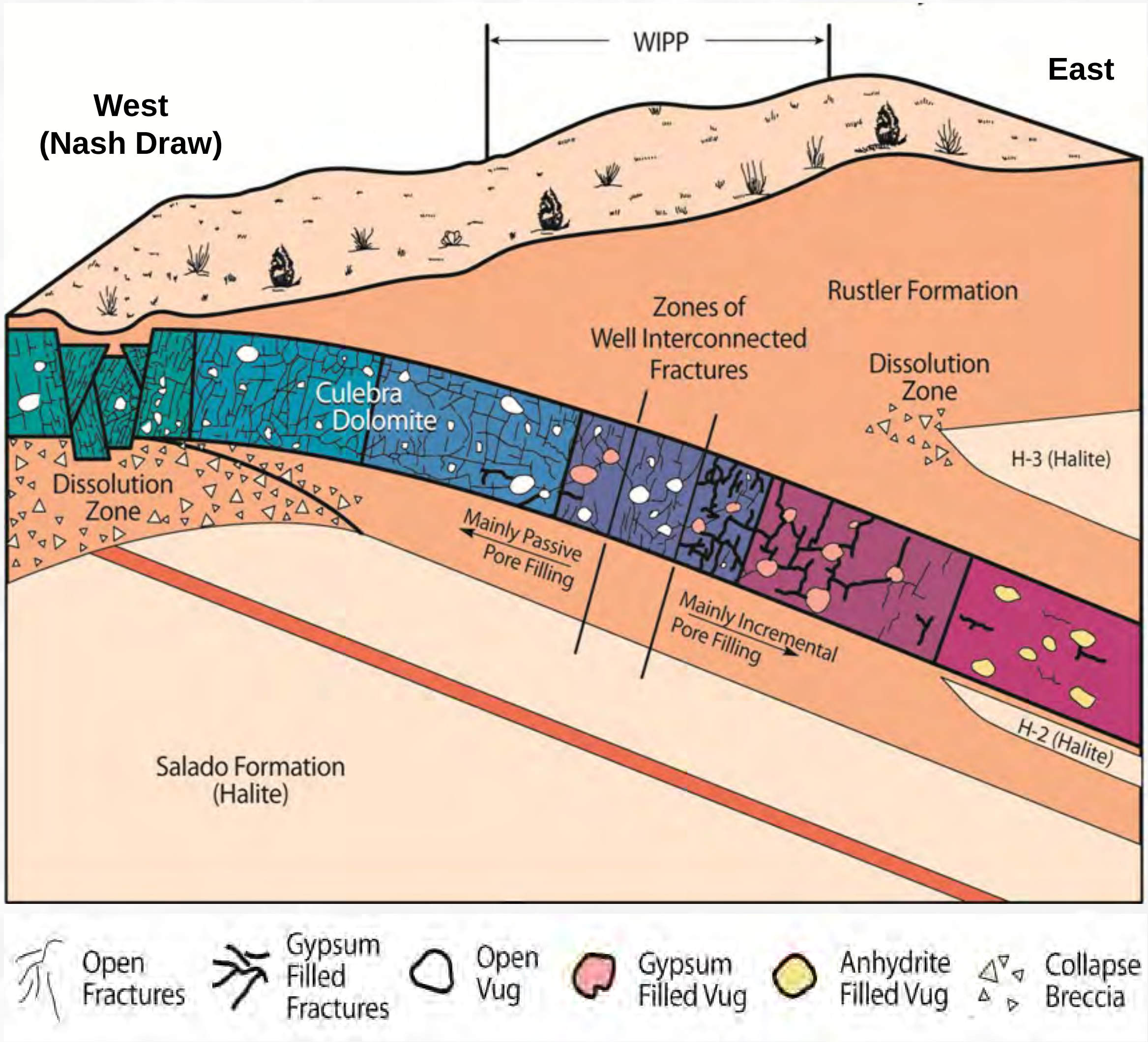
Rapid City, SD, United States
May 28-30, 2019

WIPP Hydrogeology

- Repository in Salado bedded salt formation
  - >500-m thick salt unit
- Hydrogeology of formations above salt
  - Rustler Formation
    - Culebra dolomite
    - Magenta dolomite
    - Anhydrite
    - Mudstone/Halite
  - Dewey Lake Red Beds
    - Silt/sand stones + clay
  - Dockum Group
    - Silt/sand stones + clay

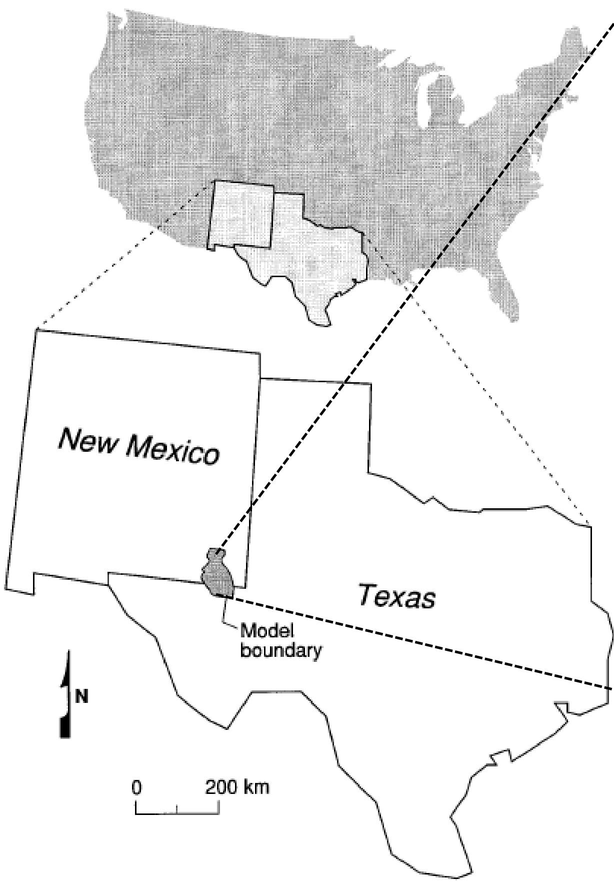


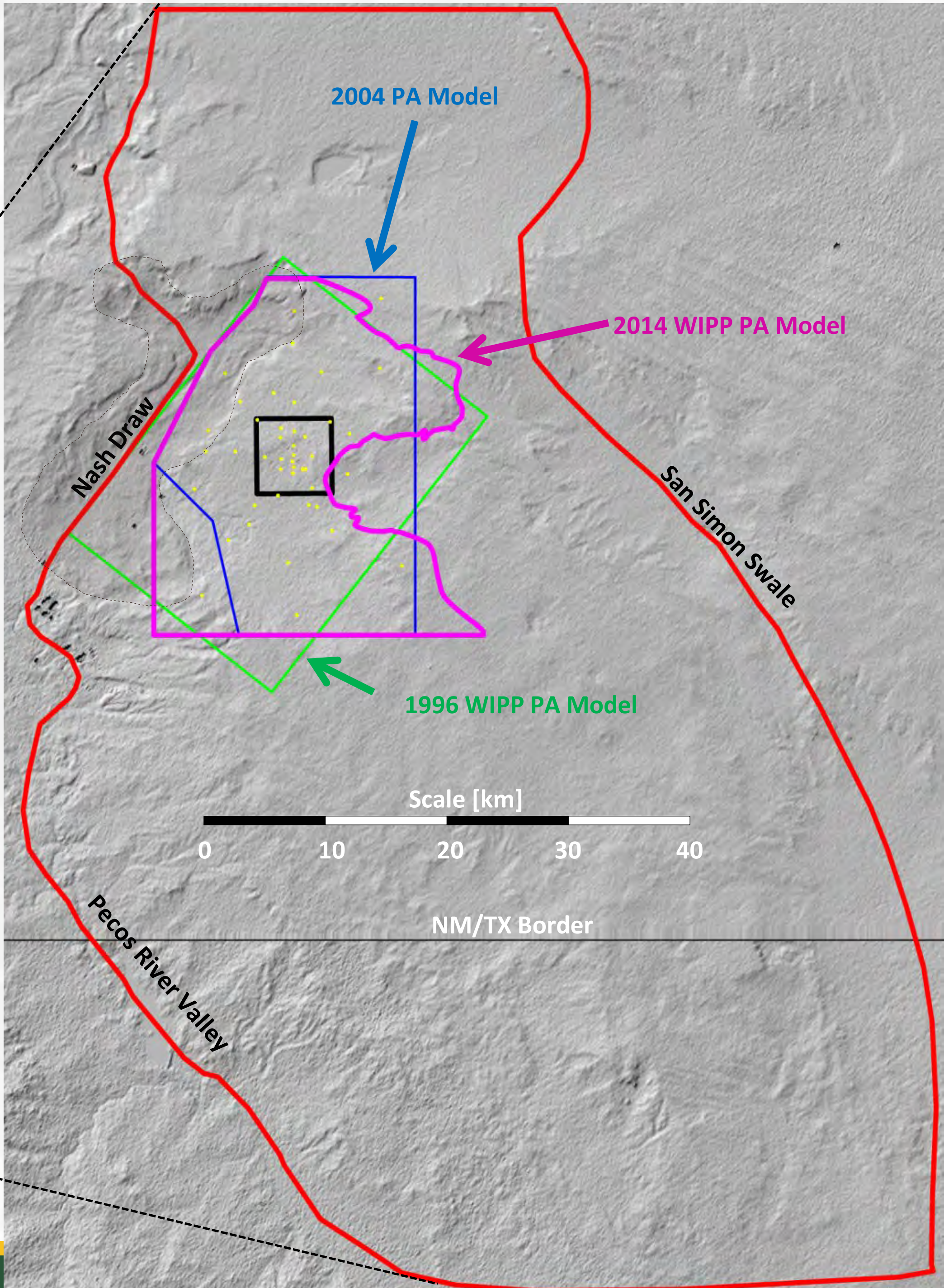
Rustler Conceptual Model



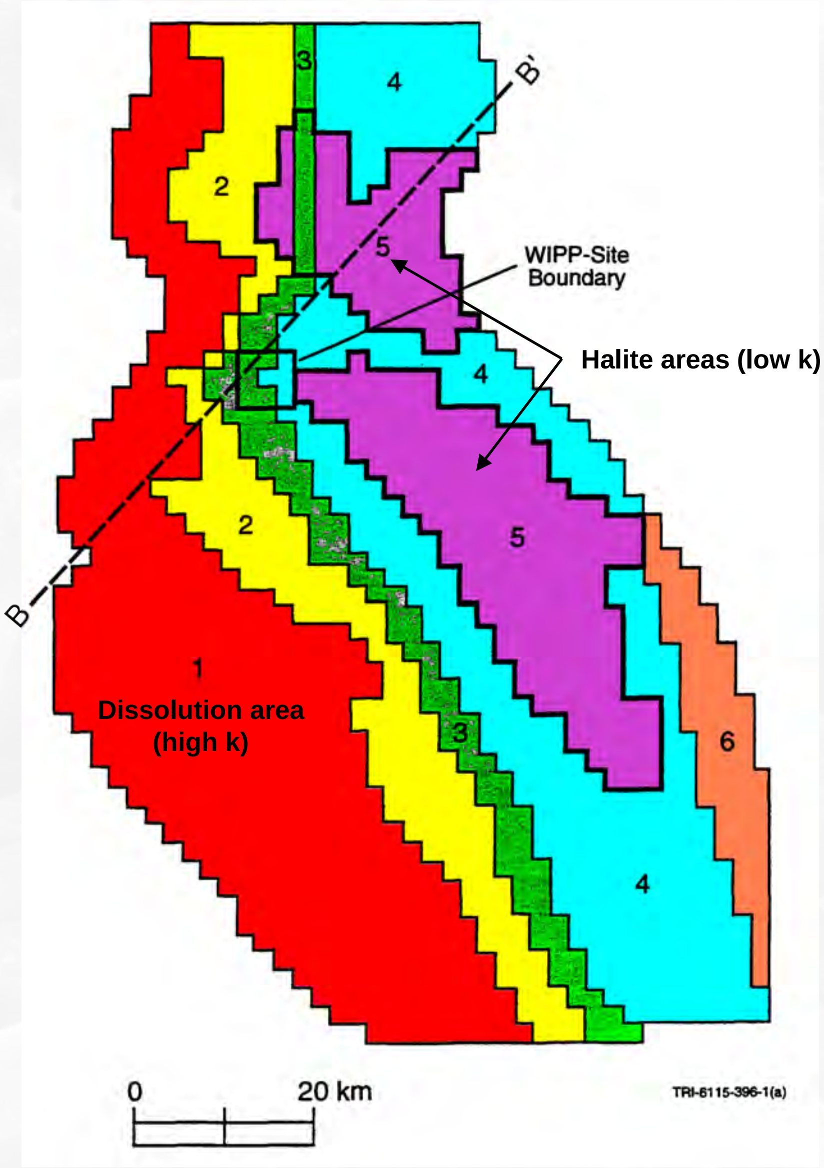
- West of WIPP
  - Shallow units
  - High permeability
  - Relatively fresh water
- East of WIPP
  - Deeper units
  - Low permeability
  - Saturated brine
- Regional groundwater
  - Flow used in WIPP PA
  - Long-term geological stability of salt

Corbet (2000) Model Domain





Corbet (2000) WIPP Model



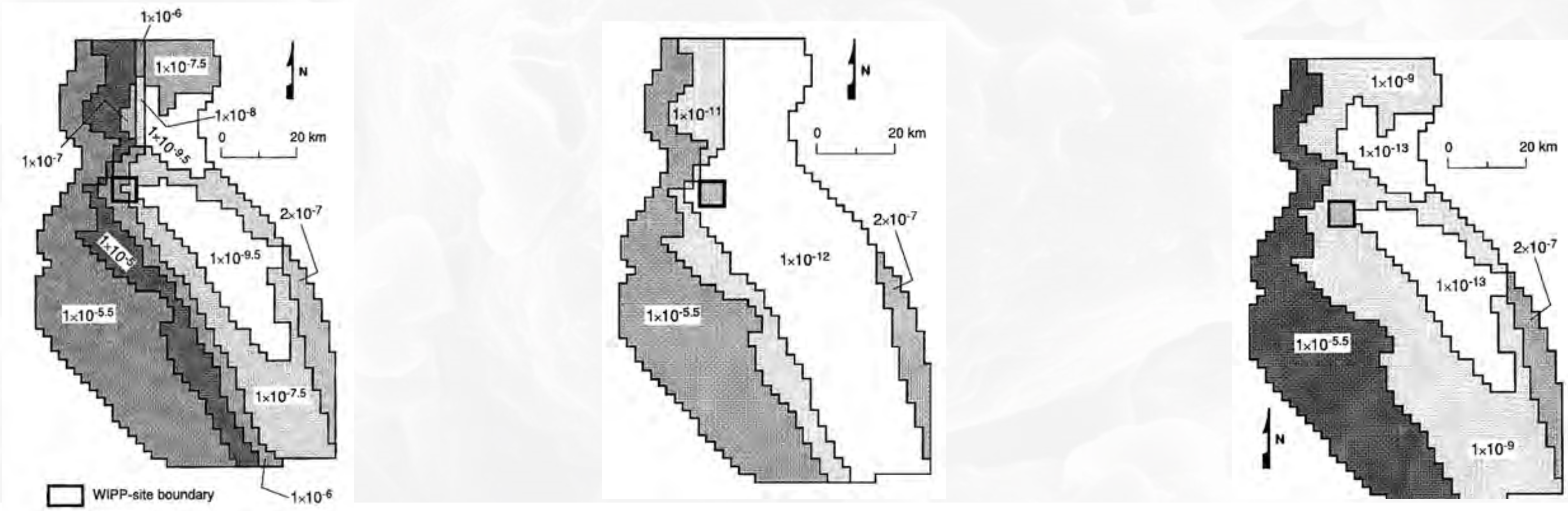
- Most of Delaware Basin
- Transient Simulation
  - Climate variation (dry vs. wet)
  - 14,000 y → present → 10,000 y
- Model Implementation
  - "water table" moving boundary model
  - ~8700 km^2 region (78 km × 112 km)
  - Coarse mesh (2 km square cells)
  - 12 model layers (10 geo layers)
  - 1,500 cells/layer
  - ~18,000 elements total

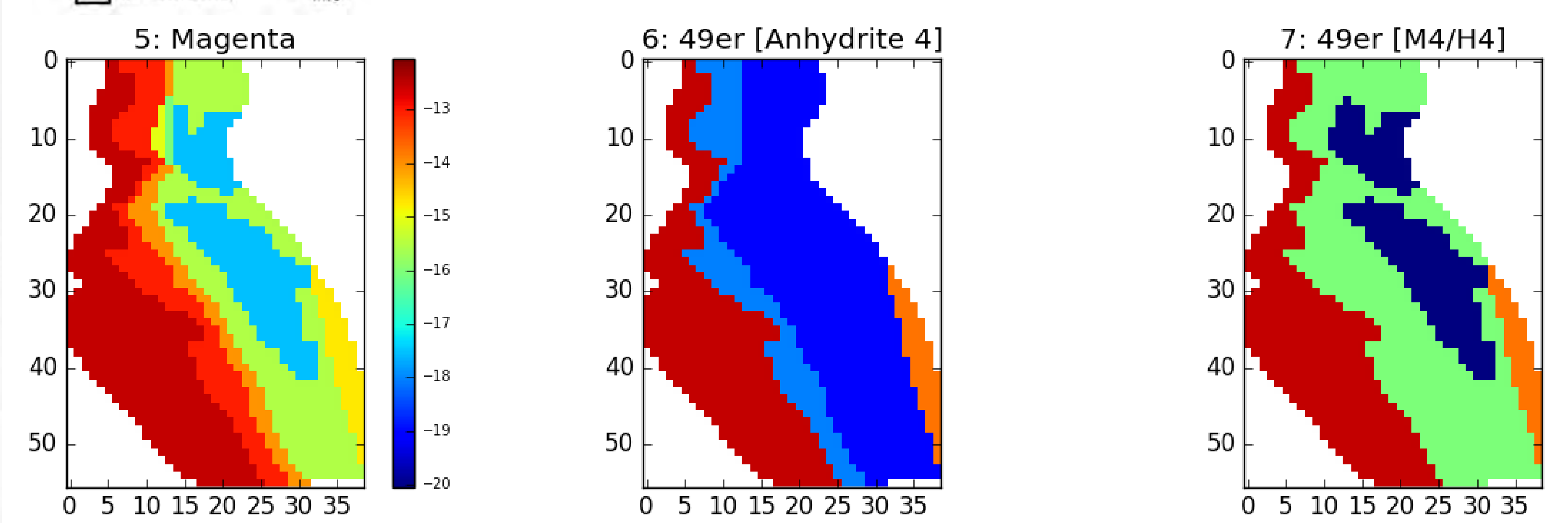
Motivation

- Benchmark against existing solution (Corbet, 2000)
- Comparison with original model
  - Old mesh, model parameters & boundary conditions
- Include new processes, features & data
  - Include density-driven flow (e.g., Davies, 1989)
  - Include chemistry & mineral dissolution
  - Investigate flow & chemistry boundary conditions
  - Test and update hydrogeological conceptual model
  - Incoporate current data: ^{81}Kr GW age data, water level data
- Comparison and Development of Models
  - PFLOTRAN (SNL)
    - Add density dependent flow
  - d^{3}f++ (GRS)

SNL PFLOTRAN version

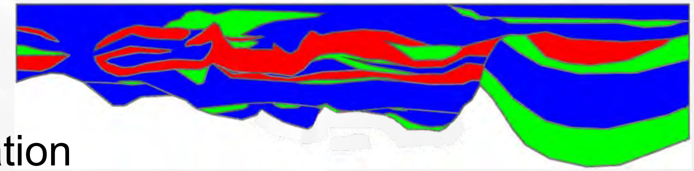
Corbet (2000): Hydraulic conductivity [m/s]



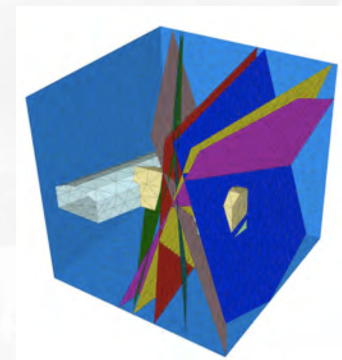


PFLOTRAN: Permeability [m^2]

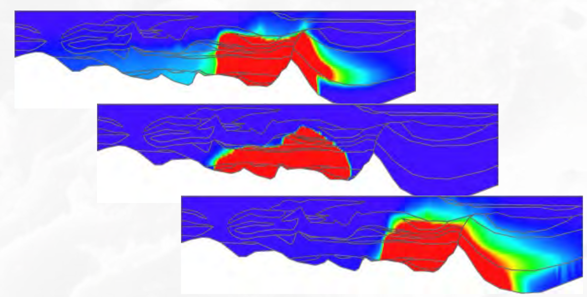
d^3f++: distributed density-driven flow



- density-driven groundwater flow
- salt and heat transport
- fluid density and viscosity depending on salt concentration and temperature
- porous and fractured media
- free groundwater surface – levelset function
- sources and sinks



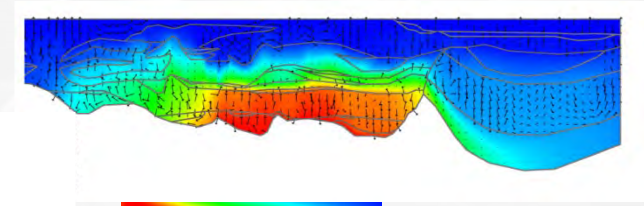
- transport of radionuclides
- decay and ingrowth
- equilibrium and kinetically controlled sorption
- precipitation/dissolution
- diffusion into immobile pore water
- colloid-borne transport

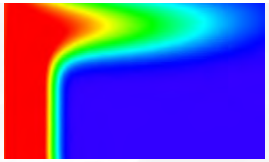


- numerics based on UG, G-CSC, Frankfurt University
- finite volume methods
- geometric and algebraic multigrid solvers
- completely parallelized (UG: scaling invest. some 100,000 proc.)

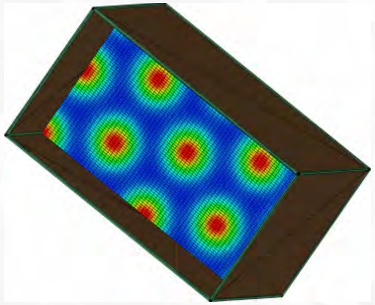
Applications of d³f++

- **Porous media, overburden of host formations**
  - *Gorleben Site:* 2D density-driven flow and RN transport in high saline environment
  - *Cape Cod:* 2D contaminant transport with pH-dependent sorption

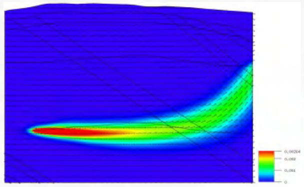


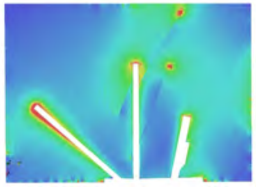


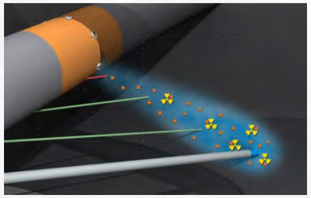
- **Low permeable media**
  - *Generic German Site in clay*: 3D diffusive transport in a low permeable anisotropic clay formation



- **Fractured media**
  - *Yeniseysky site*: Flow and transport in fractured rock
  - *Äspö (URL)*: Flow in the repository near field
  - *Grimsel (URL)*: Colloid-facilitated transport in clay

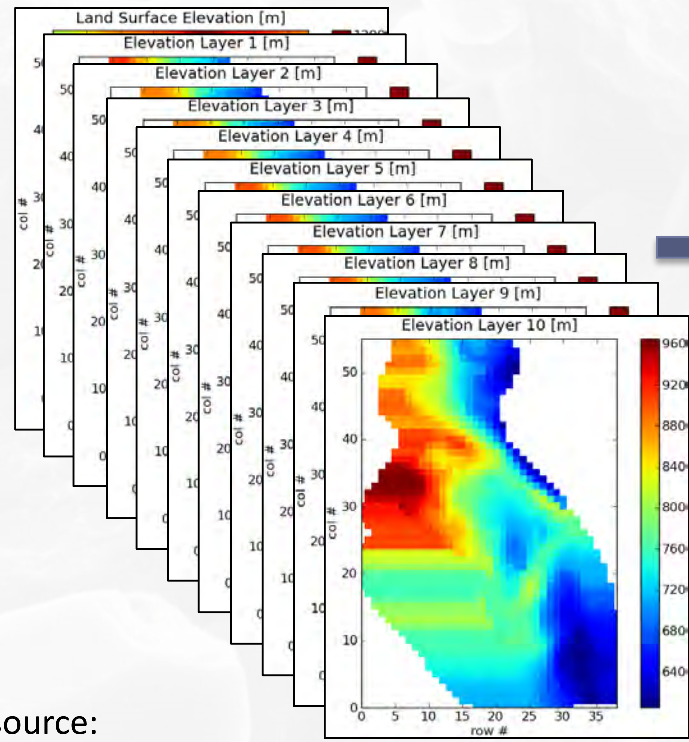






WIPP Site: „Basin-Scale“ model

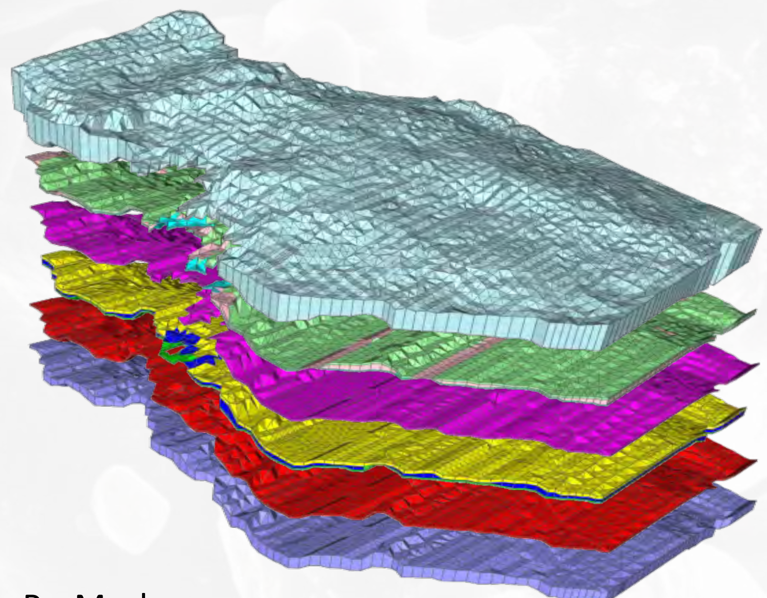
- SNL: Data of „Basin-scale“ groundwater model after Corbet & Knupp 1996
- raster data of 10 hydrogelogic units



source:
SNL, SECOFL3D

d³f++

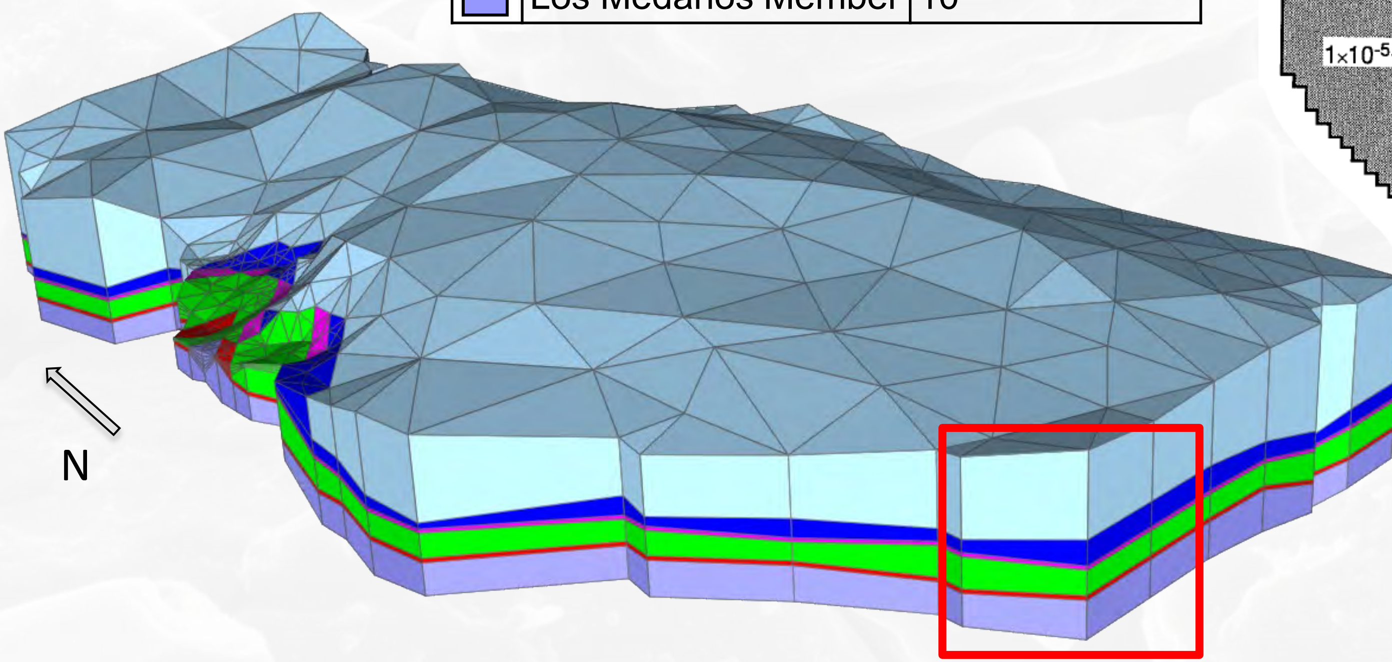
- Dewey Lake/Triassic
- Anhydrite 5 } Forty-Niner Member
- Mudstone/Halite 4 } Forty-Niner Member
- Anhydrite 4 } Forty-Niner Member
- Magenta Dolomite
- Anhydrite 3 } Tamarisk Member
- Mudstone/Halite 3 } Tamarisk Member
- Anhydrite 2 } Tamarisk Member
- Culebra Dolomite
- Los Medanos Member

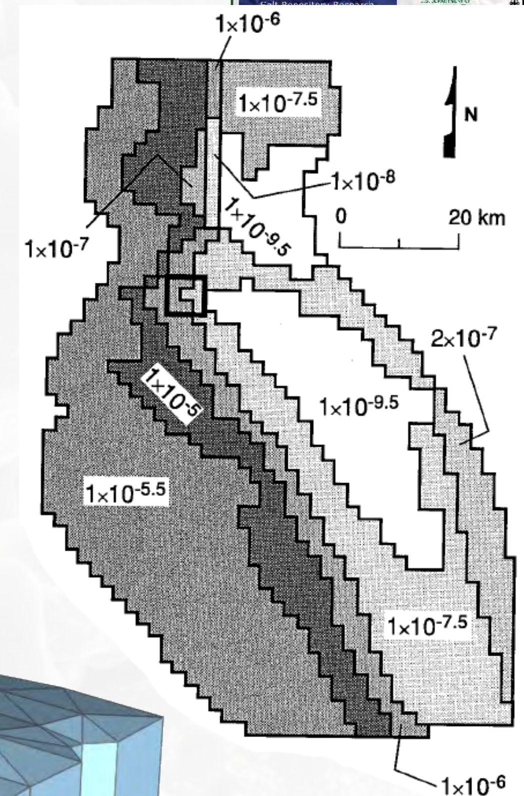


ProMesh
www.promesh3d.com

WIPP-Site: Prism grid, 6 layers

	unit	permeability [m²]
	Dewey Lake/Triassic	10^{-14}-10^{-12}
	Forty-Niner Member	10^{-20}-10^{-12}
	Magenta Dolomite	10^{-18}-10^{-12}
	Tamarisk Member	10^{-20}-10^{-12}
	Culebra Dolomite	10^{-17}-10^{-11}
	Los Medanos Member	10^{-17}



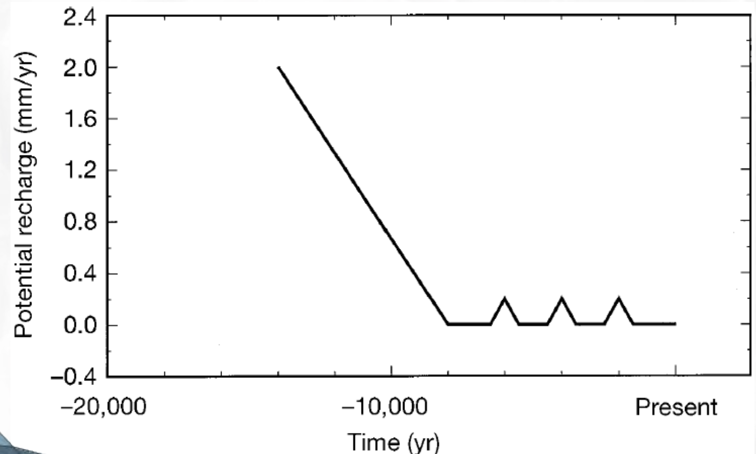


example:
Culebra Dolomite
source: Corbet 2000

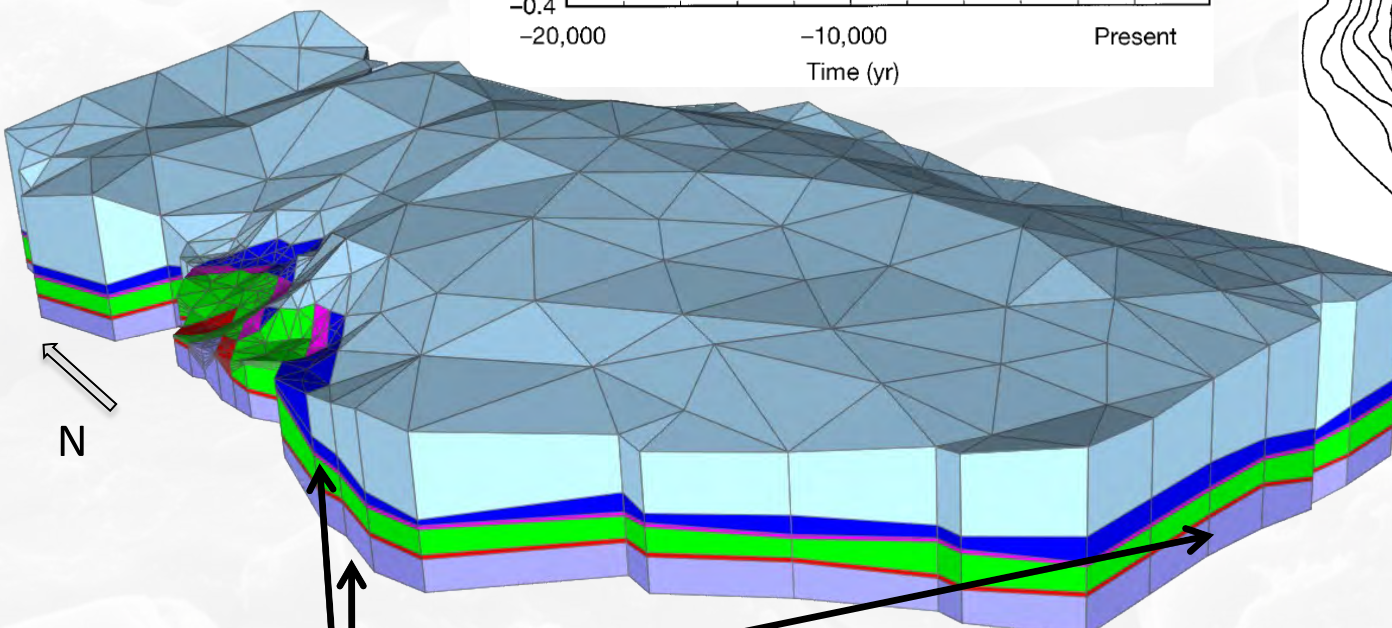
182,784 prisms (2x refined) ←→ 18,000 hexahedrons SECOFL3D
50x vertical exaggeration

WIPP-Site: Initial and boundary conditions

assumed
recharge rates
source:
Corbet 2000



initial condition:
water table
14,000 years ago
source:
Corbet &Knupp 1996

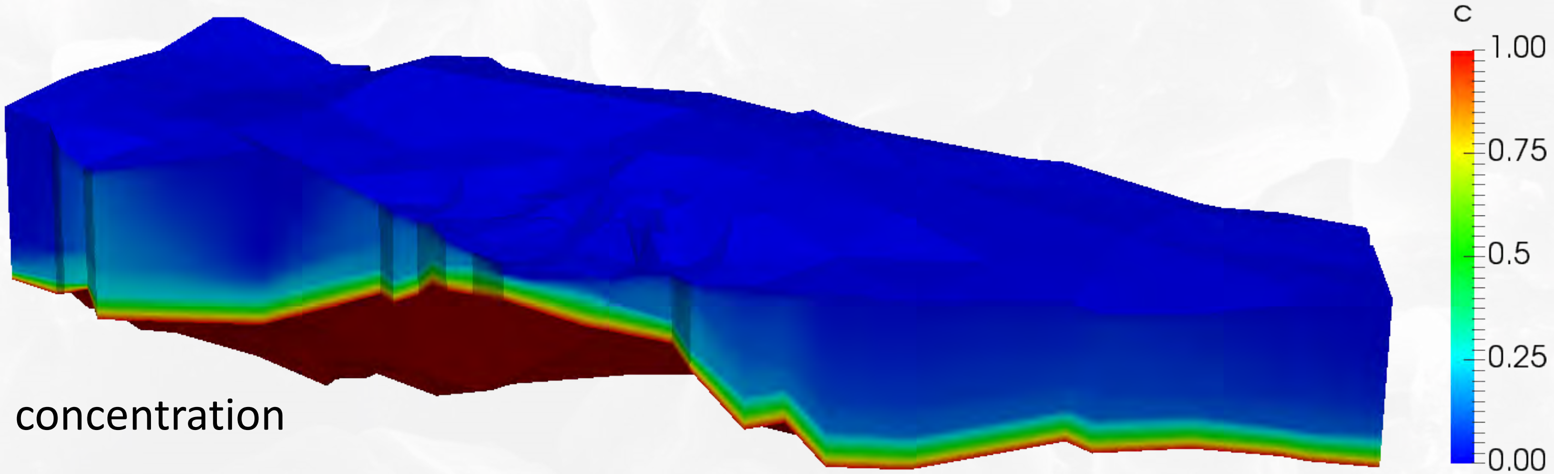


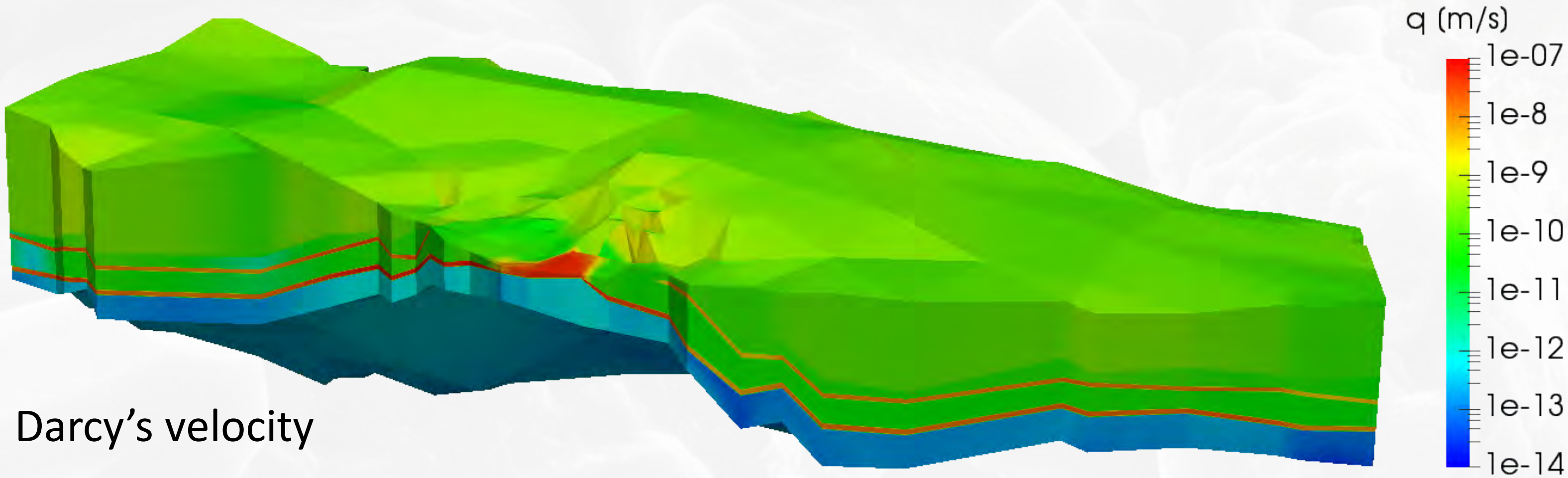
closed boundaries

c=1
(saturated brine)

WIPP-Site: d³f++ simulations

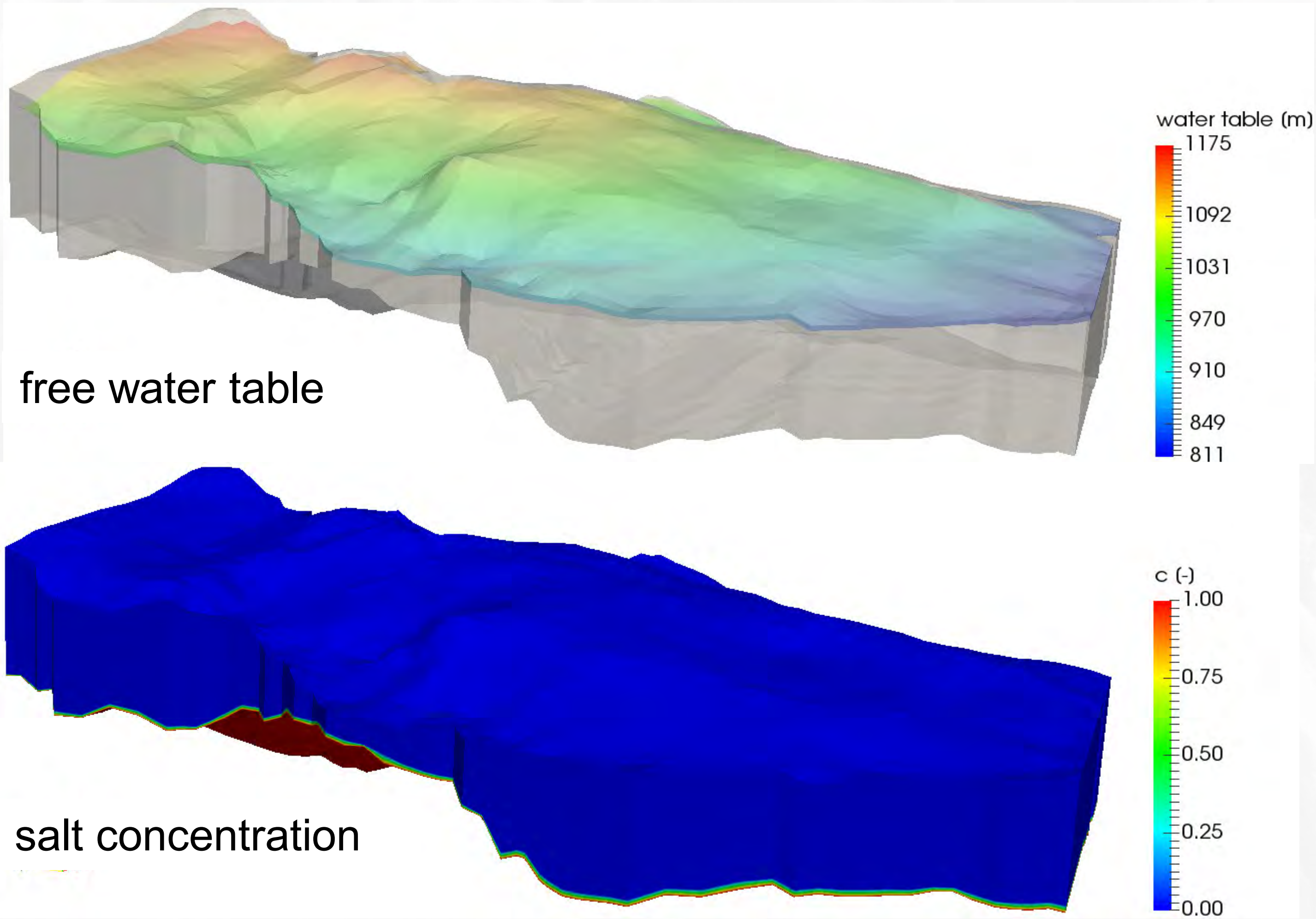
density-driven flow, **fixed water table** (top boundary), permeability const. (layers) (280,000 prisms)
model time 10,000 years, computing time 15 minutes, timestep 100 years





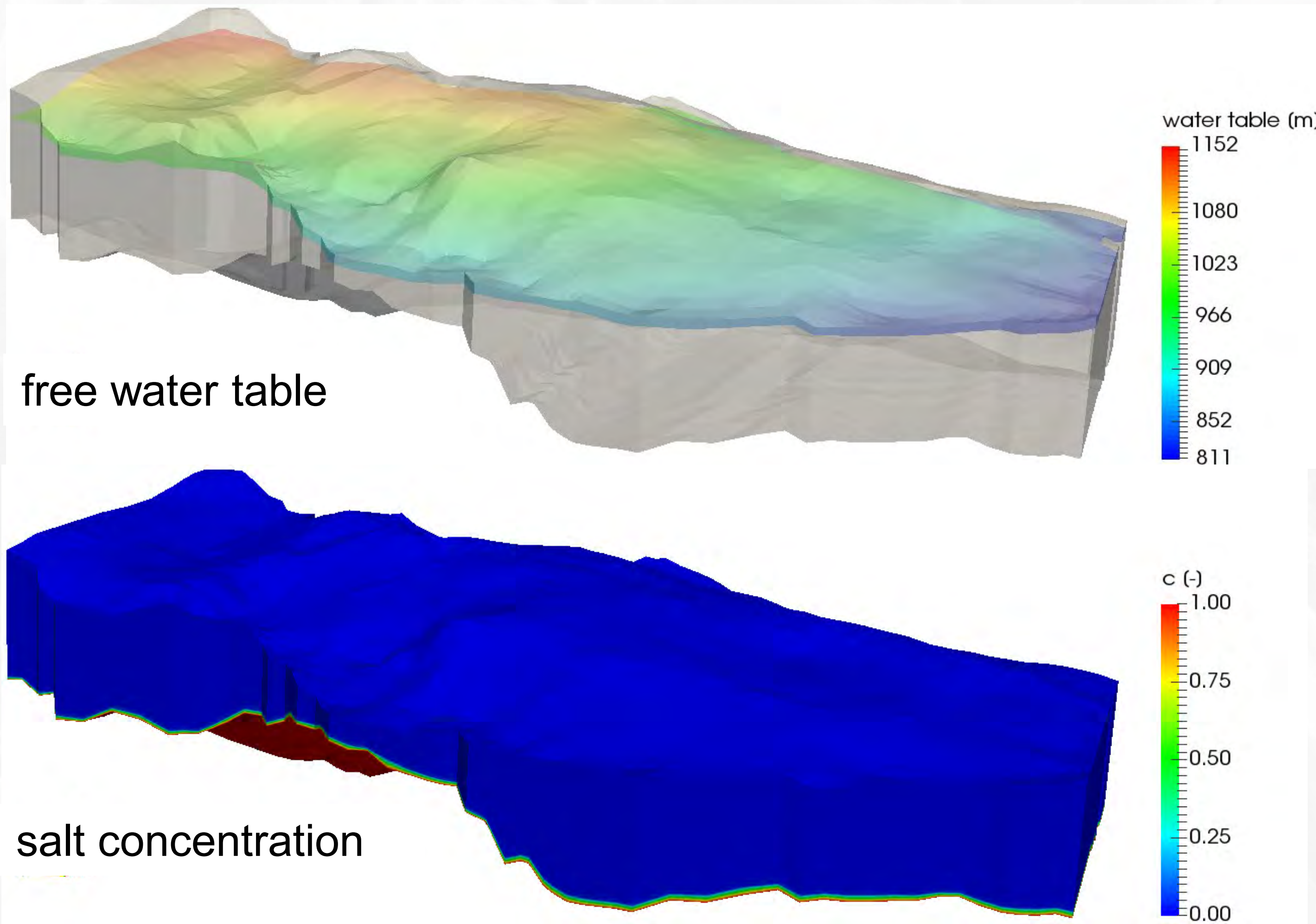
WIPP-Site: d³f++ simulations

density-driven flow, **free water table**
level 2 (182,784 prisms), initial state



WIPP-Site: d³f++ simulations

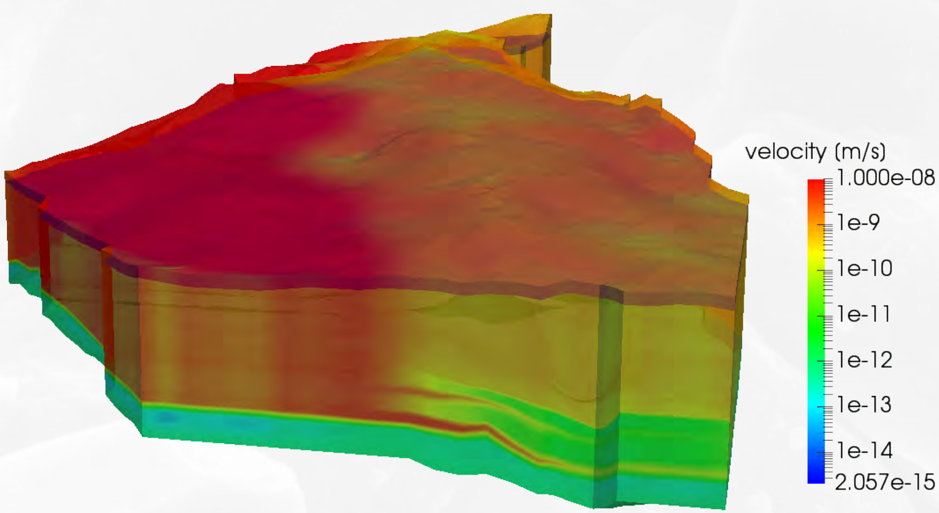
density-driven flow, **free water table**
level 2 (182,784 prisms), timestep 0.05 years, model time 150 years

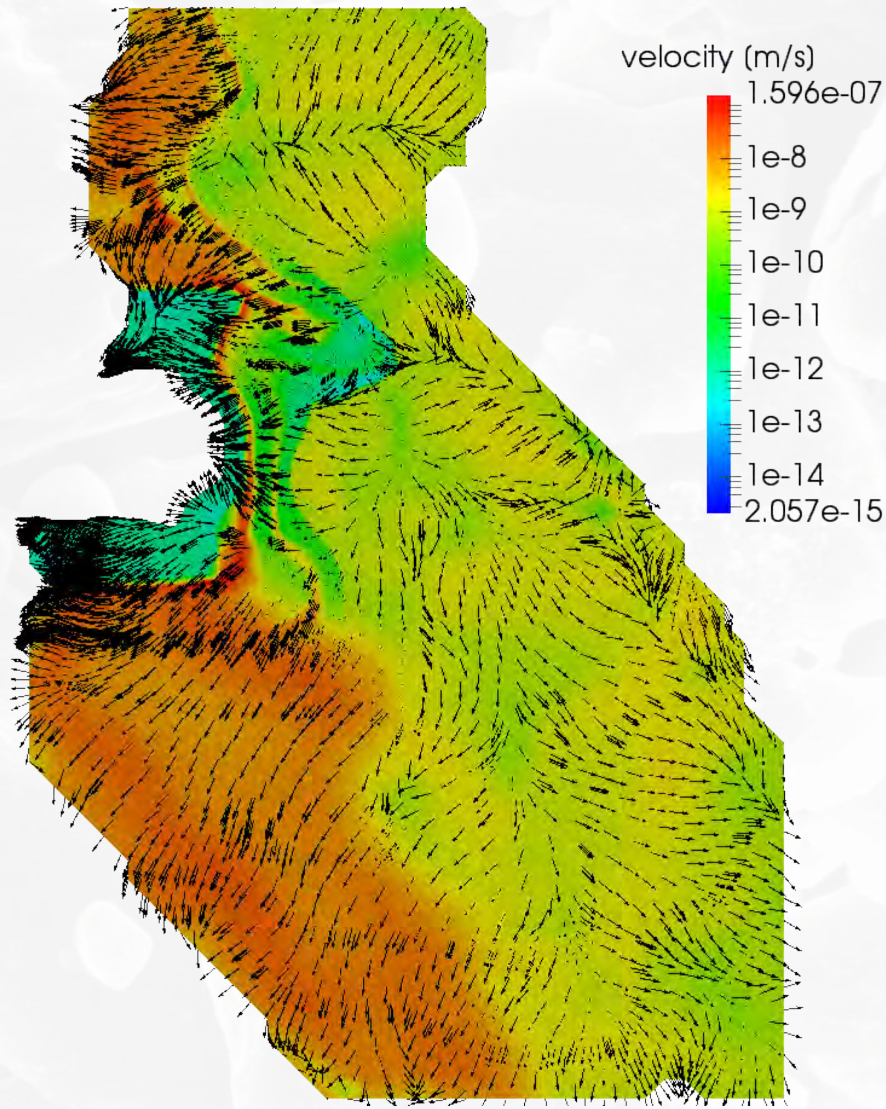


WIPP-Site: d^{3}f++ simulations

density-driven flow, **free water table**
level 2 (182,784 prisms)
model time 100 years,
timestep 0.05 year (levelset method)

Darcy's velocity, water table





Summary and outlook

- **Difficulties to overcome:**
- non steady-state density-driven flow model ✓
- strongly anisotropic (thin layers, jumping coefficients) ✓
- free groundwater surface 8,700 km² ?

- **Current work:**
- BMWi-funded joint project GRUSS (GRS, G-CSC Frankfurt University)
- improve grid generating/refinement ✓
- improve robustness of solvers (convergence, timesteps) (✓)
- implement volume of fluid (VOF) method to speed-up free surface handling (✓)

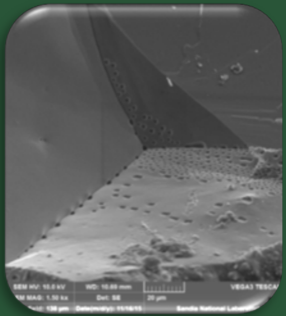
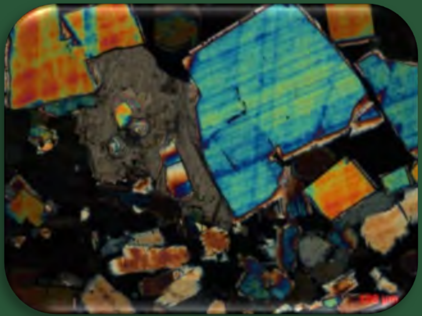
- **Next steps:**
- increase timestep levelset method, stabilize
- use VOF method

Thank you for your attention!

Supported by:

Federal Ministry
of Economics
and Energy

on the basis of a decision
by the German Bundestag

DOE-NE WIPP Heater Test Update

Kris Kuhlman
Sandia National Laboratories

Rapid City, SD, United States
May 28-30, 2019

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WIPP Salt Field Test Team

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Phil Stauffer, Hakim Boukhalfa, Eric Guiltinan, Doug Ware, Thom Rahn

Waste Isolation Pilot Plant (WIPP) Test Coordination Office (LANL)

Doug Weaver, Brian Dozier, Shawn Otto

Lawrence Berkeley National Laboratory (LBNL)

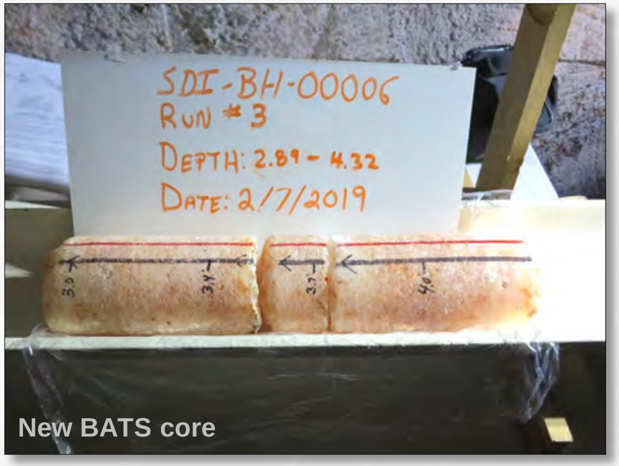
Yuxin Wu, Jonny Rutqvist, Jonathan Ajo-Franklin, Mengsu Hu

What Are We Doing?

Brine Availability Test in Salt at WIPP (BATS)

Monitoring brine distribution, inflow, and chemistry from heated salt using geophysical methods and direct liquid & gas sampling.

Boreholes drilled Feb-Apr 2019 in WIPP underground, testing begins July 2019, into FY20. Shakedown equipment tests ongoing.

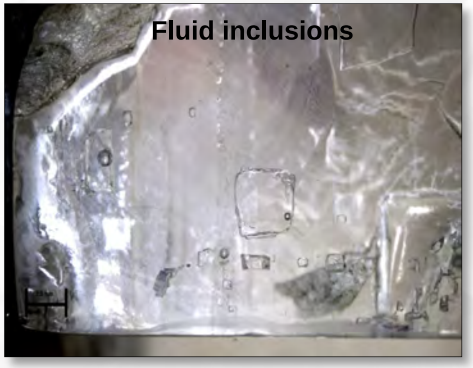


New BATS core


New BATS boreholes

Brine in Salt

- No flowing groundwater, but not dry (≤ 5 wt-% water)
- Water sources in salt
  1. Hydrous minerals (e.g., clay, bassanite)
  2. Intragranular brine (fluid inclusions)
  3. Intergranular brine (interconnected pores)



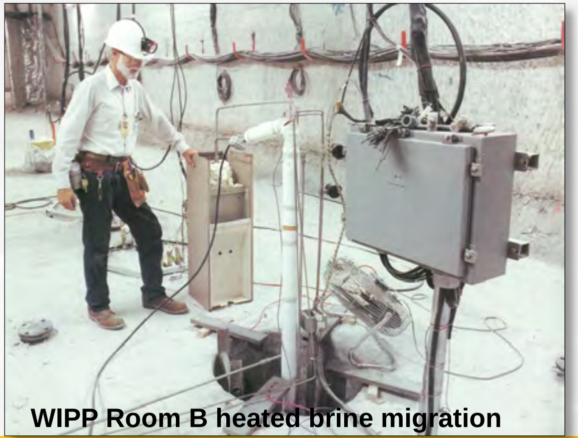
- Brine content correlates with clay content
- Only *intergranular* brine moves under pressure gradient
- Water types respond differently to heat
  - Hydrous minerals evolve water vapor, which can become brine
  - Intragranular brine migrates under thermal gradient
- Brine types have different chemical / isotopic composition

Q: How do 3 water types contribute to *Brine Availability?*

Importance to Safety Case

Brine Availability: *Distribution of brine in salt & how it flows to excavations or boreholes*

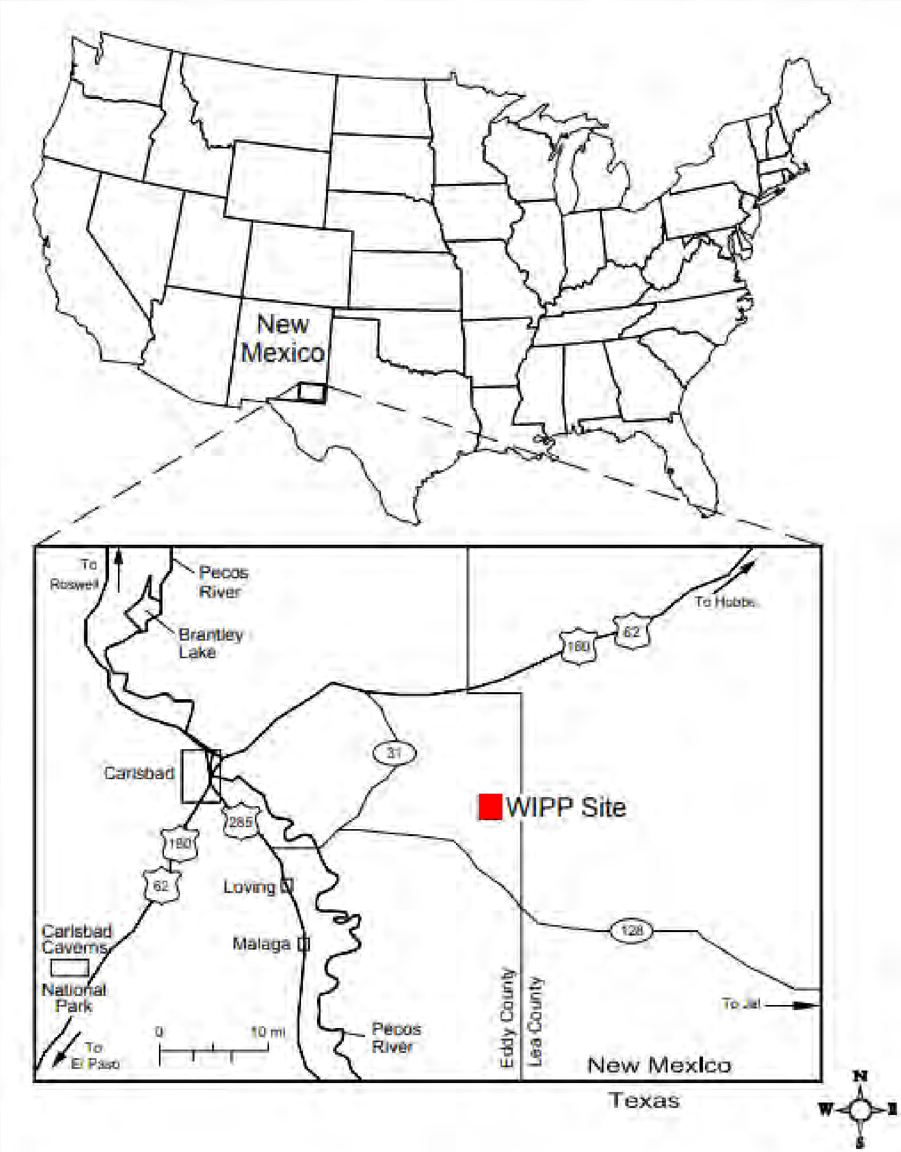
- Initial conditions to post-closure safety assessment
  - Brine migration and re-distribution
  - Evolution of disturbed rock zone (DRZ) porosity and permeability
- Brine causes corrosion of waste package / waste form
- Brine is primary radionuclide transport vector
- Liquid back-pressure can resist drift creep closure

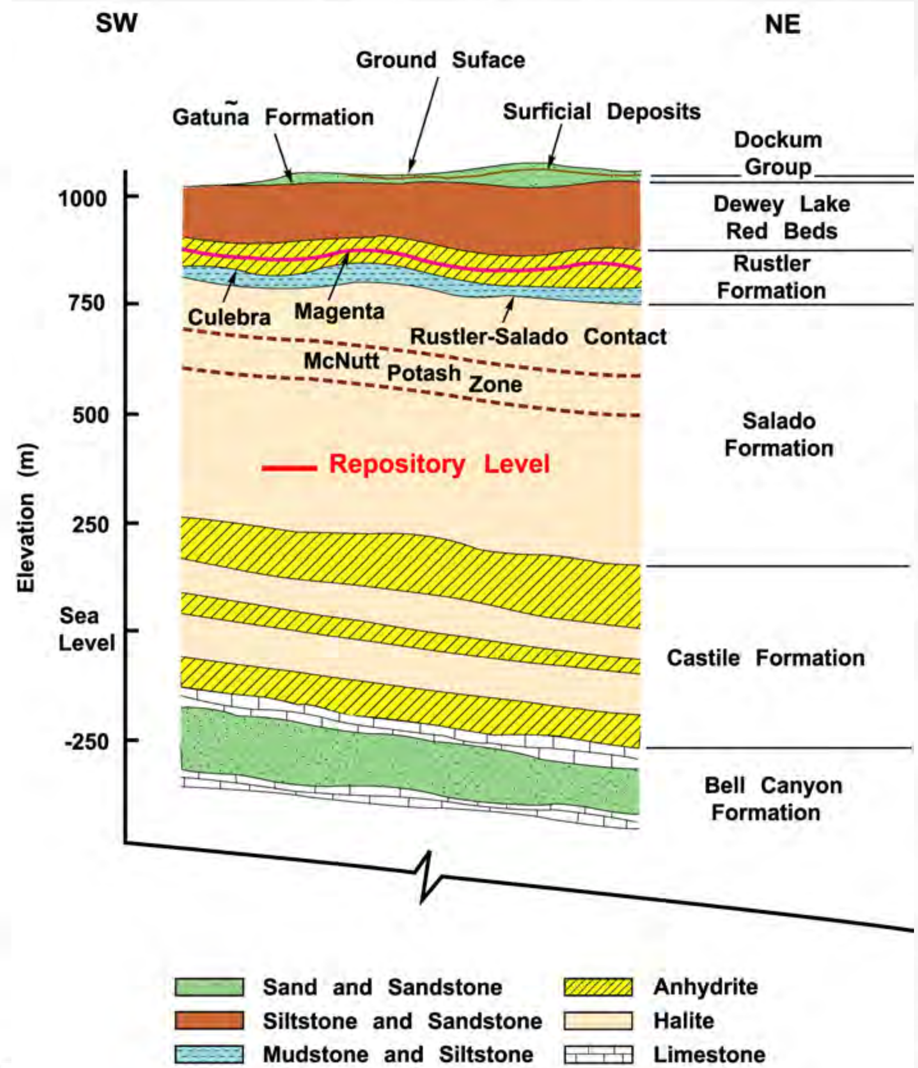

WIPP Room B heated brine migration


WIPP Room J canister tests


WIPP Room Q brine inflow

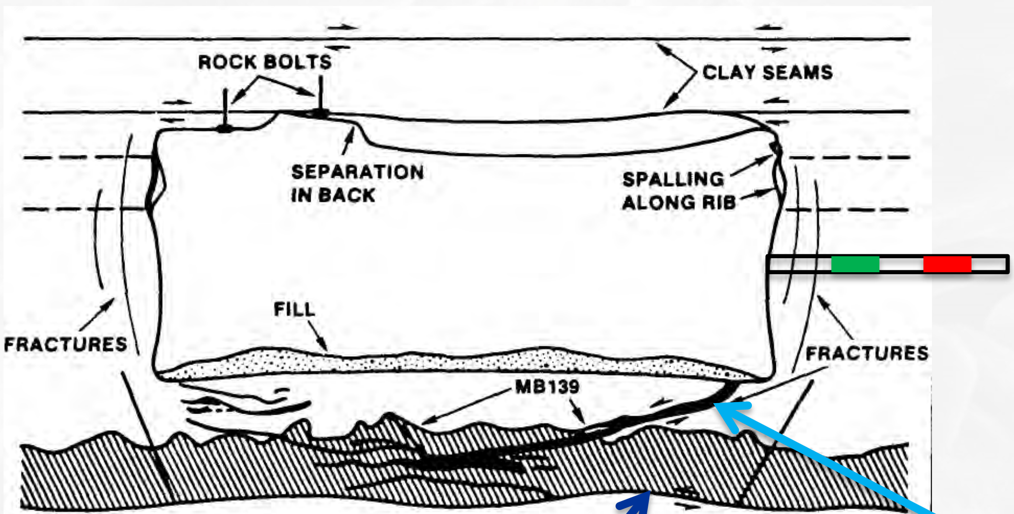
WIPP Context





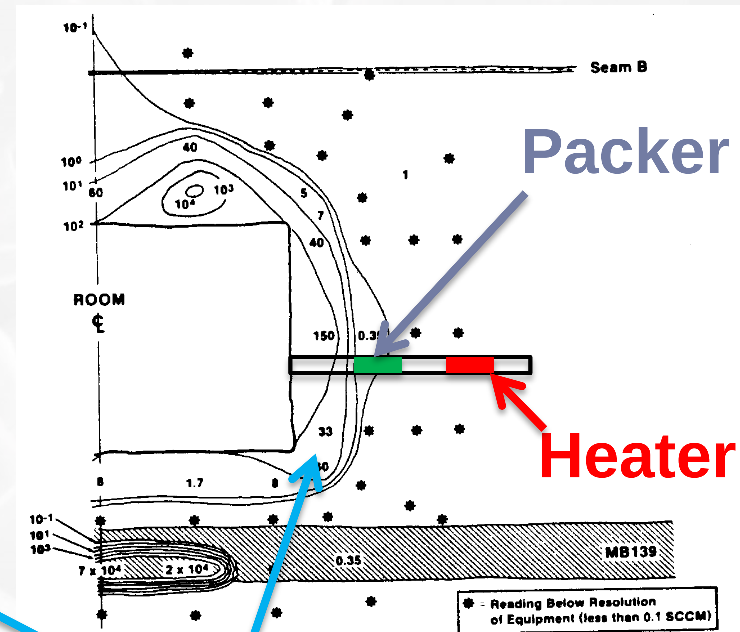
BATS Test in WIPP DRZ

Cartoon representation of test interval relative to observed DRZ at WIPP



Borns & Stormont (1988)

Contours of gas flowrate at fixed pressure (i.e., damage)

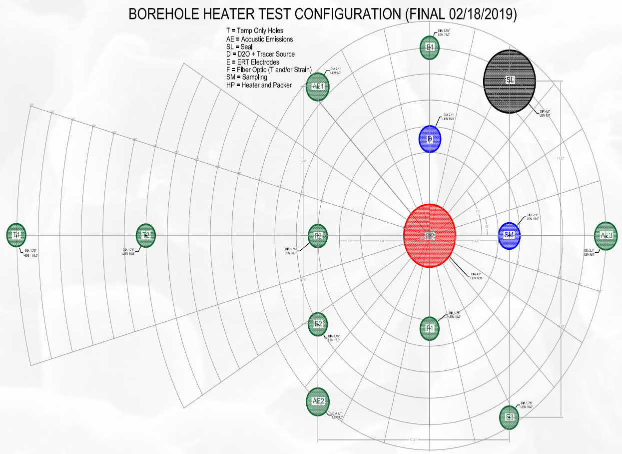


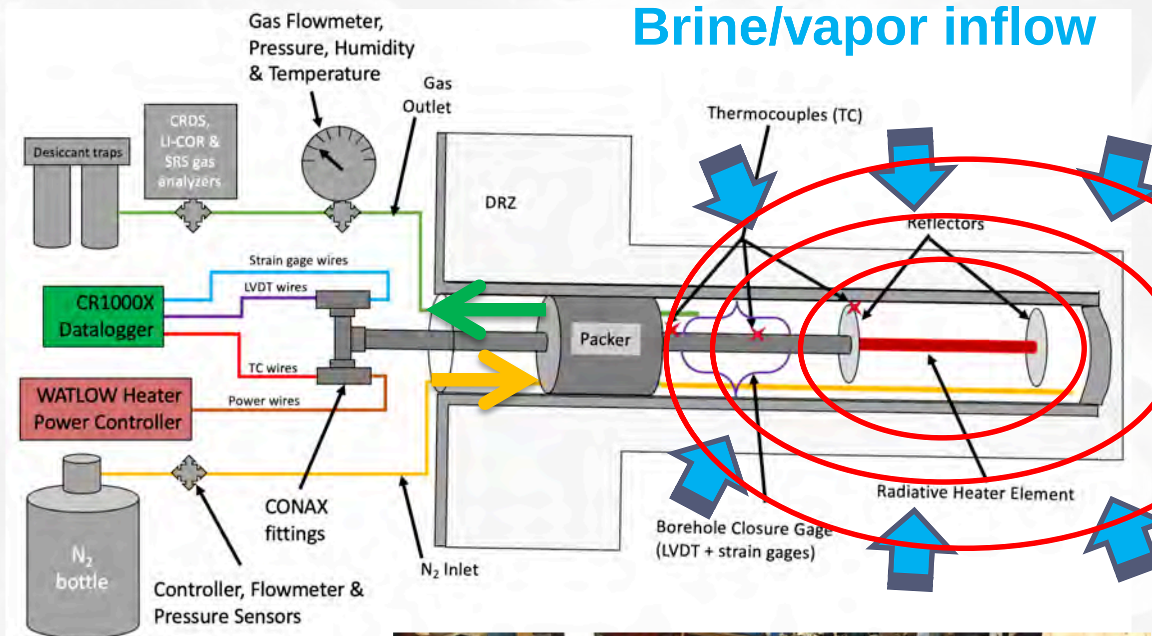
Borns & Stormont (1988)

Horizontal borehole avoids mapped clay / anhydrite layers (e.g., MB139) in Room A/B vertical heater tests

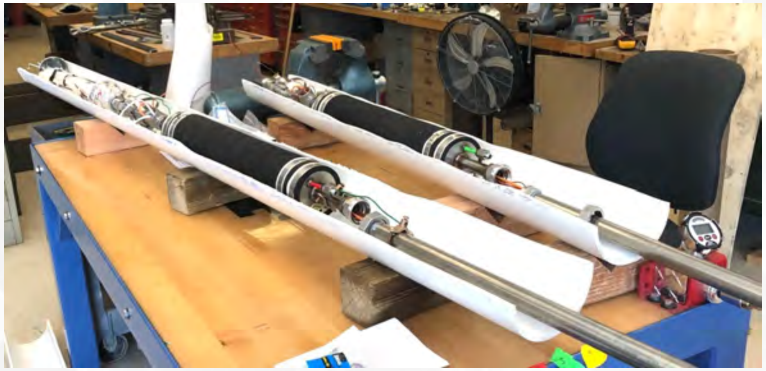
Near-drift DRZ and damage

BATS Test Instrumentation





- Two identical arrays
  - Heated (120 C) and Unheated
- Behind HP packer (right)
  - Circulate dry N_2
  - Quartz lamp heater (750 W)
  - Borehole closure gage
  - Gas permeability before / after
- Samples / Analyses
  - Cores (X-ray CT and fluorescence at NETL)
  - Gas stream (natural / applied tracers, humidity and isotopes)
  - Liquid brine (natural chemistry and natural / applied tracers)
- Geophysics
  - 3 × Electrical resistivity tomography (ERT)
  - 3 × Acoustic emissions (AE) / ultrasonic travel-time tomography
  - 2 × Fiber optic distributed strain (DSS) / temperature (DTS) sensing
  - +100 thermocouples

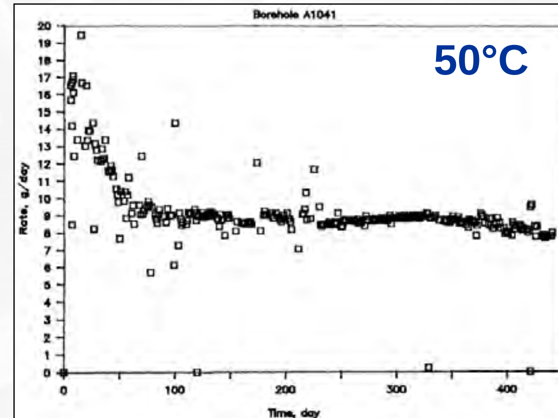


BATS Test Data

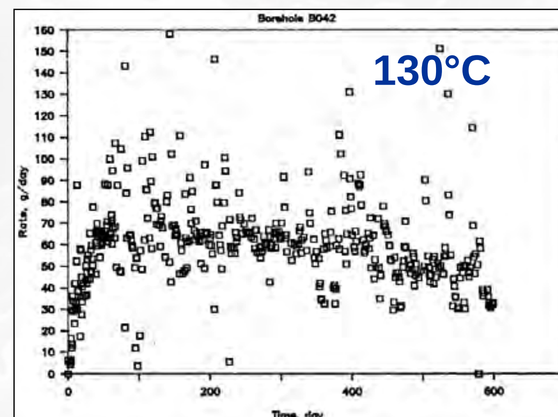
- Brine composition samples / H_2O isotope data
  - Measure change in brine sources with temperature
- Geophysics
  - Map 4D evolution of **saturation** / **porosity** / **permeability**
- Temperature distribution
  - More brine available at high temp (inclusions + hydrous minerals)
  - Thermal expansion brine driving force
  - Salt dry-out near borehole
- Gas permeability and borehole closure
  - Thermal-hydrological-mechanical evolution of salt during heating
- Tracer migration through salt
  - Estimate rate of brine / vapor movement through salt DRZ
- Post-test overcoring
  - Cement seal, tracer distribution around source, damage

Brine Inflow

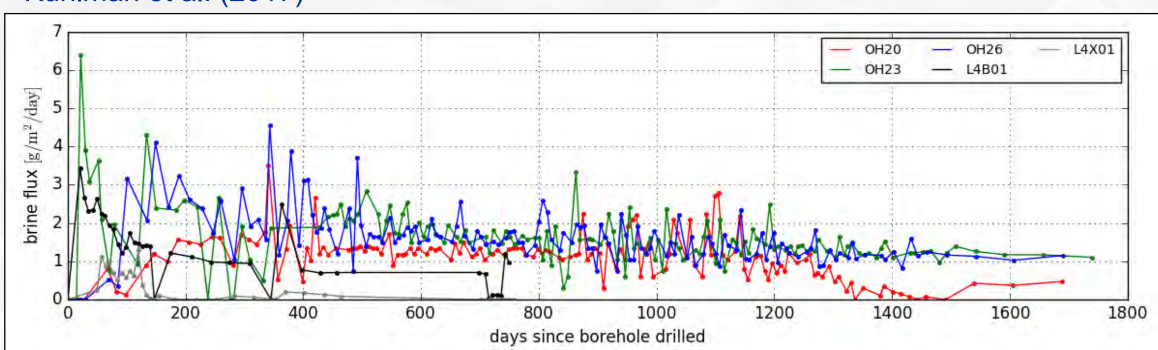
- Brine inflow
  - Highest inflow rate initially
  - Exponential decay of rate with time
- More brine inflow at higher temperatures
  - Vapor from dehydration of clay & gypsum
  - Brine from fluid inclusions
- Three forms of water contribute
  - Can we discern chemically/isotopically?



Vertical WIPP boreholes



Kuhlman et al. (2017)

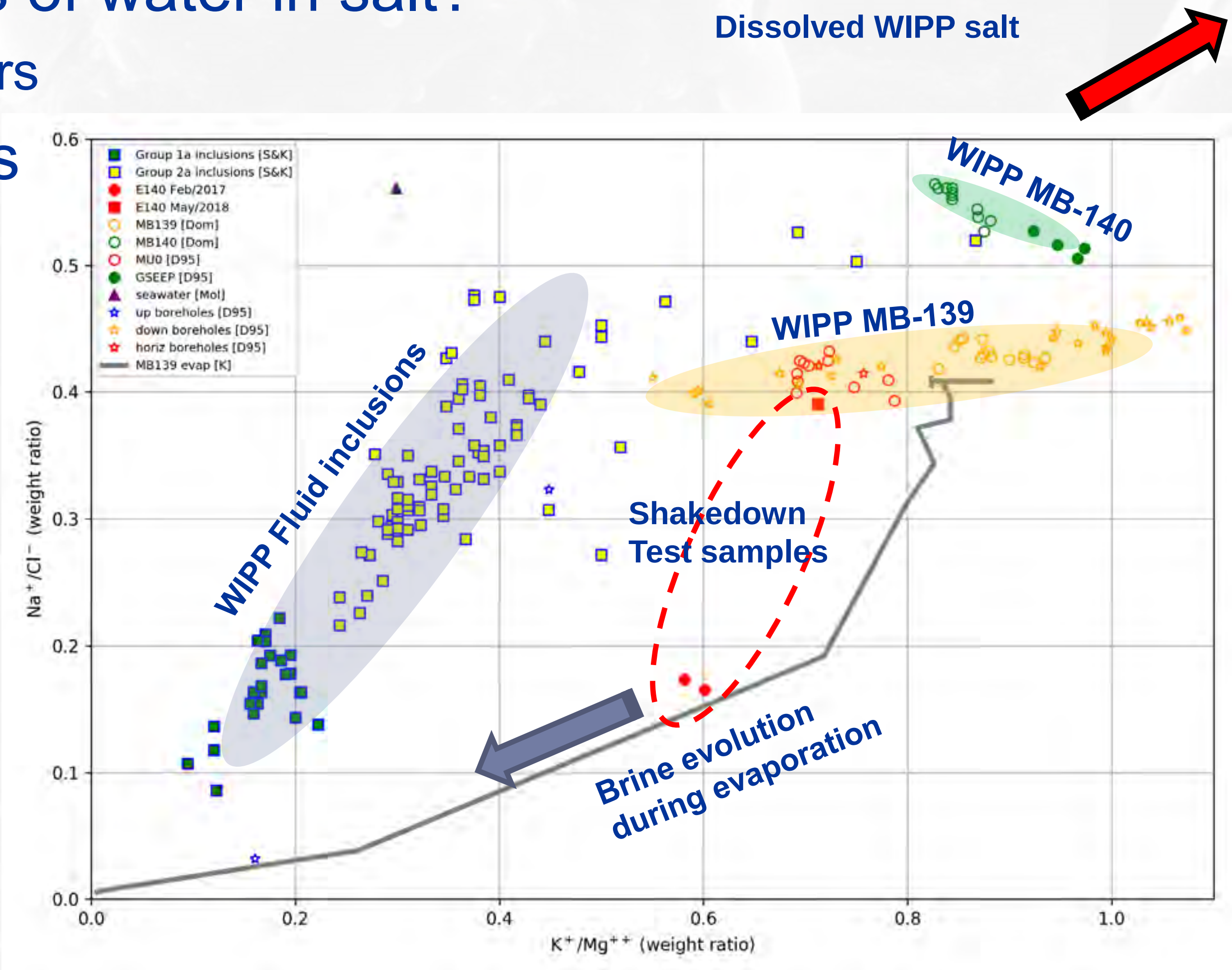


Unheated borehole brine inflow at WIPP in (did not cross mapped clay layer)

Vertical boreholes intersected clay layers (Rooms A & B)
Nowak & McTigue (1987)

Brine Composition

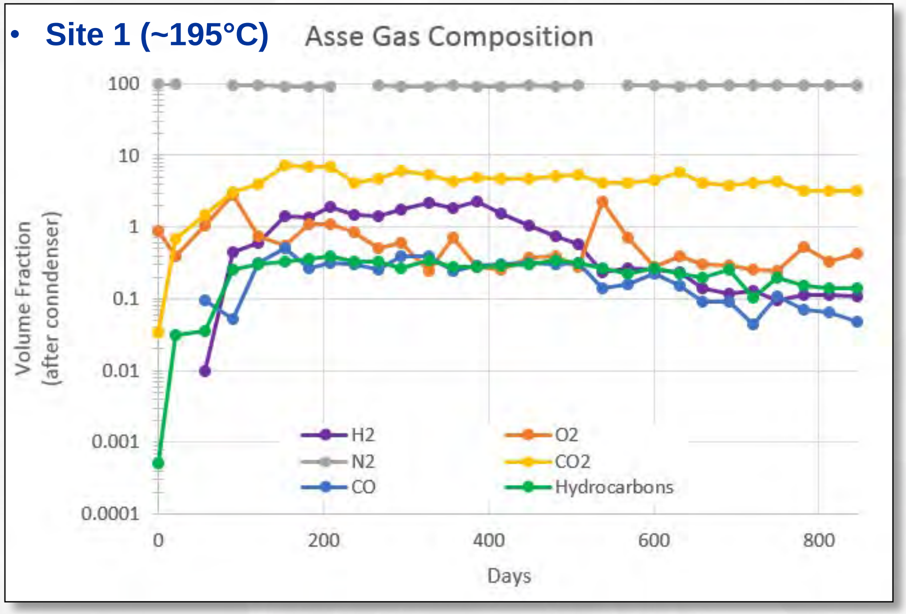
- Liquid brine samples
- Distinguish sources of water in salt?
  - Distinct endmembers
- Added liquid tracers
  - $NaReO_4$
  - Fluorescent tracer
- Data on processes:
  - Advection
  - Reaction
  - Diffusion



GAS COMPOSITION

- Gases enter borehole from
  - Dissolved gas in brine (~15 MPa pore pressure in far field)
  - Geogenic gases from salt (e.g., He & Ar)
  - Added gas tracers (Xe, Ne, Kr & SF_6)
- Water Vapor from brine
  - Natural H_2O
  - Isotopically spiked water breakthrough
    - Transport time through salt
    - Fractionation in borehole
- Analyze gases real-time
  - Mass spectrometer
  - H_2O / CO_2 infrared analyzer
  - Picarro water isotope analyzer

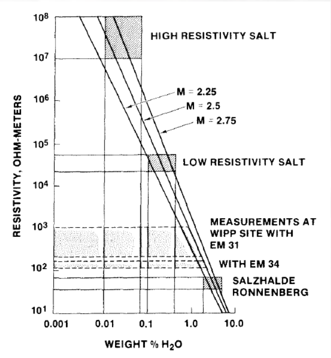
SRS quadrupole mass spec gas analyzer



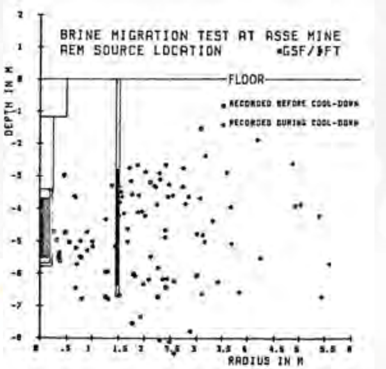
Data from Coyle et al. (1987) BMI/ONWI-624

ERT / AE Expectations

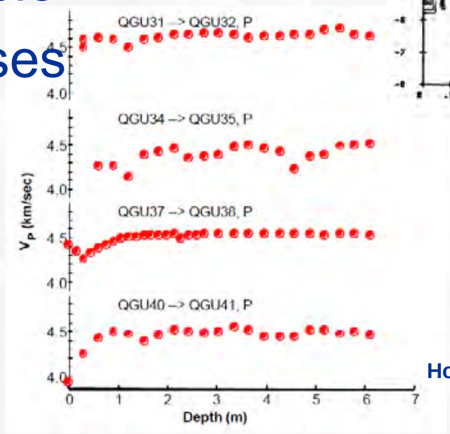
- Electrical Resistivity Tomography (ERT)
  - ERT electrodes cemented into 3 boreholes
  - Salt apparent resistivity
  - Reisitivity: reveal porosity and brine saturation
- Conduct 3D ERT surveys through time
  - Estimate evolution of porosity / saturation
- Acoustic Emissions (AE)
  - AE monitoring (especially during heat up & cooldown)
  - Locate AE sources near heated borehole
  - AE correlated with permeability increases
  - AE system installed in heated test only
- Ultrasonic Wave Travel-time Data
  - Estimate extent/evolution of DRZ



Skokan et al. (1989)



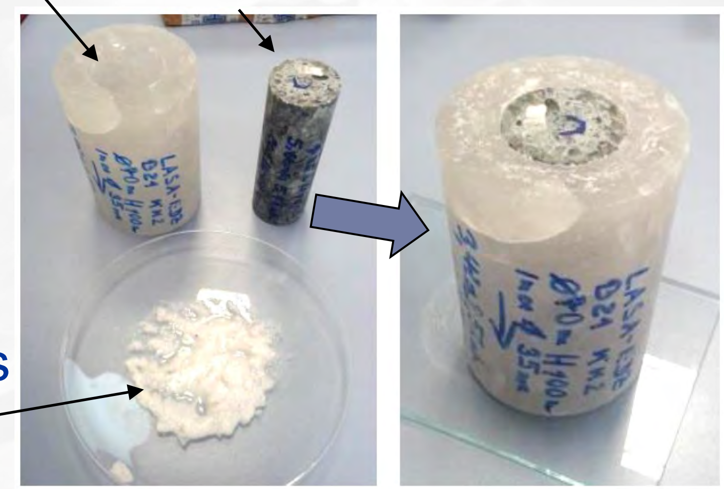
Rothfuchs et al. (1988)



Holcomb et al. (2001)

Cementitious Seals

- Emplace Pre-fabricated Cement Plug
  - Snug fit into satellite borehole
  - Tubing embedded in plug (perm. test)
  - Monitor seal evolution as borehole closes
  - Parallel tests: ambient + heated conditions
- Upscale GRS Lab Seals Tests
  - GRS test monitored permeability evolution
  - We will implement at borehole scale
- Overcore Post-test to Analyze Interfaces
- Collaboration with GRS
  - Use same cement formulas in field as lab experiments
  - Send WIPP salt and brine recipe to GRS for lab experiments



Czaikowski & Wieczorek (2016)

Proposed DECOVALEX Task

- DECOVALEX 2023: Proposed Task H
- Construction/Testing
  - New boreholes cored/driled Feb-Apr 2019
  - Test constructed/installed in new boreholes (June 2019)
  - Heated test conducted for ~6 months (two phases)
  - Unheated test conducted ~12 months

- *2019:* Initial test execution
- *2020:* Distribute initial test data
- *2021:* Simulate single processes (+ thermal)
  - Brine production, D_2O transport
  - Thermal-Hydrologic, Thermal-Mechanical, Thermal-Chemical
  - Follow-on test data available
- *2022:* More coupled processes
  - Salt permeability/porosity as a function of damage
- *2023:* Include data from ERT/AE/brine composition

- Interested Parties
  - US (SNL, LANL, LBNL), Germany (BGR, GRS), UK (RWM), Netherlands (COVRA)

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

10th US/German Workshop “Salt Repository Research, Design, and Operation”

Modyfing magnesia cement for preparing geotechnical constructions and injection grout

May 29th , 2019 / Rapid City

Thomas Meyer (BGE TECHNOLOGY GmbH)

Dr. Nina Müller-Hoeppe, Dr. Lieselotte v. Borstel, Dr. Joachim Engelhardt (BGE TECHNOLOGY GmbH)

Dr. Antje Carstensen, Lutz Teichmann, Matthias Heydorn, Marcus Tresper (BGE GmbH)

BGE TEC BGE TECHNOLOGY GmbH

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

contents

1. overview
2. construction material / injection grout
3. quality control and preservation of evidence
4. machinery and equipment
5. field of application

$$3\ MgO + MgCl_2 + 11\ H_2O \rightarrow 3\ Mg(OH)_2 \times 1\ MgCl_2 \times 8\ H_2O$$
$$5\ MgO + MgCl_2 + 13\ H_2O \rightarrow 5\ Mg(OH)_2 \times 1\ MgCl_2 \times 8\ H_2O$$

components		sorel concrete		injection grout	
binder	filler	A1	A0	IM-Asse-1	MFBBa-17/3/30
$MgCl_2$-solution		25.0	13.0	33.0	50.0
NaCl-solution			18.0		
brucite [$Mg(OH)_2$]					3.0
magnesium oxide [MgO]		11.3	14.0	18.8	17.0
barite [$BaSO_4$]					30.0
salt grit [NaCl]		63.7	55.0	48.2	
density without air space ratio [kg/m³]		1941	1844	1840	1986
application		backfilling	binding of NaCl-fluids	filling of gaps	injection of fissures

CONSTRUCTION MATERIAL SOREL CONCRETE A1

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- **from 01/2003 till today, BGE TECHNOLOGY GmbH prepared and documented 1,700 samples within the scope of material investigations**

<u>average parameters for sorel concrete A1:</u>

< 3°	angle of creep
530 mm	flow channel extent
110°C	max. adiabatic hardening temperature
56 MPa	compressive strength, uniaxial*
2,6E-18 m^2	hydraulic permeability, expected value
22 GPa	coefficient of elasticity*
0,23	Poisson‘s ratio*
22 %	porosity*
65 %	of porosity is fluid saturated*

* D. Weise, P. Kamlot, D. Brückner, D. Naumann: Bericht zu Laboruntersuchungen an Rückstellproben aus Sorelbeton A1 der Chargen 31 bis 38. Institut für Gebirgsmechanik, Leipzig, 04.06.2007

- Long-term stabel under saliniferous conditions

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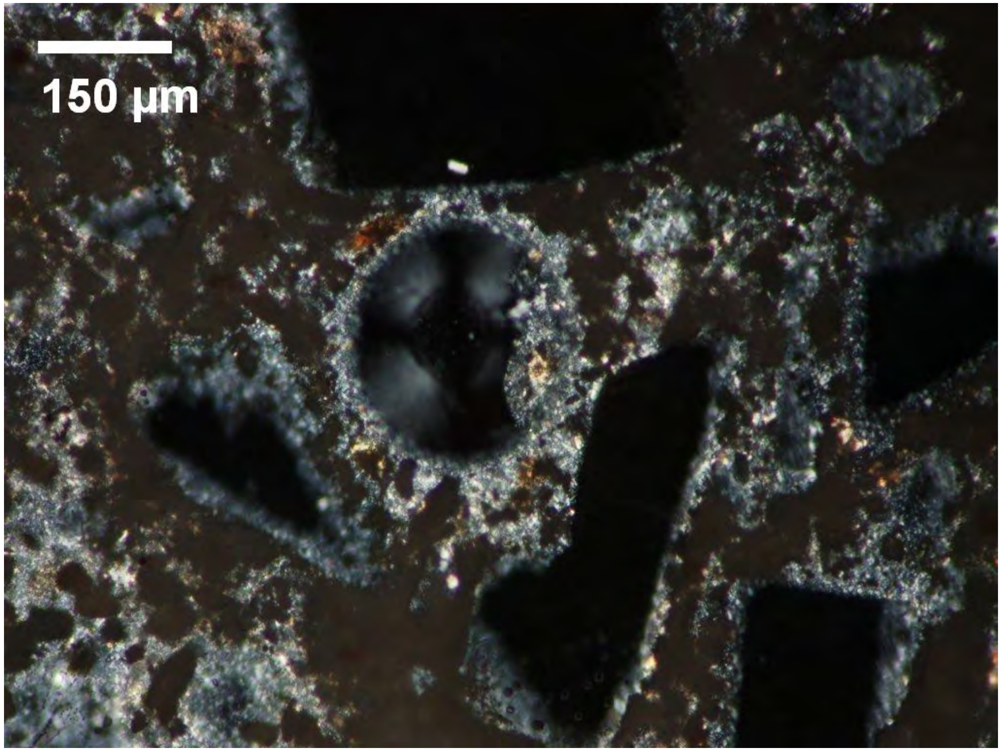
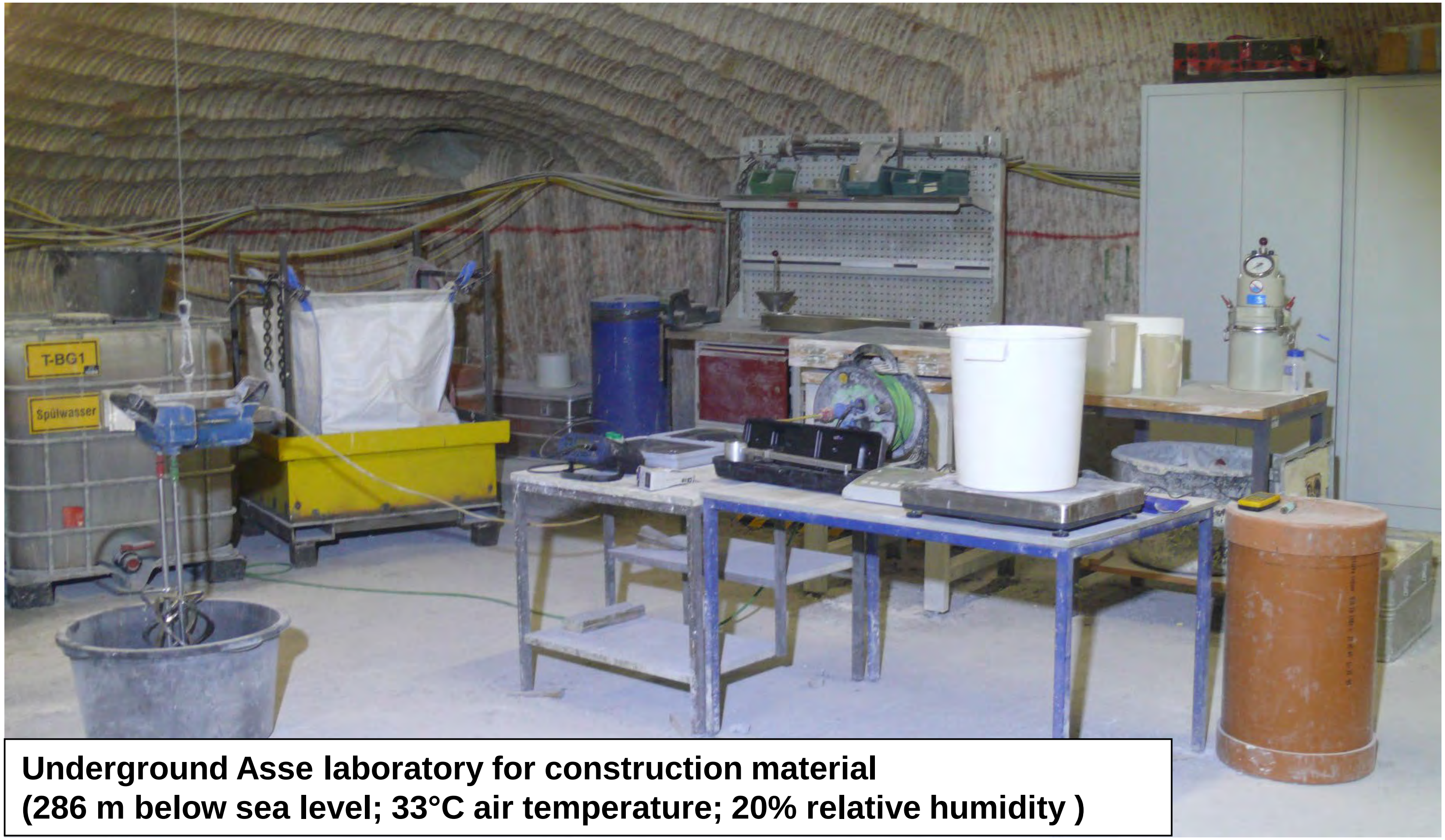
thin section of sorel concrete A1 with crossed nicols



halite grains (black) and pore (gray) with reaction fringe caused by microcrystalline phase of Korshunovskit [$Mg_2Cl(OH)_3 \times 4H_2O$].

QUALITY CONTROL – UNDERGROUND



Underground Asse laboratory for construction material
(286 m below sea level; 33°C air temperature; 20% relative humidity)

QUALITY CONTROL – STANDARD UNDERGROUND

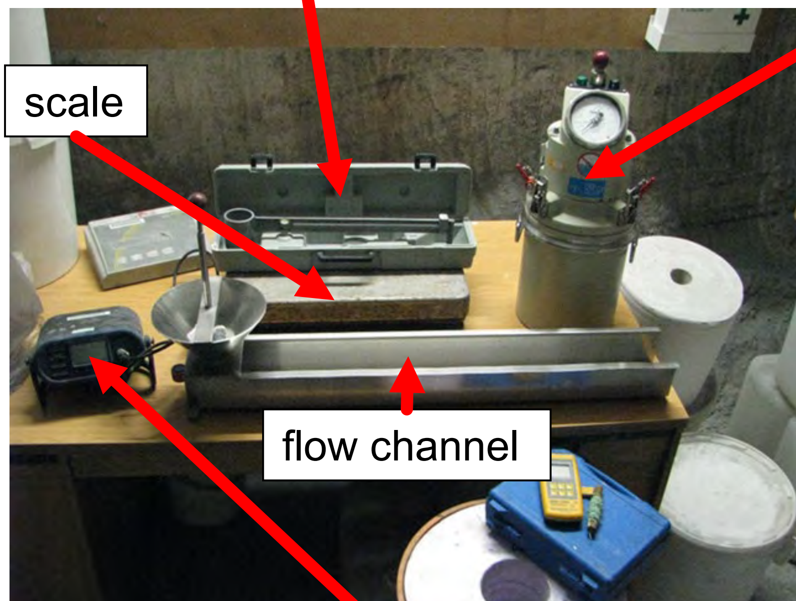
BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

quasiadiabatic temperature measurement

density measuring equipment

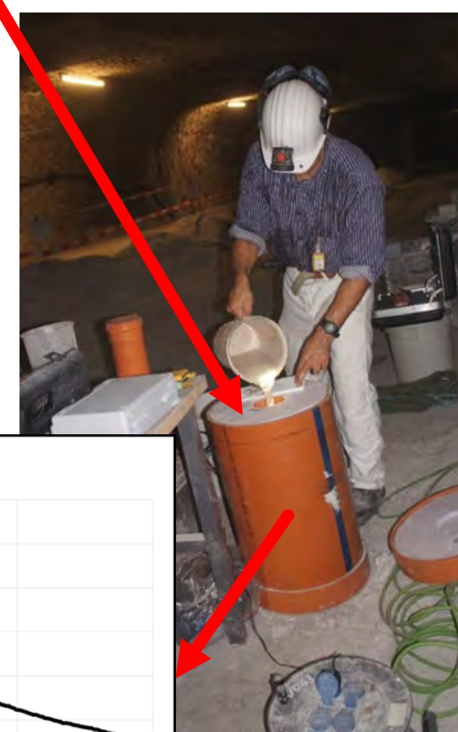
air entrainment meter

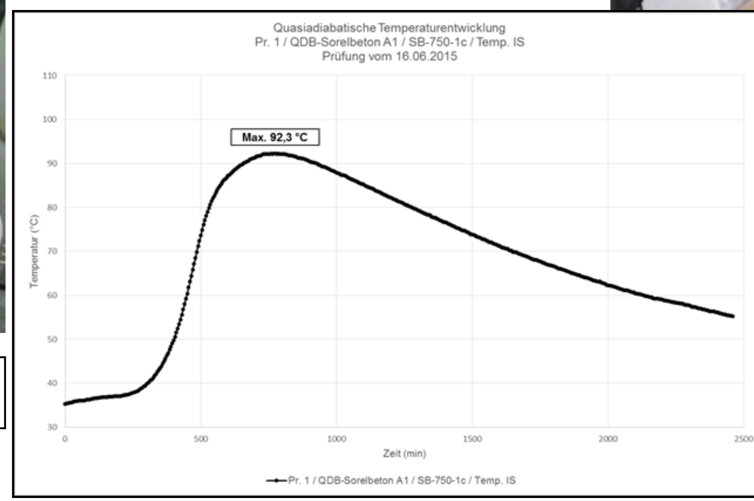
scale



flow channel

temperature measuring equipment



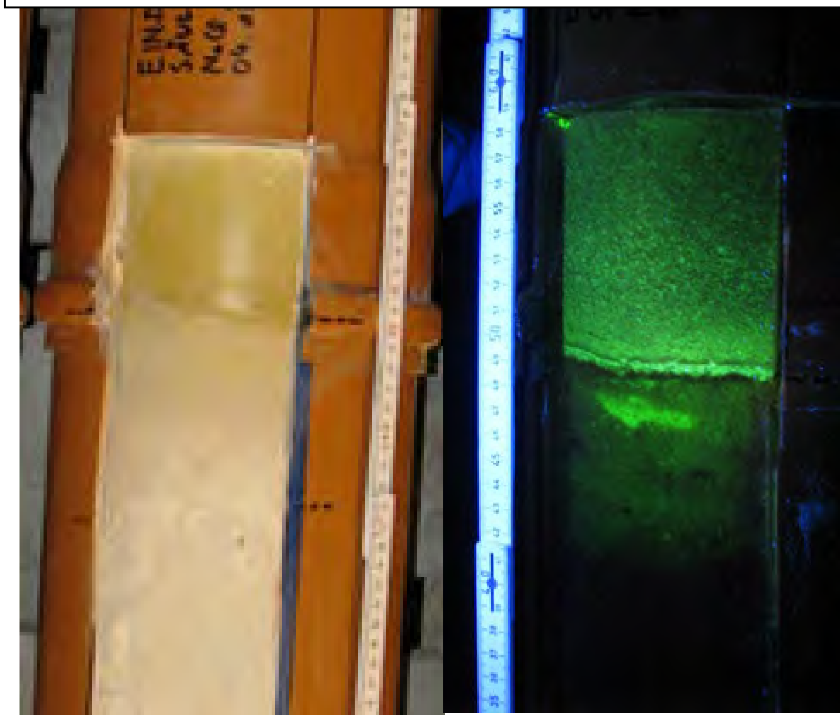


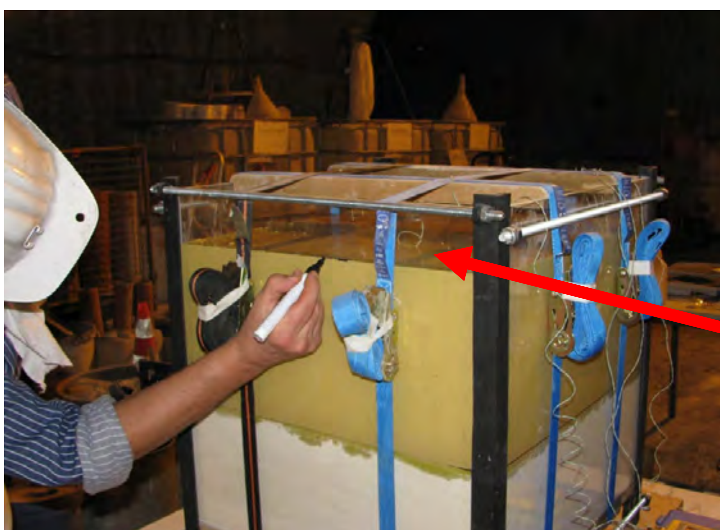
QUALITY CONTROL – SPECIAL APPLICATION UNDERGROUND

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

expansion measuring equipment

flourescenced column test without pressure





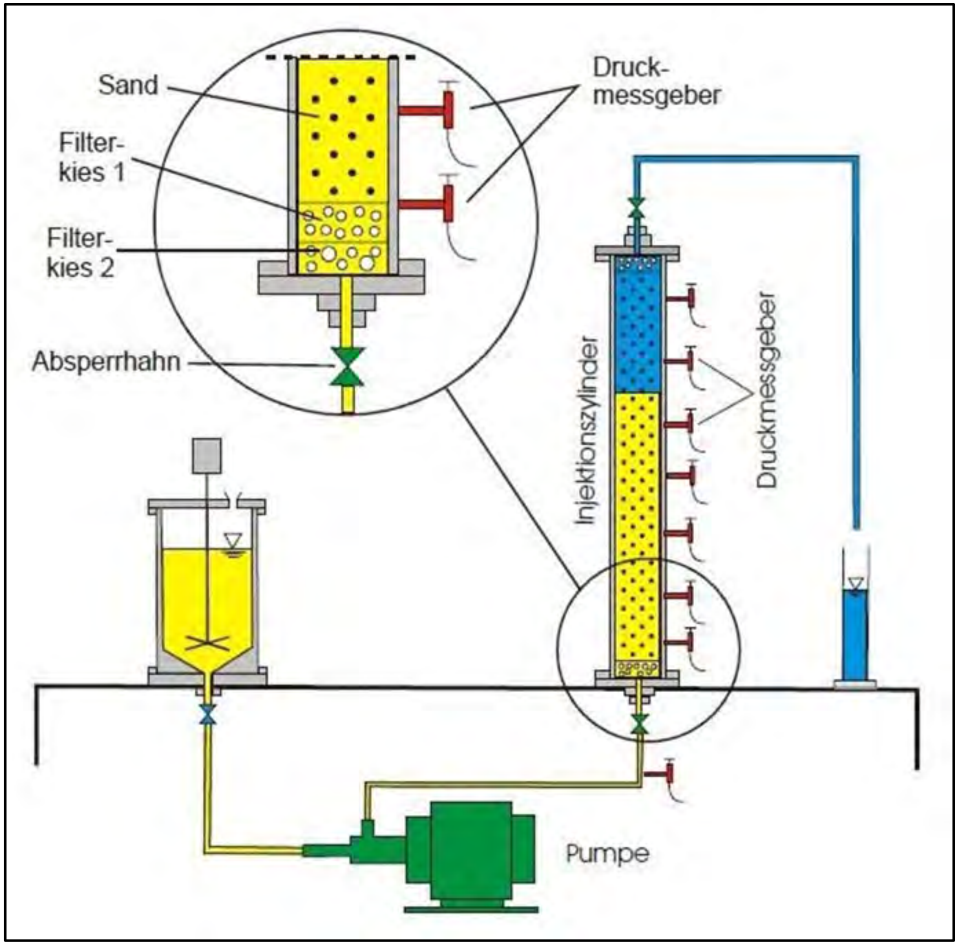
penetration measuring equipment

SA

BGE TEC
BGE TECHNOLOGY GmbH

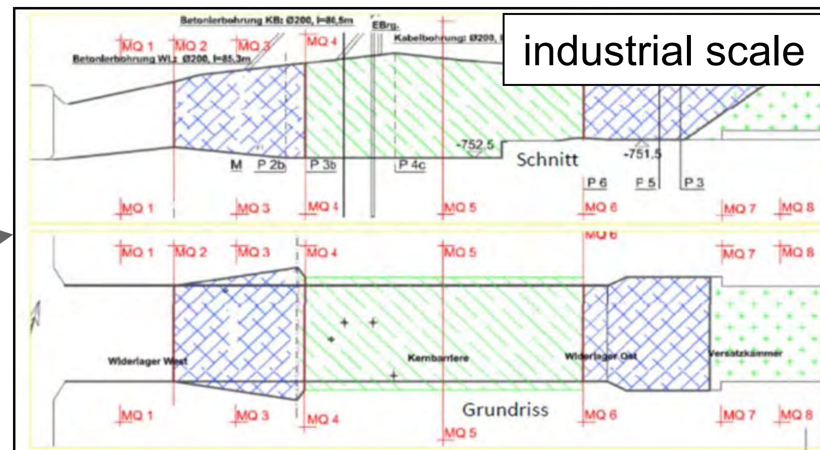
QUALITY CONTROL – SPECIAL APPLICATION UNDERGROUND

column test with pressure



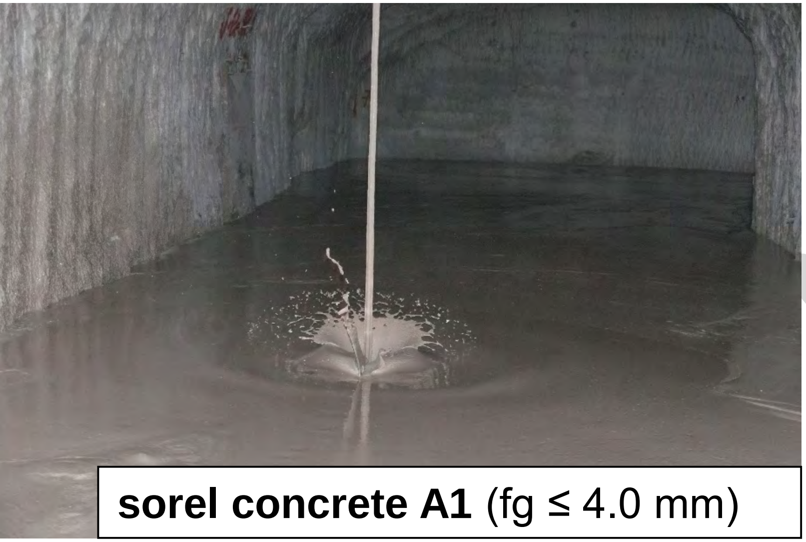
UPSCALING OF RESEARCH PROCEDURE

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG



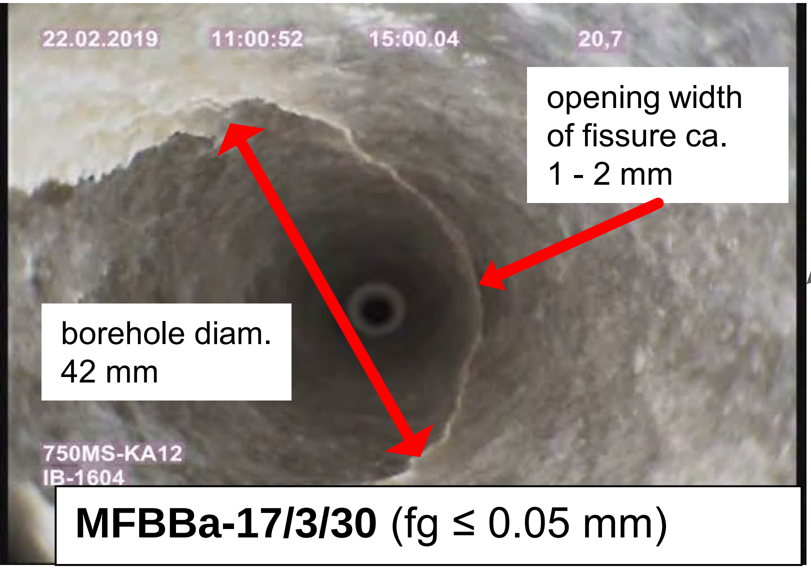
DOWNSCALING OF FILLER GRAIN SIZE (FG) DEPENDING ON OPEN SPACE

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG



sorel concrete A1 (fg ≤ 4.0 mm)

IM-Asse-1 (fg ≤ 0.3 mm)



MFBBa-17/3/30 (fg ≤ 0.05 mm)

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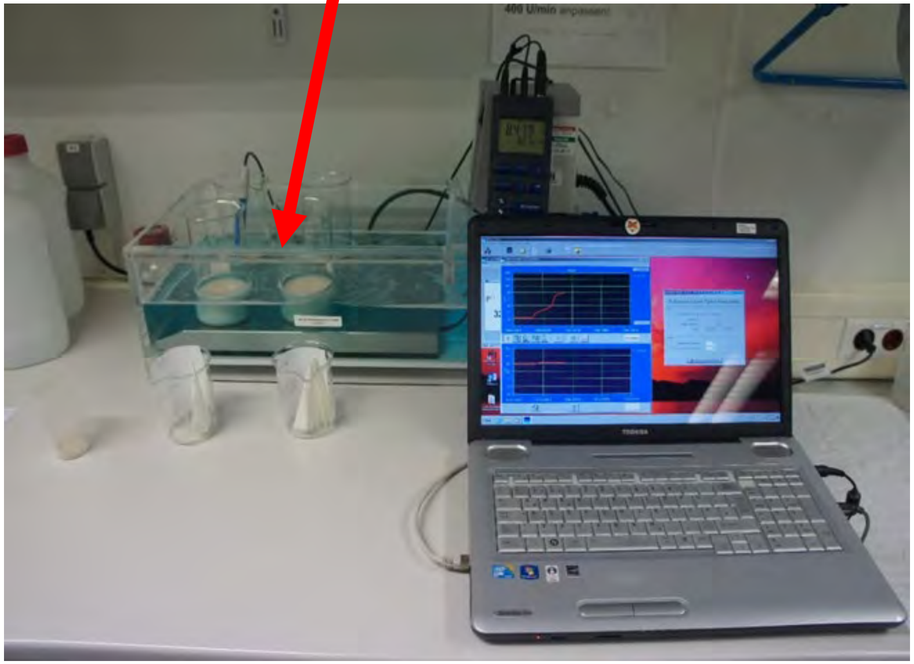
inductively coupled plasma optical emission spectrometry (ICP-OES)

reactivity test MgO



Asse laboratory for testing fluids and reactivity of MgO / intake and quality control

QUALITY CONTROL – ABOVE GROUND

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grain size measurement with laser granulometer

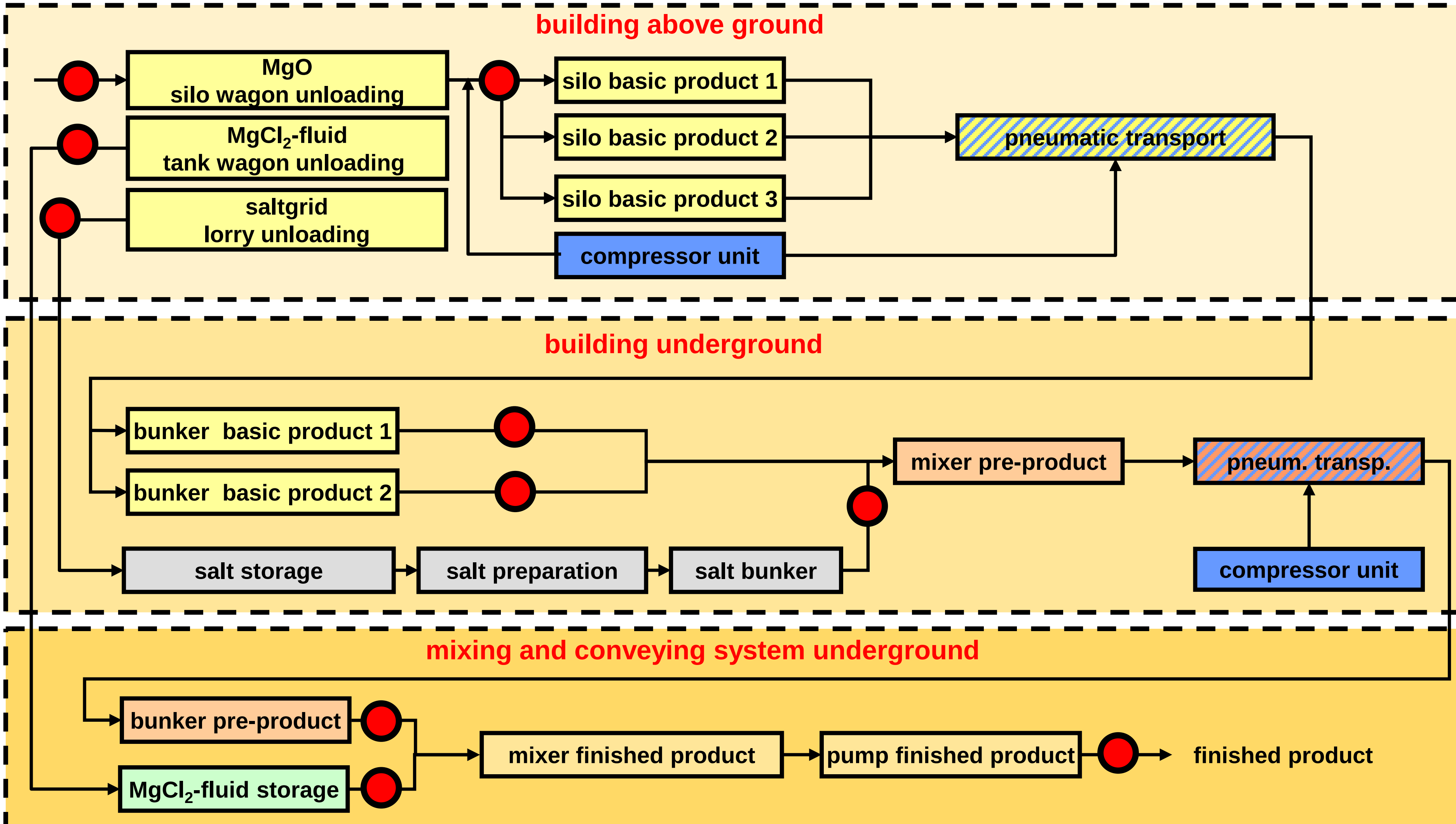
grain density measurement with helium pygnometer

mineralogical analysis using X-ray diffraction

Asse laboratory for construction material / intake and quality control

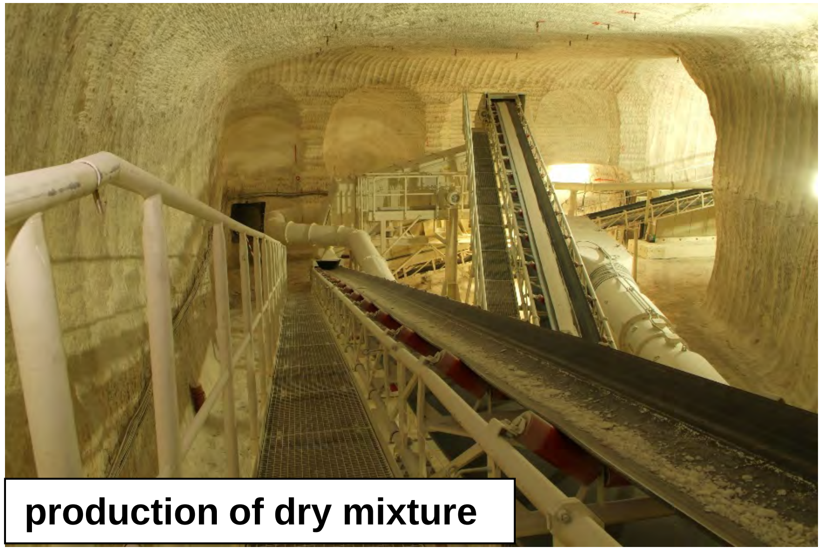
WORKFLOW – CONSTRUCTION COMPONENTS OF BARRIERS – SCHEMATIC FACILITY STRUCTURE

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG



sampling for quality assurance

MACHINERY AND EQUIPMENT – UNDERGROUND



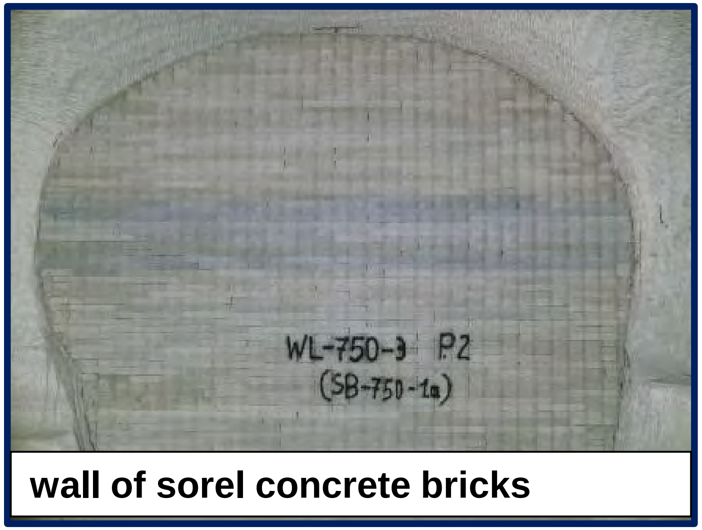
production of dry mixture

production of sorel concrete to bind contaminated fluids

production of sorel concrete A1 and A0

FIELD OF APPLICATION – BARRIERS

concrete formwork



wall of sorel concrete bricks

pumping of sorel concrete

void filled with sorel concrete

FIELD OF APPLICATION – INJECTIONS

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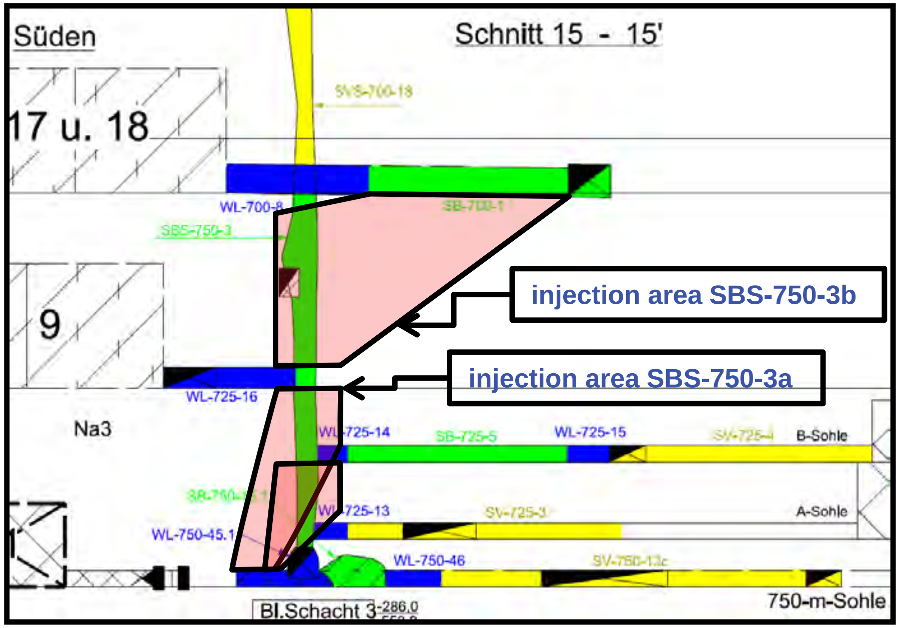


BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

construction material

- **amount of sorel concrete placed so far**
  - **sorel concrete A0 (since 2009): 19300 m^3**
  - **sorel concrete A1 (since 2006): 329450 m^3**

- **amount of injection grout placed so far**
  - **IM-Asse-1 (since 2003): 152146 l**
  - **MFBBa-17/3/30 (since 2011): 69362 l**

mechanical engineering

constructions

- **building constuction (sorel concrete A1)** **max. 60 bar; 20 m³/h**
- **BAK (sorel concrete with contaminated fluids)** **max. 25 bar; 3 m³/h**

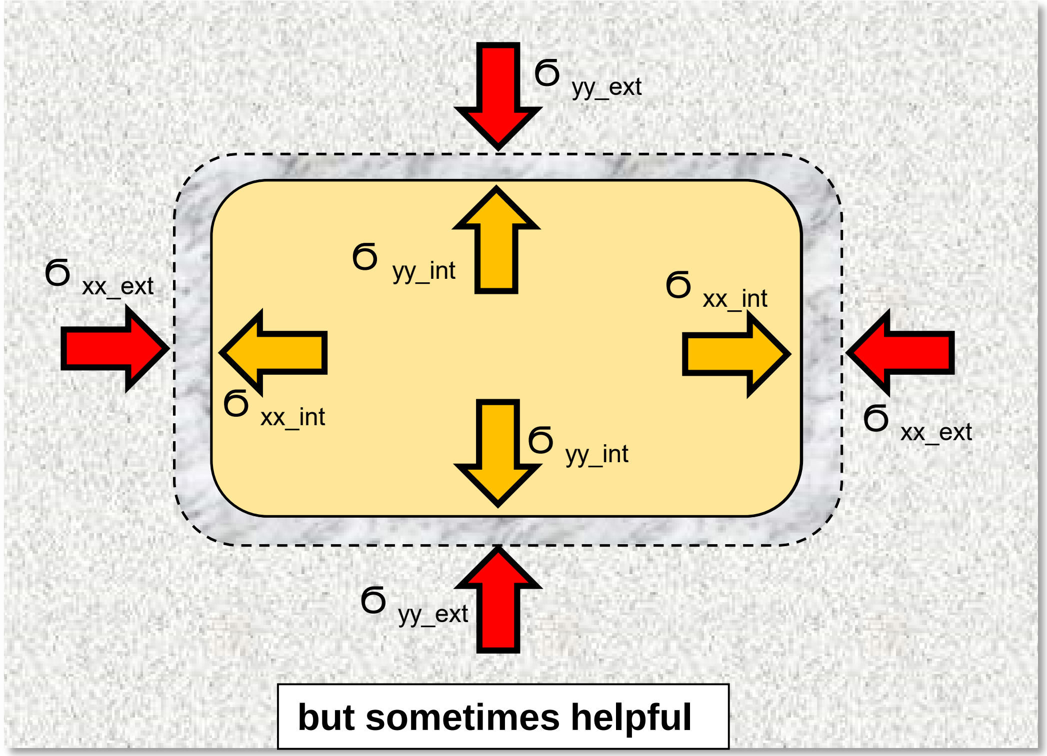
injections

- **MAT-colloidal mixer (MFBBa)** **20 l / charge; 965 U/min**
- **PFT-pumps (IM-Asse-1)** **max. 25 bar; 12 l/min**
- **MONTANBÜRO-pump EH 300-3 (IM-Asse-1)** **max. 120 bar; 3 m³/h**
- **Obermann-pumps DP-36-2-G (MFBBa)** **max. 150 bar; 11 l/min**

OUTLOOK

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

expansion is not always beautiful



but sometimes helpful

LESSONS LEARNED

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- in the case of radioactive waste disposal in saliniferous host rock, sorel concrete and grout can play important roles in the construction of geotechnical structures
- upscaling from small-scale, to lab scale, to pilot scale, to industrial scale is useful for optimization process
- every step has to be accompanied by an adapted quality control program
- laboratories located underground and above ground are necessary for a continous quality assurance
- within the scope of the emergency measures carried out at the Asse mine, the successful use of sorel concrete has been demonstrated
- sorel concrete is like good wine – its quality improves with age

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BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

10th US/German Workshop “Salt Repository Research, Design, and Operation”

Experiences from an In-Situ Test Site for Sealing Element in Shafts and Vertical Excavations in Rock Salt

May 29th , 2019 / Rapid City

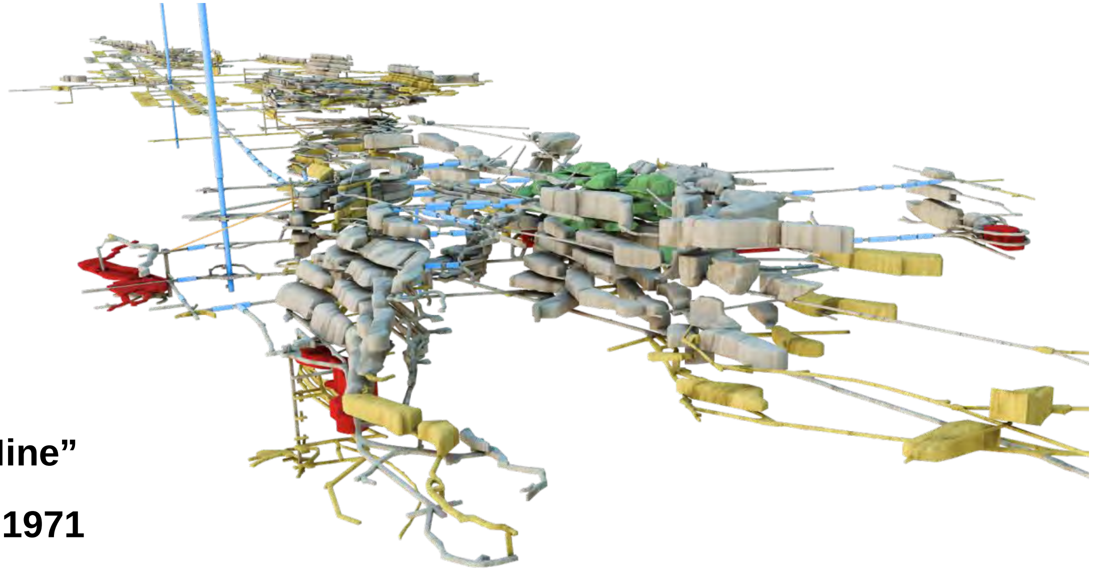
Dr. Thomas Schröpfer (BGE GmbH)

Jan Bauer, Dr. Monika Kreienmeyer, Beatrix Stielow, Dr. Jürgen Wollrath (BGE GmbH)

Introduction ERAM – Repository in a Former Production Mine

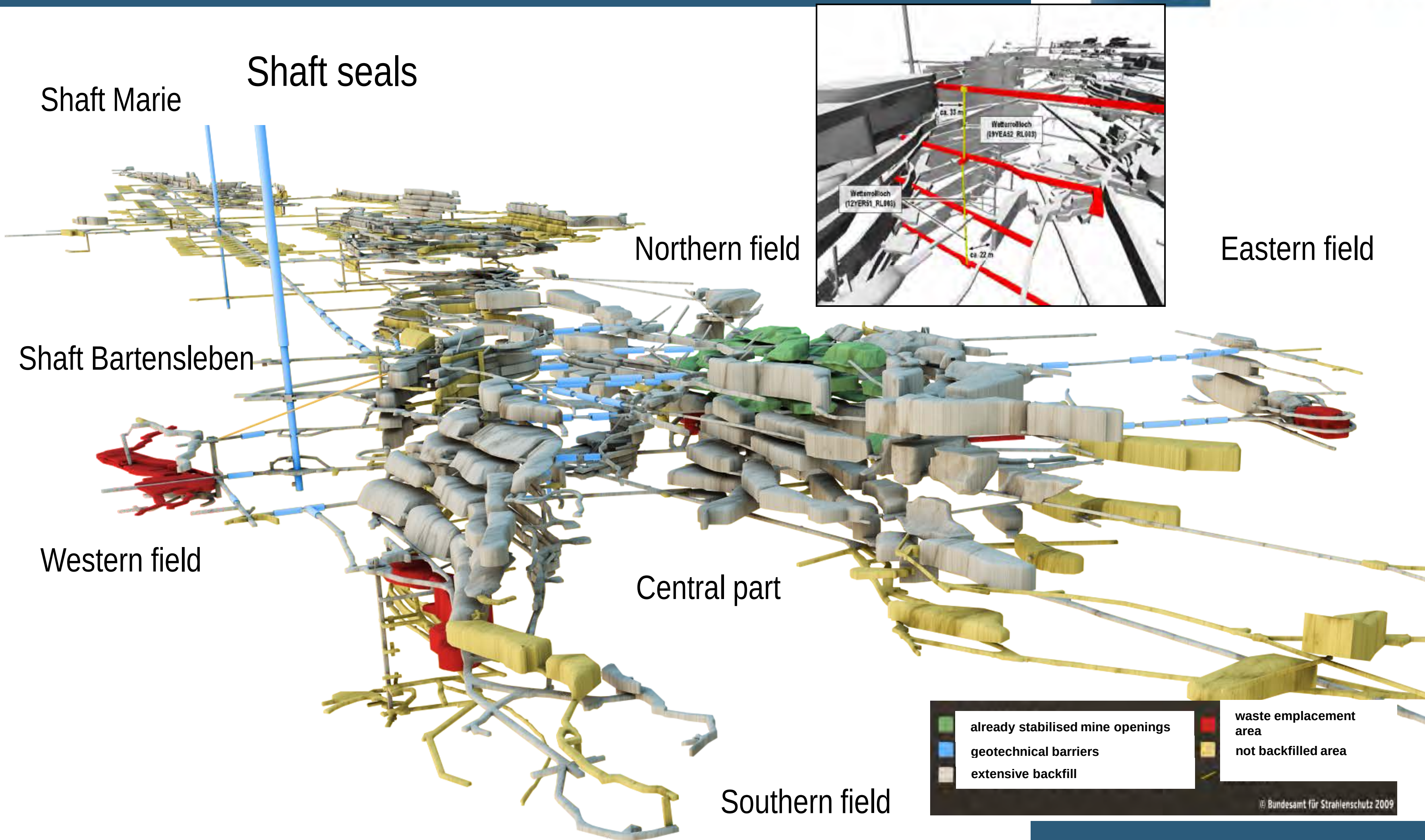
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

- **2 connected mines: “Bartensleben Mine” and “Marie Mine”**
- **Production of Potassium and Rock Salt from 1913 to 1969**
- **Total volume of mined structures: ~ $8.7 \cdot 10^6$ m^3**

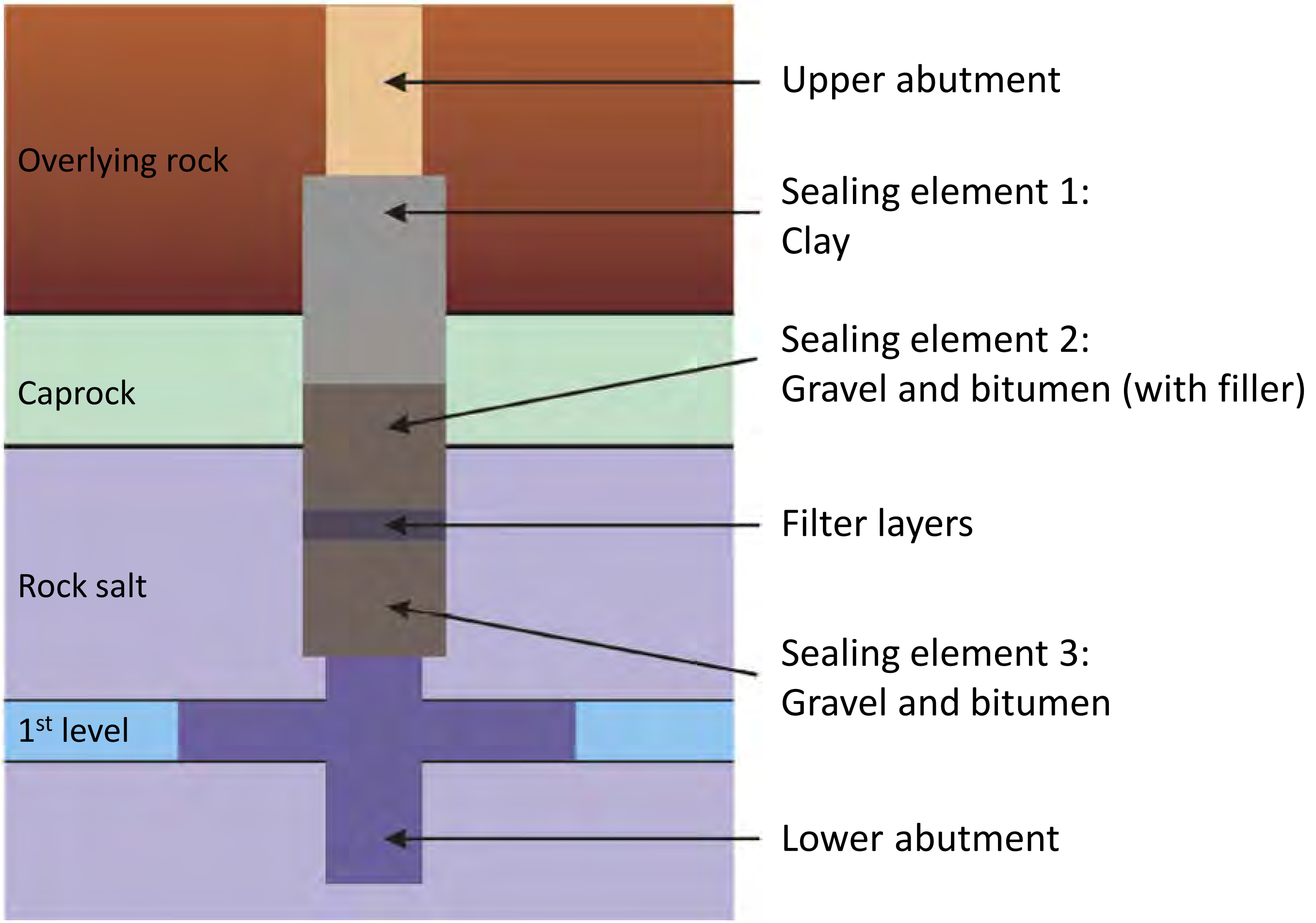


- **Waste emplacement exclusively in “Bartensleben Mine”**
- **Waste emplacement started in 1971 and ended in 1998**
- **36,800 m^3 of waste with activity of < $6 \cdot 10^{14}$ Bq**
- **Licensing procedure for closure initiated**

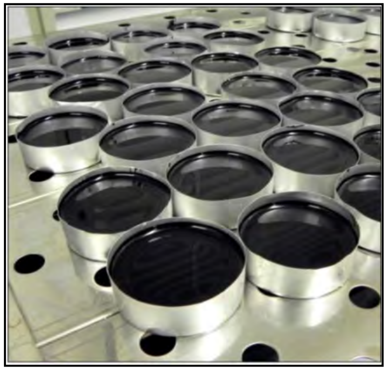
Closure concept



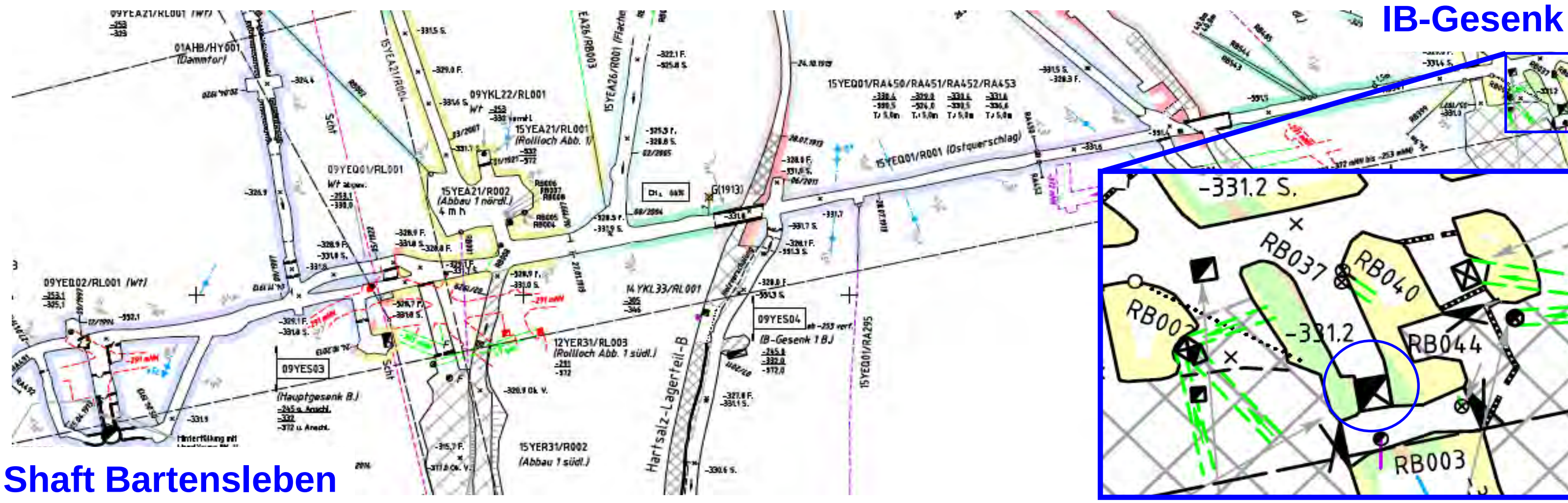
Shaft sealing concept



Stepwise planning and testing



IB-Gesenk 1B



Shaft Bartensleben

Stepwise planning and testing

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Scope and Objectives

Show the technical feasibility concerning

- logistic boundary conditions
- quality management
- health and safety assessment

as well as

- measure the temperature influence of hot asphalt on gravel and rock salt
- proof the hydrostatic pressure of the asphalt

Additionally, the remaining pore value is assessed (goal: < 3%)

Principle sketch and instrumentation

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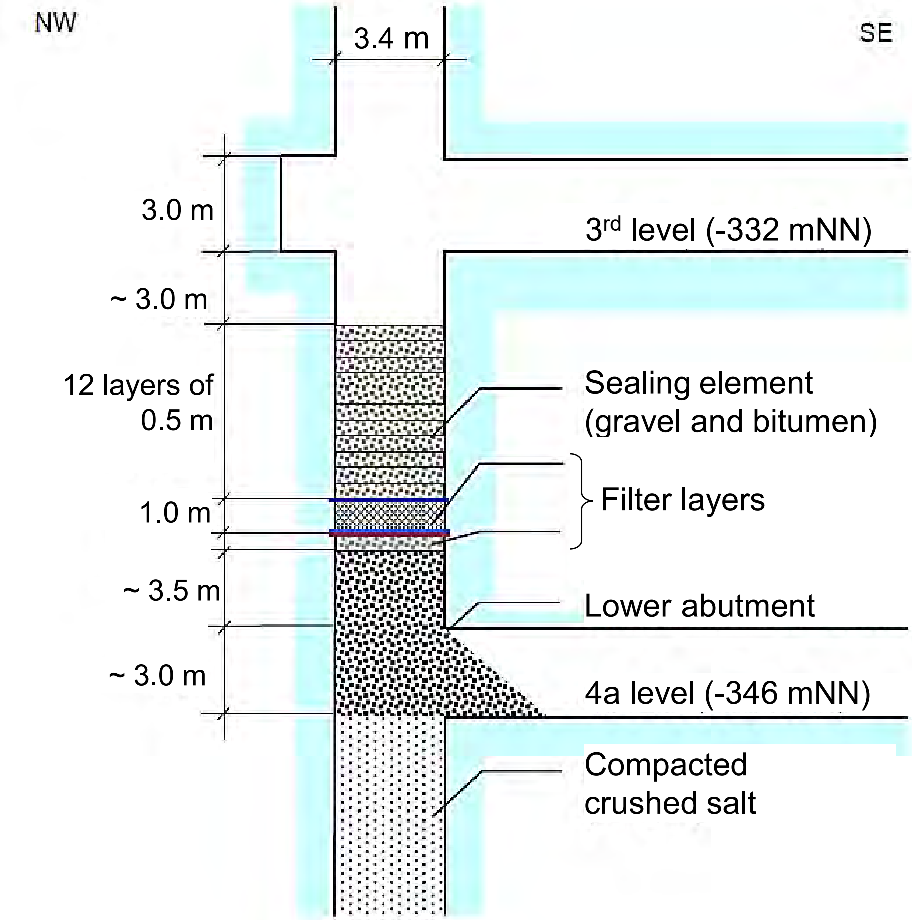
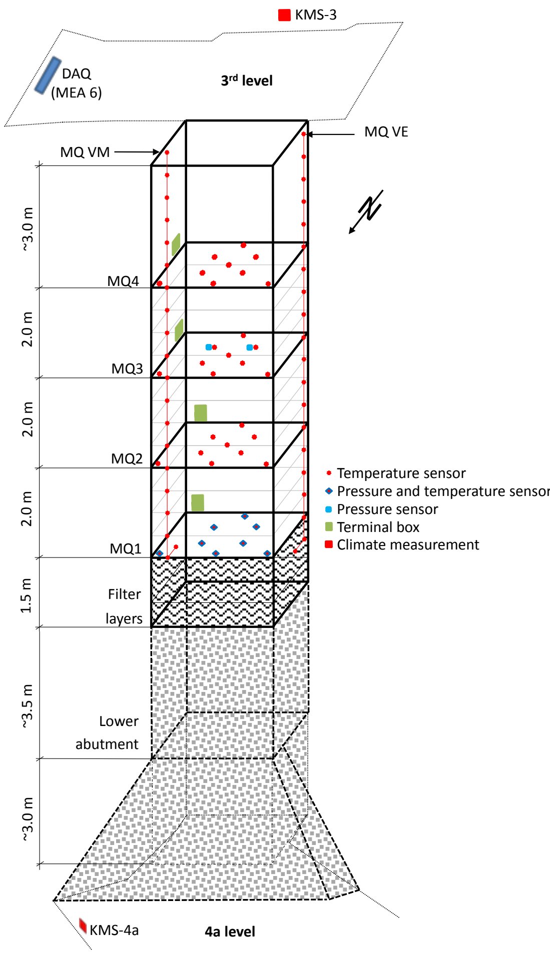




Preliminary work

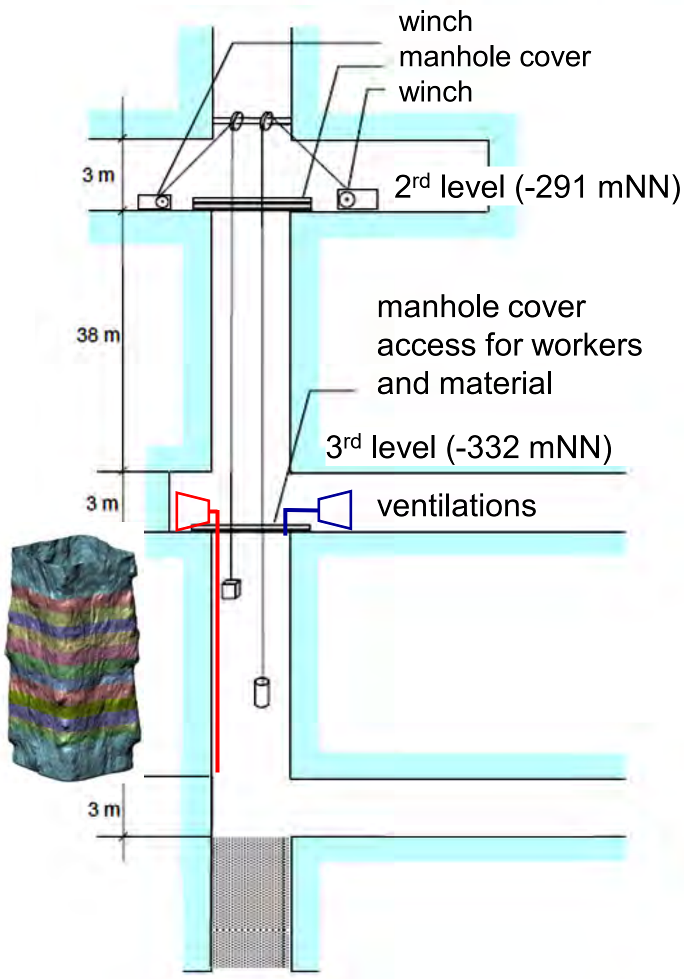
Installation of winches for personnel and material transport

Preliminary work

Production of the bitumen (after preproduction)

Construction process

– detailed stratigraphical analysis
– 3D scan
– installation of sensors for vertical temperature measurements
– testing the compaction of the gravel
– building the abutment and the filter layers
– installation of temperature and pressure sensors in MQ1
– construction of the sealing element in three sections of four layers each
– stepwise installation of additional sensors in MQ2 to MQ4



Construction process

Test of gravel compaction

Construction process

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Transport and compaction of the gravel

Construction process

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Delivery and heating of asphalt

Construction process

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Transport of the bitumen to the test site

Construction process

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Lowering of the asphalt heater via the blind shaft

Construction process

Transportation of the personnel via the blind shaft

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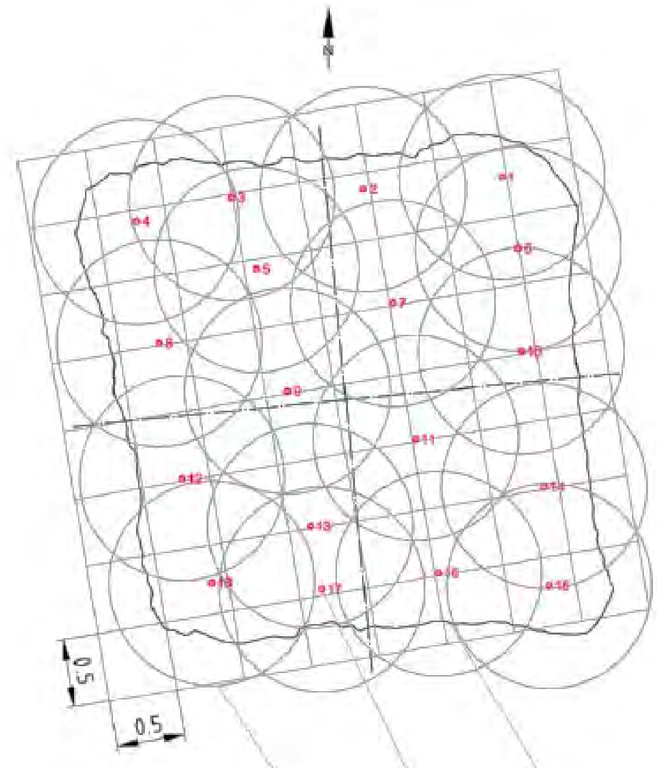
Filling in the hot asphalt



Construction process

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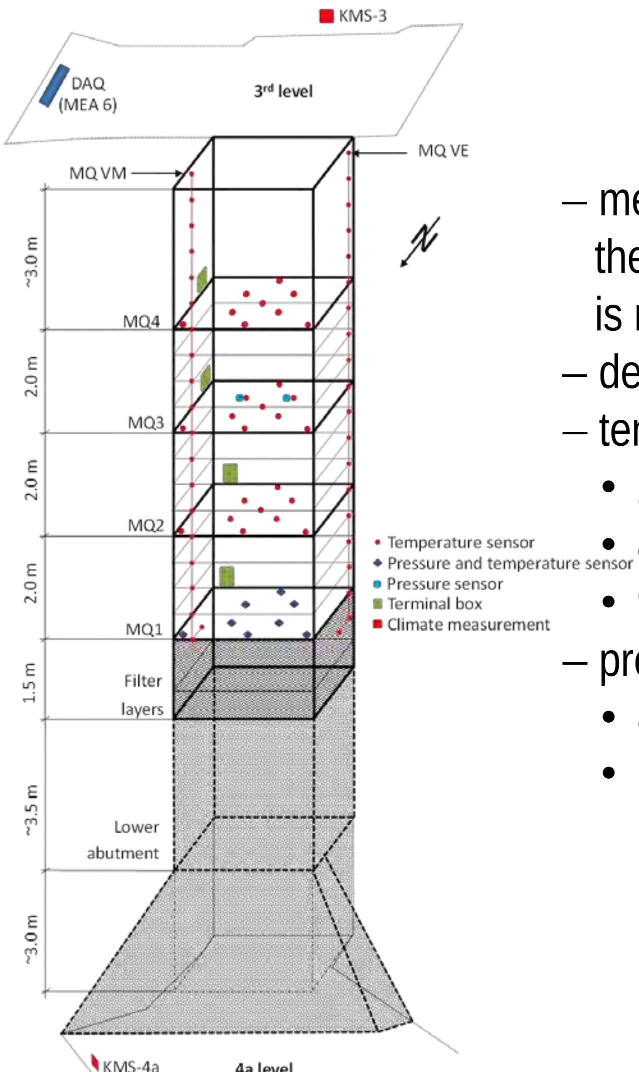
Geotechnical instrumentation



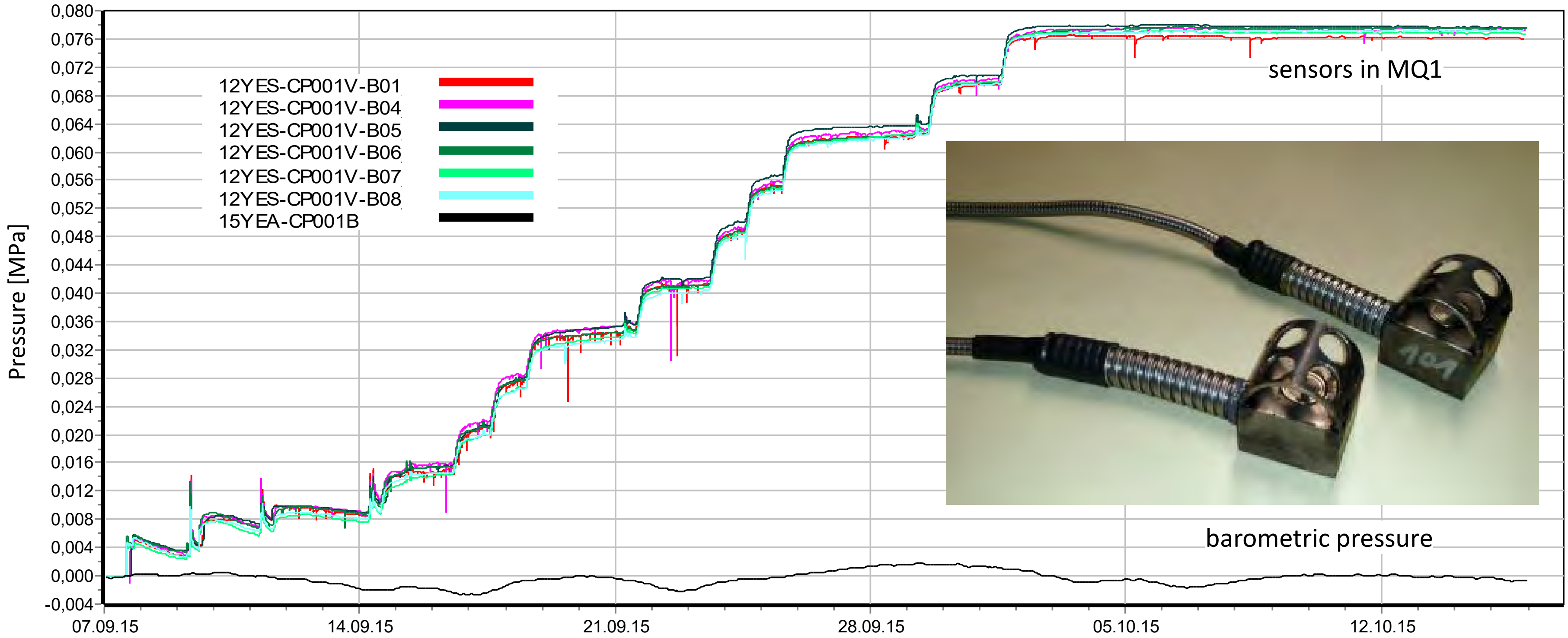
– measuring the thermal impact of the hot asphalt during the construction process and until the initial temperature is reached again
– demonstrating the hydrostatic pressure of the asphalt
– temperature sensors
  • 2 vertical chains with 20 sensors on the surrounding rock
  • 8 temperature sensors at the bottom (MQ1)
  • 9 temperature sensors at 2, 4, and 6 m (MQ2 - MQ4)
– pressure sensors
  • 8 pressure sensors at the bottom (MQ1)
  • 2 additional pressure sensors at 4.0 m (MQ3)

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Installation of sensors for vertical temperature measurements

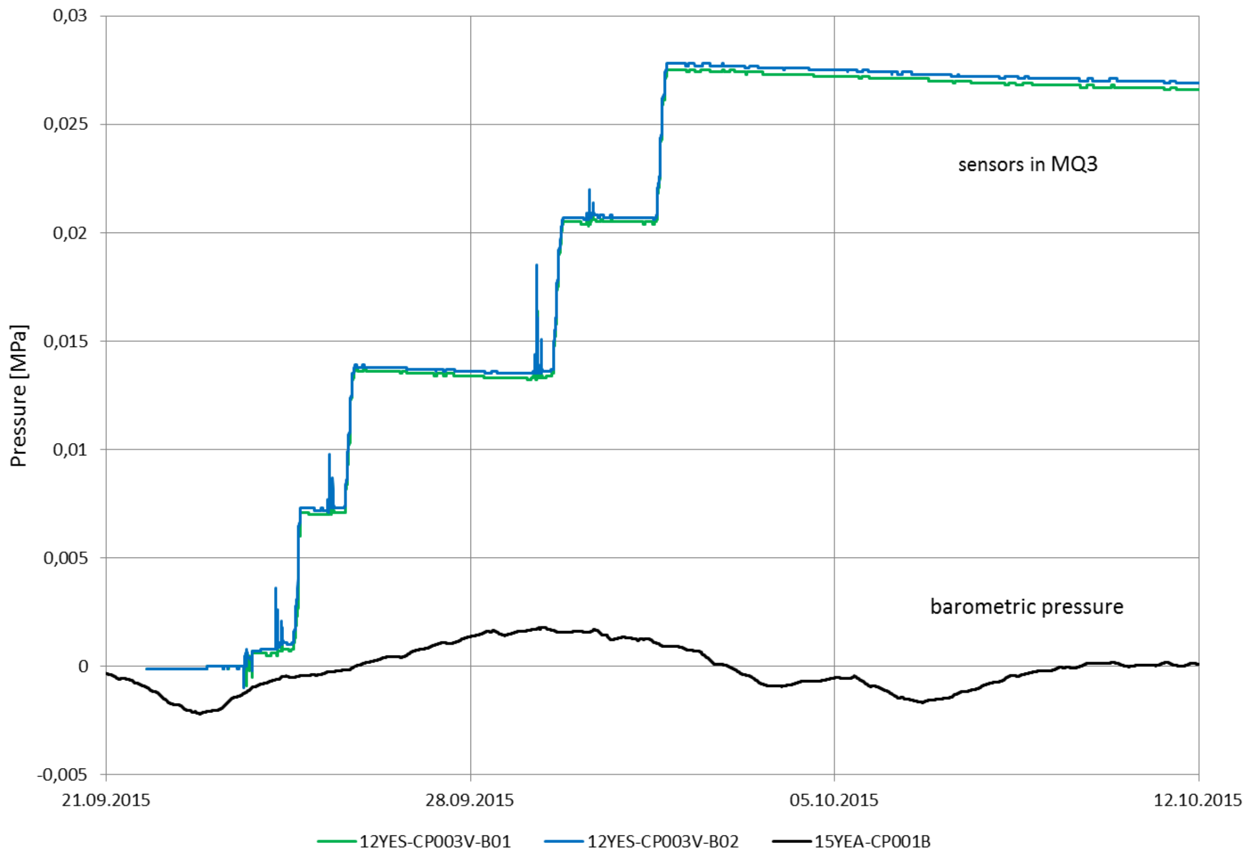
Results

Pressure measurements in MQ1 (0.0 m)



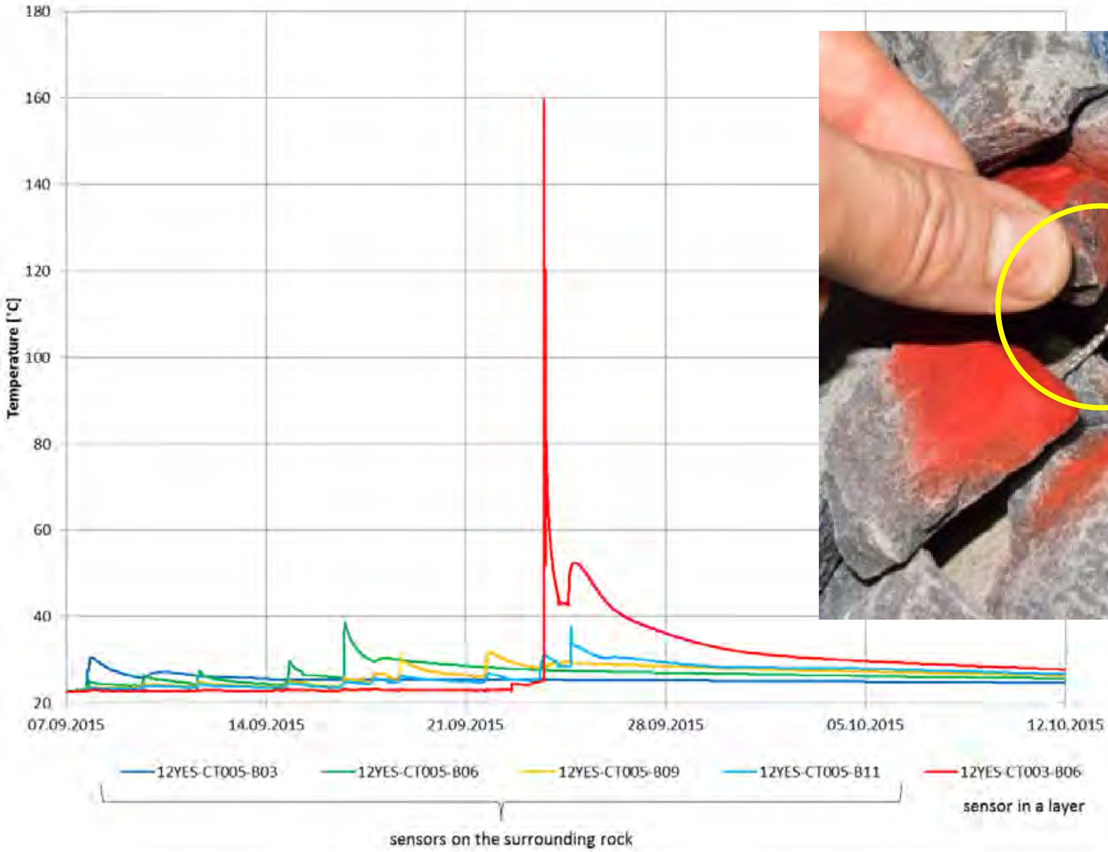
Results

Pressure measurements in MQ3 (4.0 m)



Results

Temperature measurements in MQ3 (4.0 m)



Results

Remaining pore volume

$$= \frac{(\textbf{excavation volume} - \textbf{gravel volume} - \textbf{asphalt volume})}{\textbf{excavation volume}}$$

Calculation of volumes by

- 3D scan of the excavation
- weighing of gravel and asphalt
- measuring densities

- Calculated for each layer during the contruction process
- Calculated as an integral value to evaluate the filling
    - approx. 0.9 % ± 1%

Bitumen surface after 2 months

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Summary

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

- technical feasibility has been demonstrated
- all quality requirements were met
- health and safety assessment was successful
- temperature ist back to initial temperature after several months
- evaluation of the remaining pore volume
  - by masses: approx. 0.9 % ± 1%
  - by pressure measurements: approx. 1.7 % ± 0.3%

→ Test successful … and without any accident!

Special Thanks to

the contractors

and to all my colleagues, who worked on this project especially the blue-collar workers from the site

Thank you for your attention!

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

WIPP Panel Closure Program

Rey Carrasco
NWP - WIPP

Scope of Presentation

- Panel Closure System Background
- Design Review Guidelines
- HWDF Panel Closure System Design Criteria
- Panel Closure System Design Alternatives

Design Review Guidelines

- Design Review per WP 09-CN3018
- List of Alternatives
- HWDF Performance Specifications
- Additional Schedule and Cost Considerations
- Judge and Rank Alternatives to Assist in final selection

HWDF Criteria

The panel closure system is designed to meet the following requirements that were established by the DOE for the design to comply with 20.4.1.500 NMAC (incorporating 40 CFR §264.601(a)):

- the panel closure system shall perform its intended functions under loads generated by creep closure of the tunnels Waste Isolation Pilot Plant
- the nominal operational life of the closure system is 35 years
- the panel closure system may require minimal maintenance per 20.4.1.500 NMAC (incorporating 40 CFR 264.111)
- materials shall be compatible with their emplacement environment and function

Operational Criteria

- PCS Design shall Limit VOCs Migration
- Flow of VOCs through the Disturbed Rock Zone (DRZ)
- Shall Consider Methane Gas Explosion
- 35 Year Design Life
- Occasional As Opposed to Routine Maintenance
- Address Most Severe Ground Conditions

Design Criteria

- PCS Performs Intended Function Under Creep Closure Loads
- Treat Closure Surfaces

Safety Criteria

- Class III B Using Standard Construction Methods
- Structural Analysis Based Upon WIPP Data

Structural/Material Criteria

- Selected Materials Compatible with Underground Environment
- Thermal Cracking for Concrete Components
- PCS Sustains Pressure and Temperature Loads from a Methane Explosion

Construction Criteria

- Conventional Mining Practices
- QA/QC Program for Material Properties
- Consideration of Available Underground Services

Should We Design for Restricted Flow?

- Uncertainty in Source Term of VOCs
- Uncertainty in Molar Gas Generation Rates
- Uncertainty in VOCs Flow Through Large Scale Seal Components
- Uncertainty in Volumetric Closure Rates
- HWDF VOCs Limits Must Be Achieved in Real Time or WIPP Operations Could Be Shut Down for Violation of the RCRA Permit

Should We Design for Restricted Flow?

- Flow Restriction Would Allow Time to Evaluate VOCs Flow Trends and Take Remedial Action Without Shutting Down WIPP Operations
- Barriers for Protection of Underground Personnel Should be of "Substantial Construction"

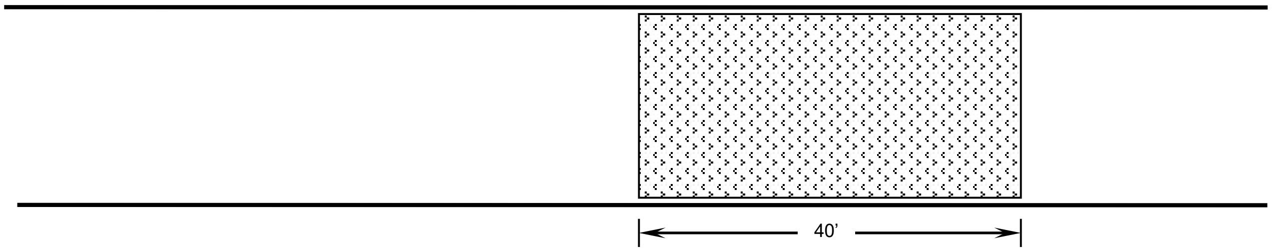
Evaluation of Design Alternatives

- Estimated Effective Intrinsic Permeability and Conductance
- Estimated Costs
- Weights Established for the Broad Categories
- Alternatives Worksheet to Score from 1 to 10 for each of the HWDF Design Criteria

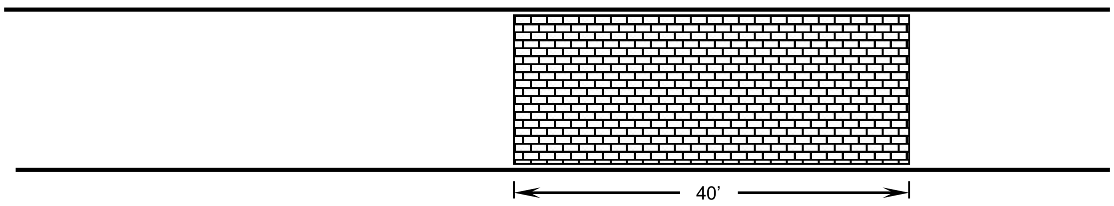
List of Alternatives

- Simple Operational Alternatives
- Original Options A through D
- Monoliths of Various Materials
- Block Wall Options
- Backfills
- Combination of Block Walls and Backfills

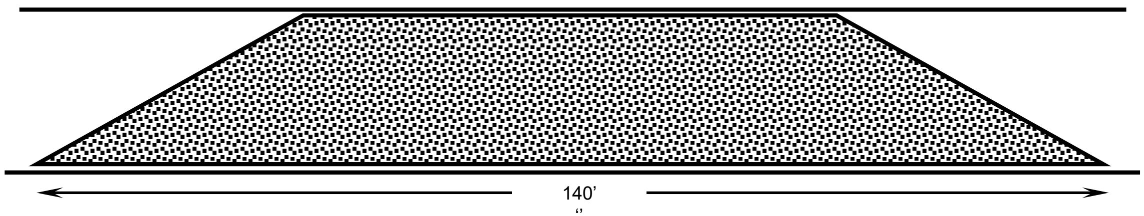
Option 9 Concrete Monolith



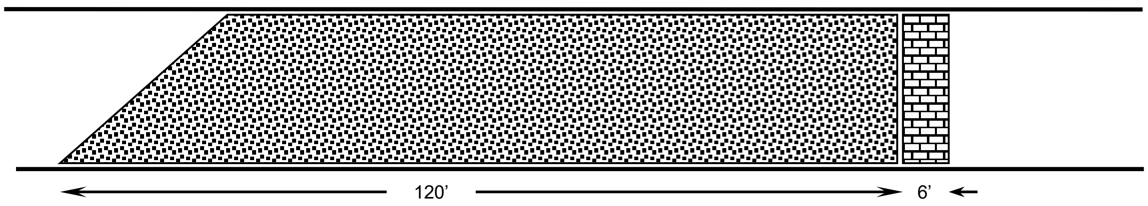
Option 10 Block Wall



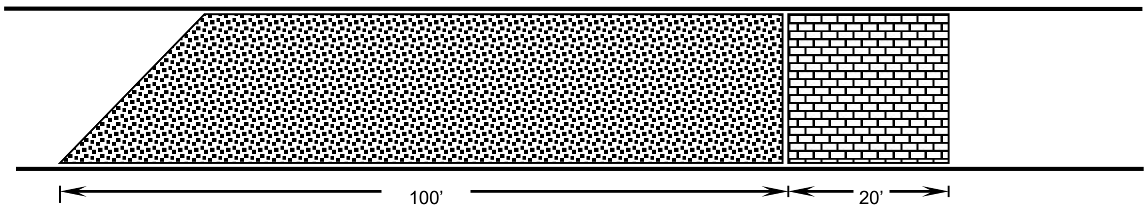
Option 11 Granular Material



Design Combinations

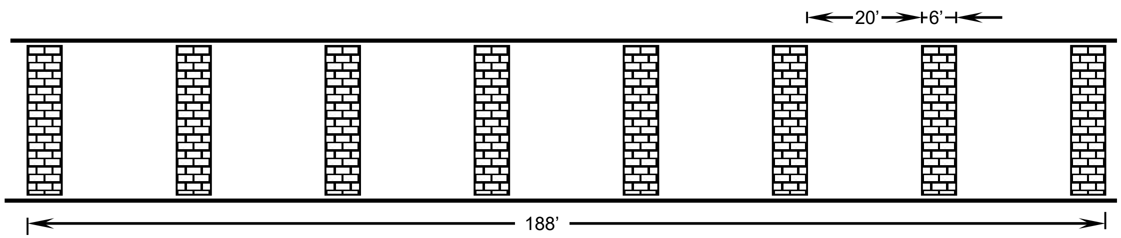


Option 12

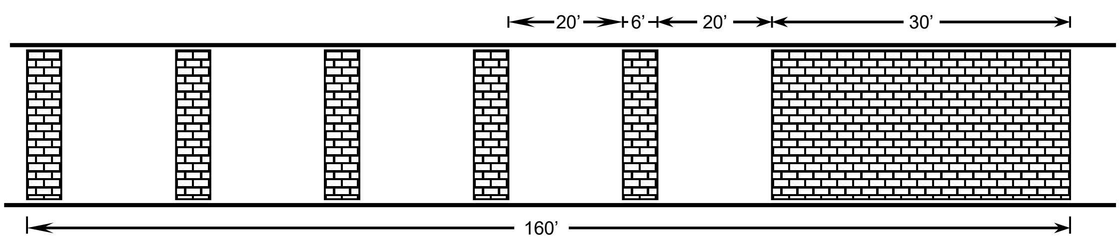


Option 13

Intermittent Walls

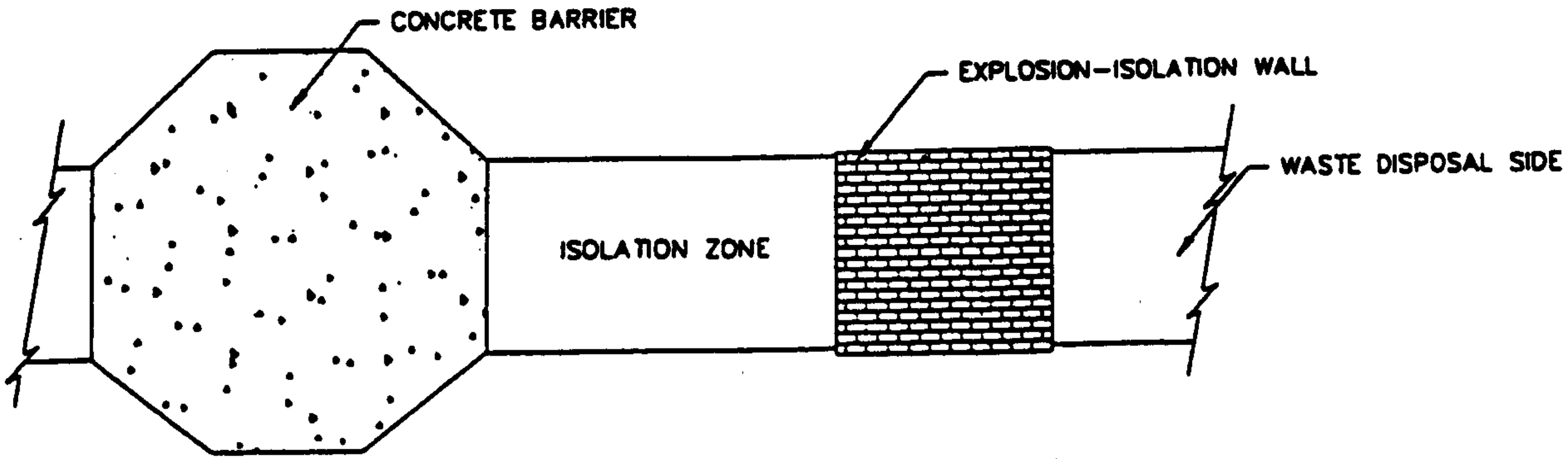


Option 14



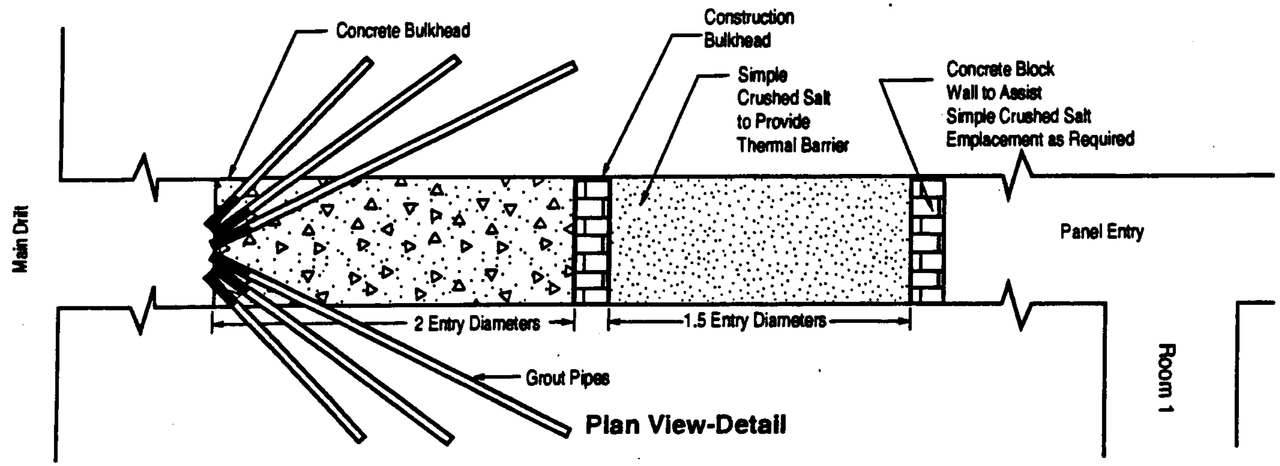
Option 15

EPA Selected Option D



D. CONCRETE BARRIER WITH DRZ REMOVED AND EXPLOSION ISOLATION WALL

PCS Conceptual Design - 1995



Note that design components will be selected for radiation protection and fire suppression.

LEGEND

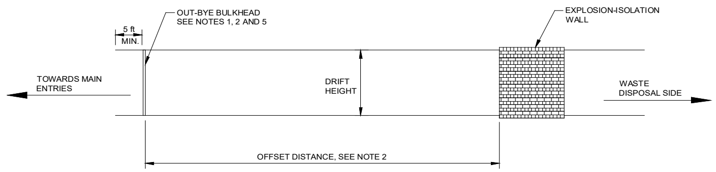
ROM SALT

NOTES

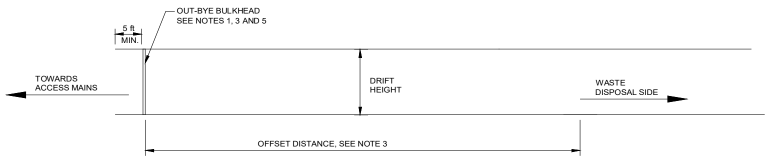
1. RECESS OUT-BYE BULKHEAD MIN. 5 FT FROM INTERSECTION WITH ANOTHER DRIFT OR MAIN ENTRY.
2. OFFSET OUT-BYE BULKHEAD FROM EXPLOSION-ISOLATION WALL. MINIMUM OFFSET DISTANCE IS 2.0 x ACCESS DRIFT HEIGHT.
3. FOR PANELS WITHOUT EXPLOSION-ISOLATION WALLS, OFFSET OUT-BYE BULKHEAD FROM WASTE CONTAINERS. MINIMUM OFFSET DISTANCE IS 22 FT.
4. INSTALL IN-BYE BULKHEAD AT LEAST 22 FT FROM THE NEAREST WASTE CONTAINER.
5. WPC-B BULKHEADS SHOULD BE PLACED AT LEAST 5 FT FROM THE TOE OF ROM SALT (IF APPLICABLE) ASSUMING ROM SALT END SLOPES OF 2H:1V.
6. MINIMUM LENGTH OF WPC-B ROM SALT IS A FUNCTION OF THE MAIN ENTRY WIDTH AS FOLLOWS:

MINIMUM ROM SALT LENGTH - EXLUDING END SLOPES

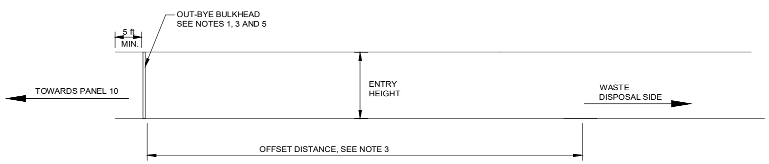
ENTRY WIDTH (ft)	MIN. ROM SALT LENGTH (ft)
14	35
16	40
20	50
25	65



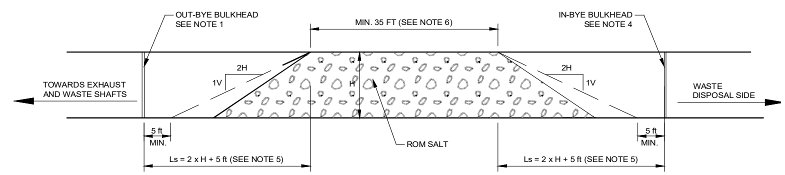
WPC-A FOR PANEL ACCESS DRIFTS WITH EXPLOSION-ISOLATION WALLS - PANELS 1, 2 AND 5
NOT TO SCALE



WPC-A FOR PANEL ACCESS DRIFTS W/OUT EXPLOSION-ISOLATION WALLS - PANELS 3, 4, 6, 7 AND 8
NOT TO SCALE



WPC-A FOR PANEL 9 - WASTE PLACEMENT SOUTH OF S2750
NOT TO SCALE



WPC-B FOR PANEL 10 - WASTE PLACEMENT SOUTH OF S1600
NOT TO SCALE

CLIENT
NUCLEAR WASTE PARTNERSHIP LLC

PROJECT
WIPP CLOSURE
GEO-MECHANICAL COMPLIANCE

CONSULTANT
Golder Associates

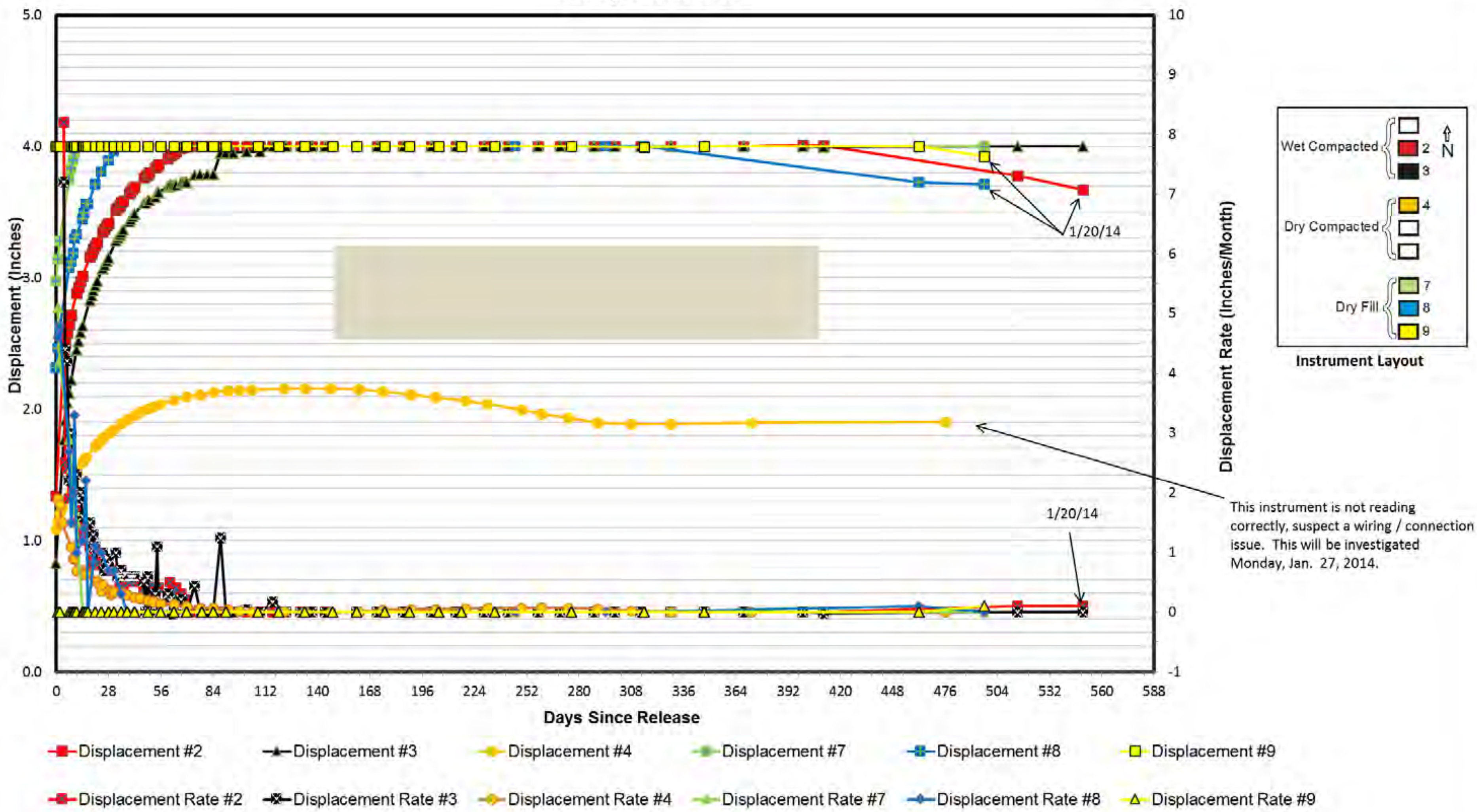
YYYY-MM-DD	2016-07-18
PREPARED	GG
DESIGN	GG
REVIEW	WTT
APPROVED	WTT

TITLE
WPC DETAILS
BULKHEAD AND ROM SALT LOCATIONS

PROJECT No.	CONTROL	Rev.	FIGURE
063-2213NEW		----	4


WACKER NEUSON

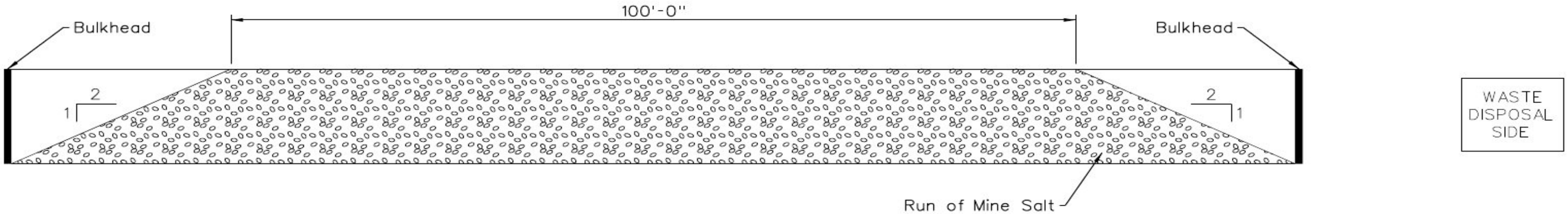
Compaction Test



EPA Approved Panel Closure System

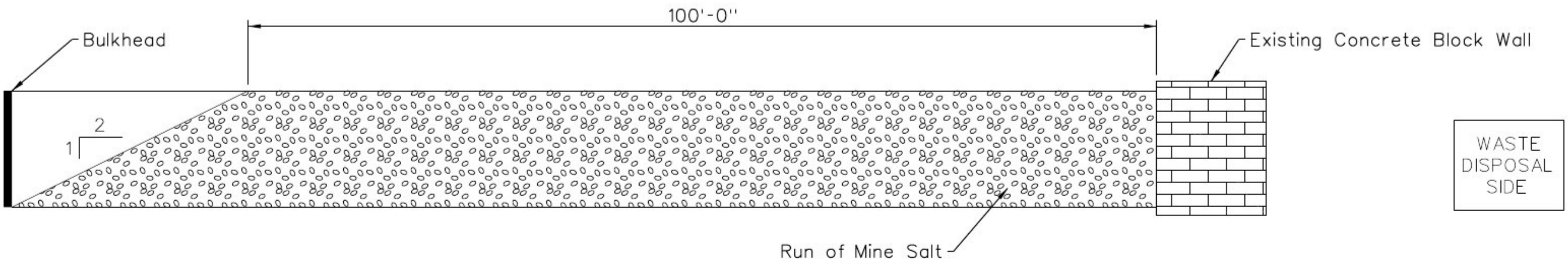
- Approved by EPA in October 2014
  - Minimum 100 feet of run-of-mine salt between steel bulkheads
  - Minimum 100 feet of run-of-mine salt between steel bulkheads and explosion-isolation walls

EPA Approved Panel Closure System Between Panels 9 and 10 and in Access Drifts to Panels 3, 4, 5, 6 and 7



1. Salt Zone 100'-0" minimum length.
2. Salt layers can be inclined within specifications.
3. Detailed design drawings are presented in Appendix D.
4. The ROM salt shall be placed to fill up to the back.
5. ROM salt is a porous salt in the loose state derived from underground mining operations at WIPP.

EPA Approved Panel Closure System Panels 1, 2 and 5



1. Salt Zone 100'-0" minimum length.
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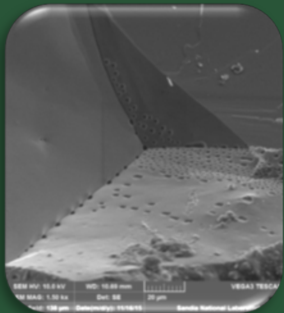
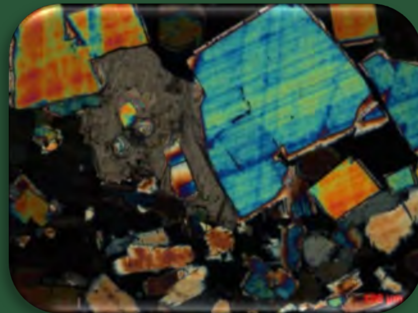
4. The ROM salt shall be placed to fill up to the back.
5. ROM salt is a porous salt in the loose state derived from underground mining operations at WIPP.

TYPICAL INTAKE/EXHAUST DRIFT

Conclusions

- Presentation of the Design Review Guidelines
- Presentation of the HWDF Panel Closure System Design Criteria
- Presentation of Panel Closure System Conceptual Design Alternatives
- Evaluation of Conceptual Design Alternatives
- *Selection of a Single Conceptual Design by a Broad Consensus That Achieves the HWDF Criteria at Lowest Cost and Least Impact on Operations*

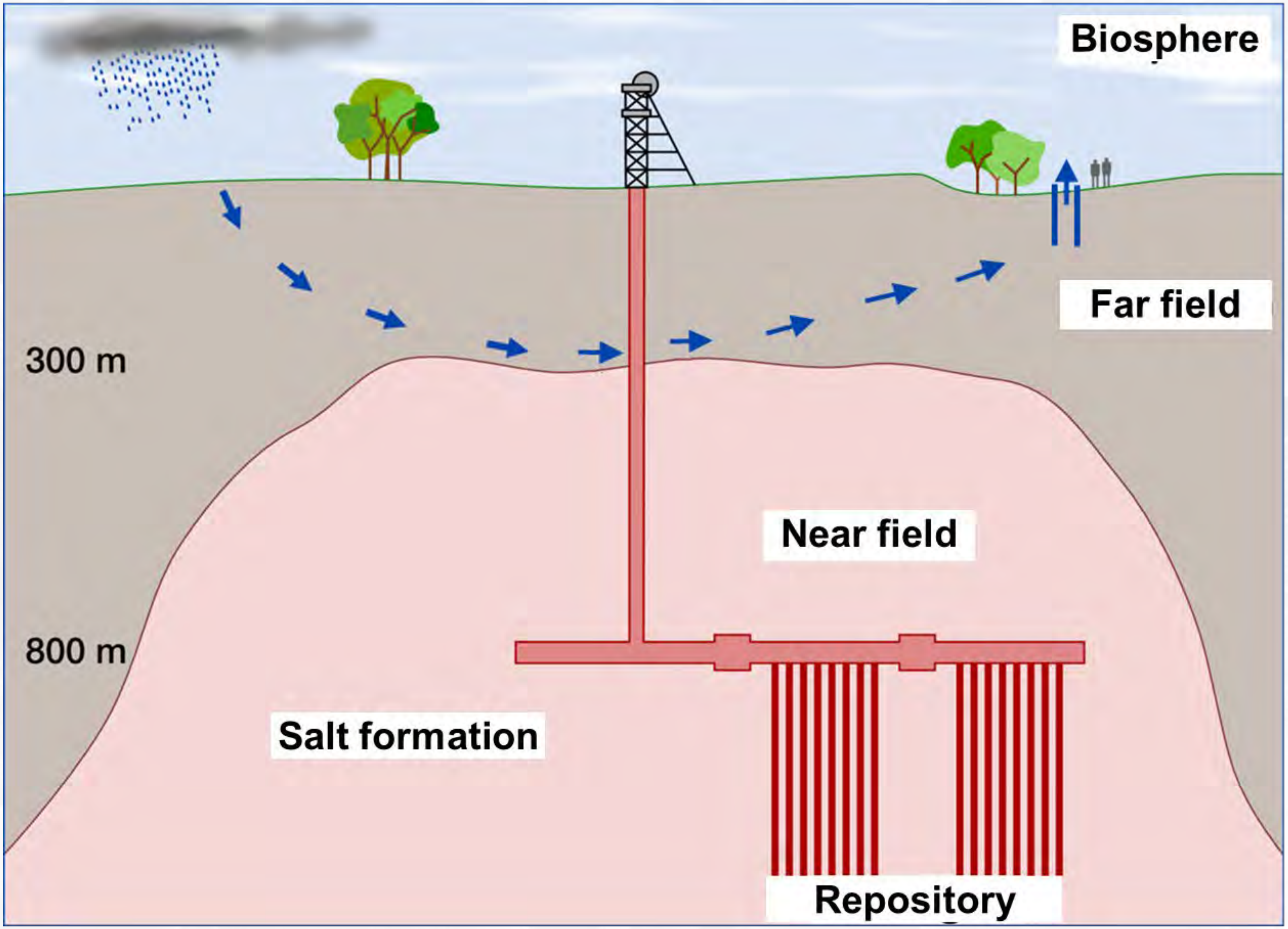
Crushed salt behavior – why it has become so important

part I: long-term safety perspective
part II: KOMPASS project objective

Jens Wolf & Oliver Czaikowski
GRS

Rapid City, SD, United States
May 28-30, 2019

Repository system in rock salt

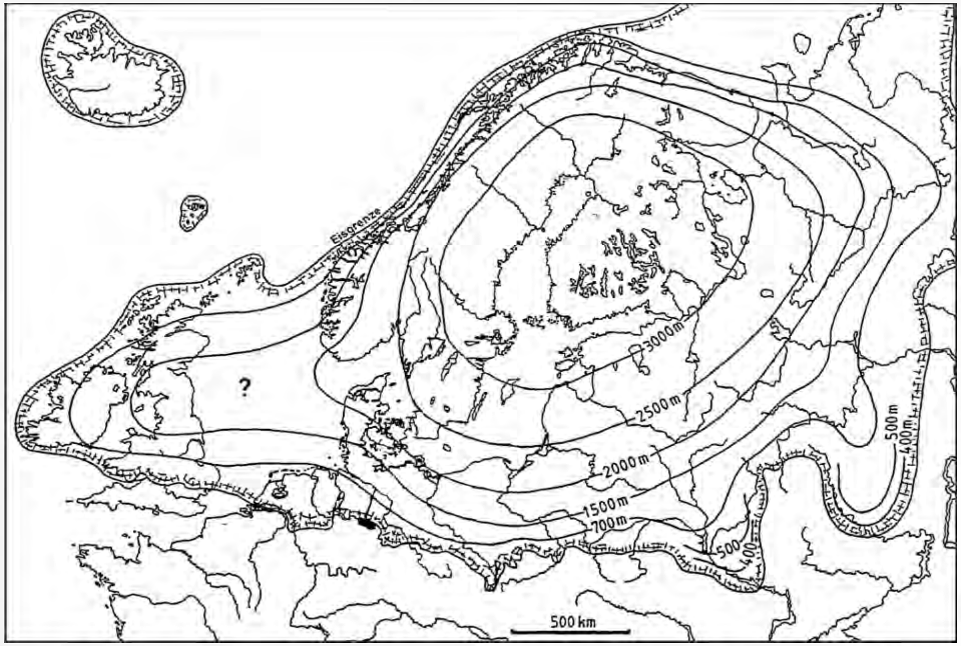


[GRS-333]

Expected evolution of the repository system

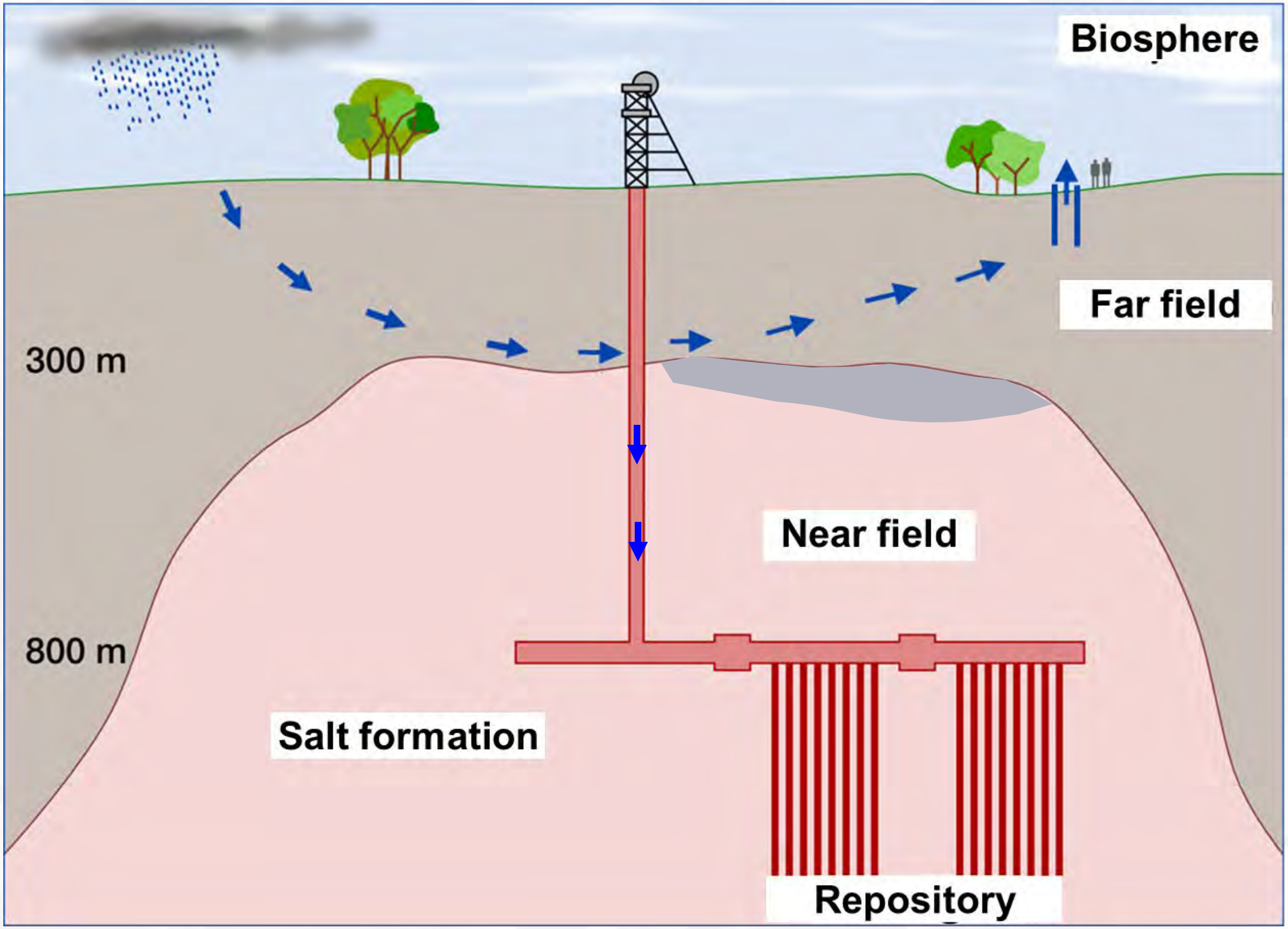
- For domal salt the following general statement can be made [GRS-284]:
  - No advective transport through undisturbed rock salt
  - Diffusive transport through undisturbed host rock neglectable
  - Shaft seal functionality can be guaranteed for at least 50.000 years

[Stackebrandt 2001]



[Feldmann 2002]

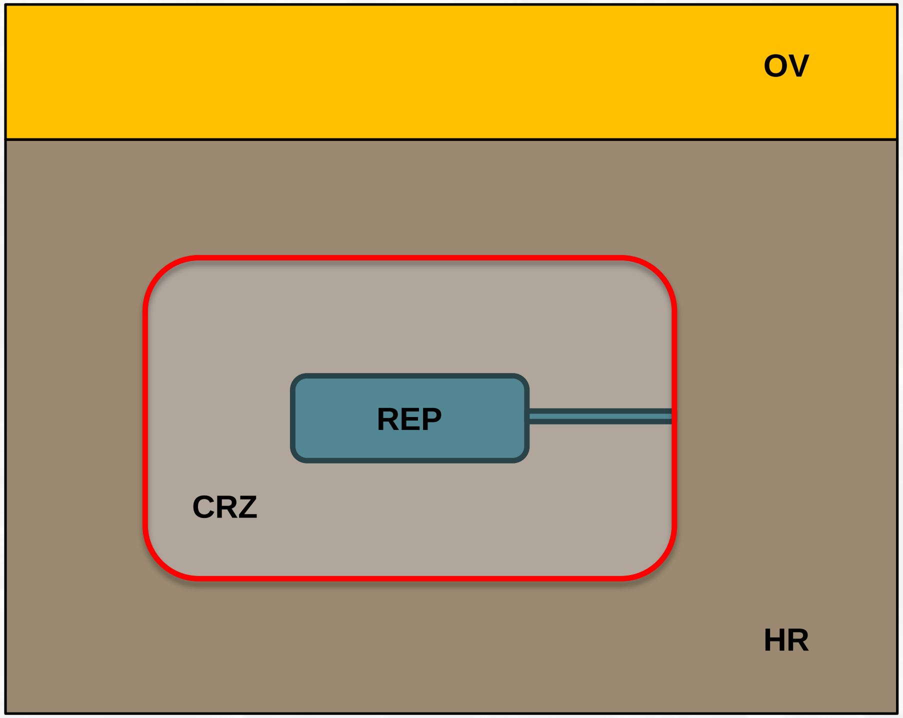
Repository system in rock salt

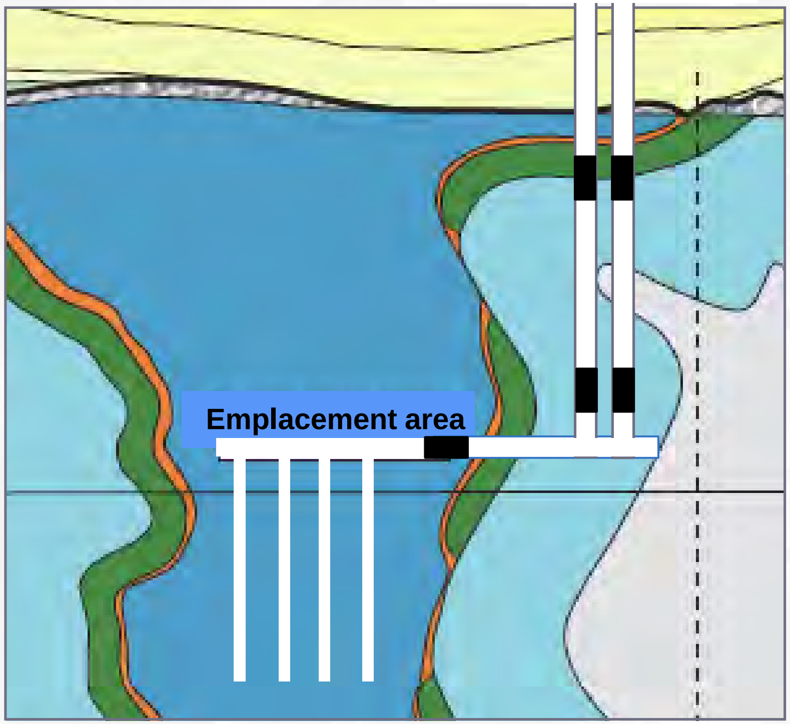


[GRS-333]

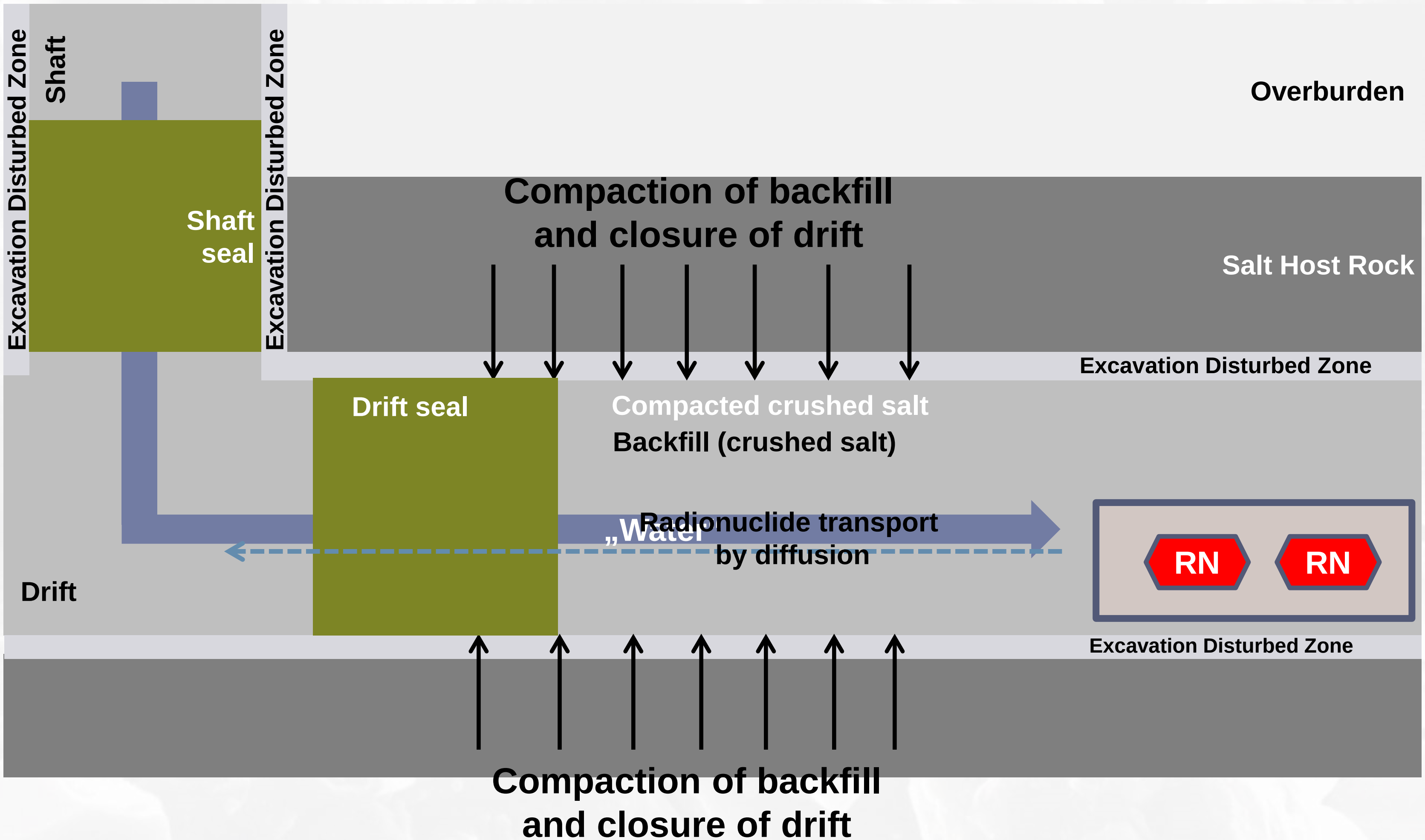
Safety Concept

- Containment (in CRZ) is achieved by
  - Salt barrier
  - Short-term: Constructed shaft and drift seals
  - Long-term: **Compacted crushed salt backfill** in drifts





Transport of contaminants in compacted crushed salt?



Transport of contaminants

- Transport of contaminants depends on
  - Transport medium
  - Compaction process
    - Compaction behavior (rate f (T, p, S))
    - Final structure/texture of compacted crushed salt
    - Final porosity / permeability

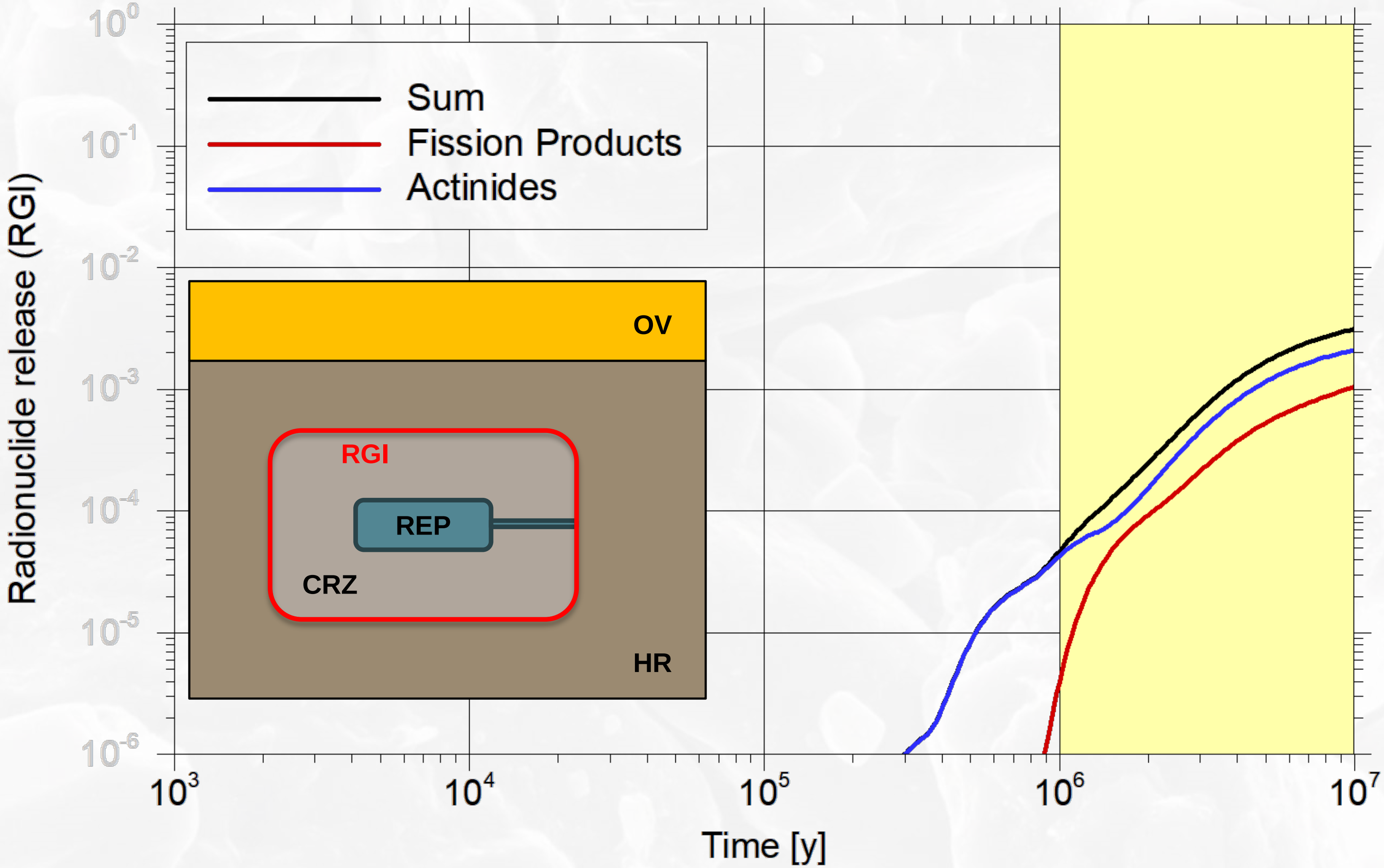
→ Natural Analogues
→ REPOPERM I / II
→ VSG
→ **KOMPASS**

} **compaction to a porosity of ~1% in less than 1.000 years**

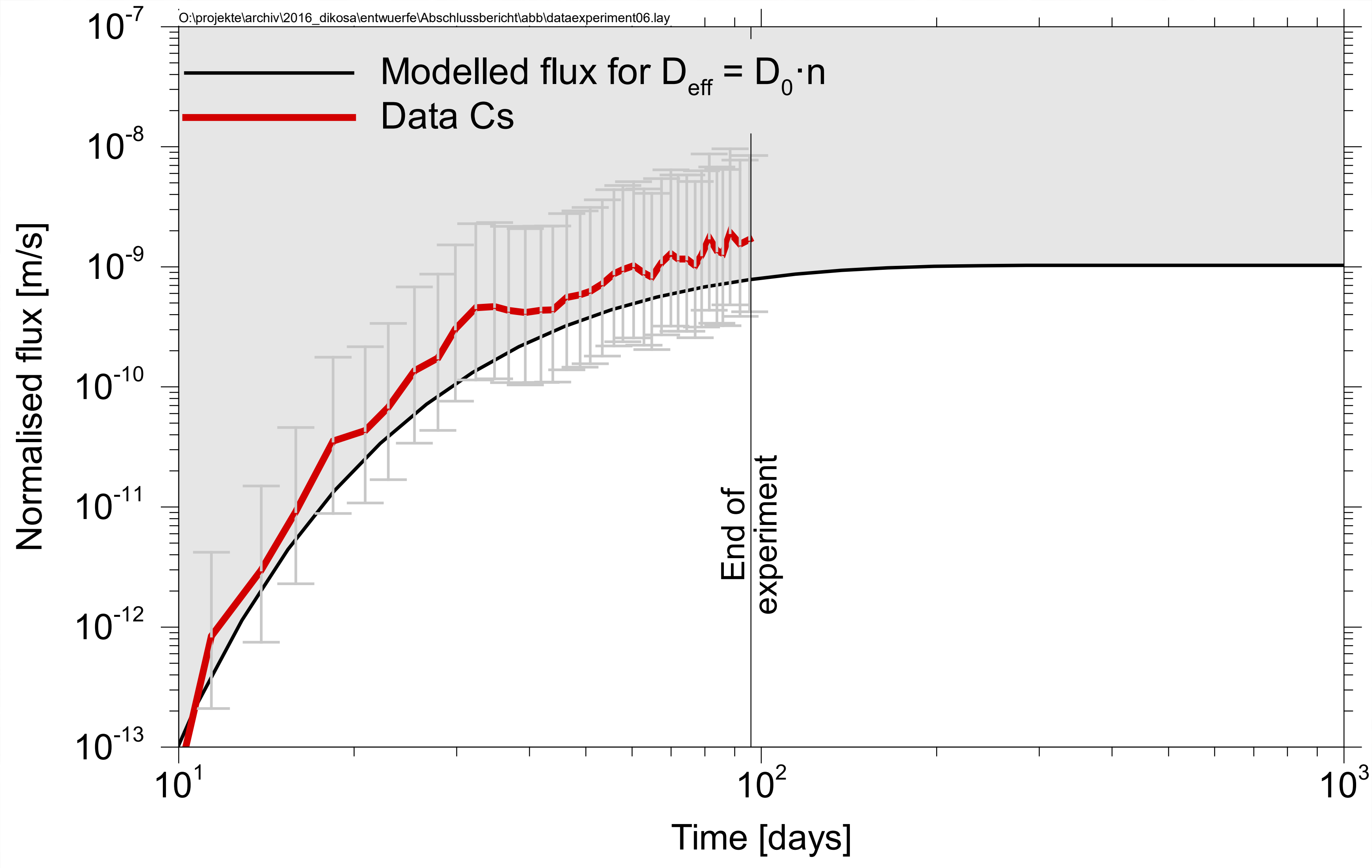
what does it mean for long-term safety?

Radionuclide release from HLW repository in salt

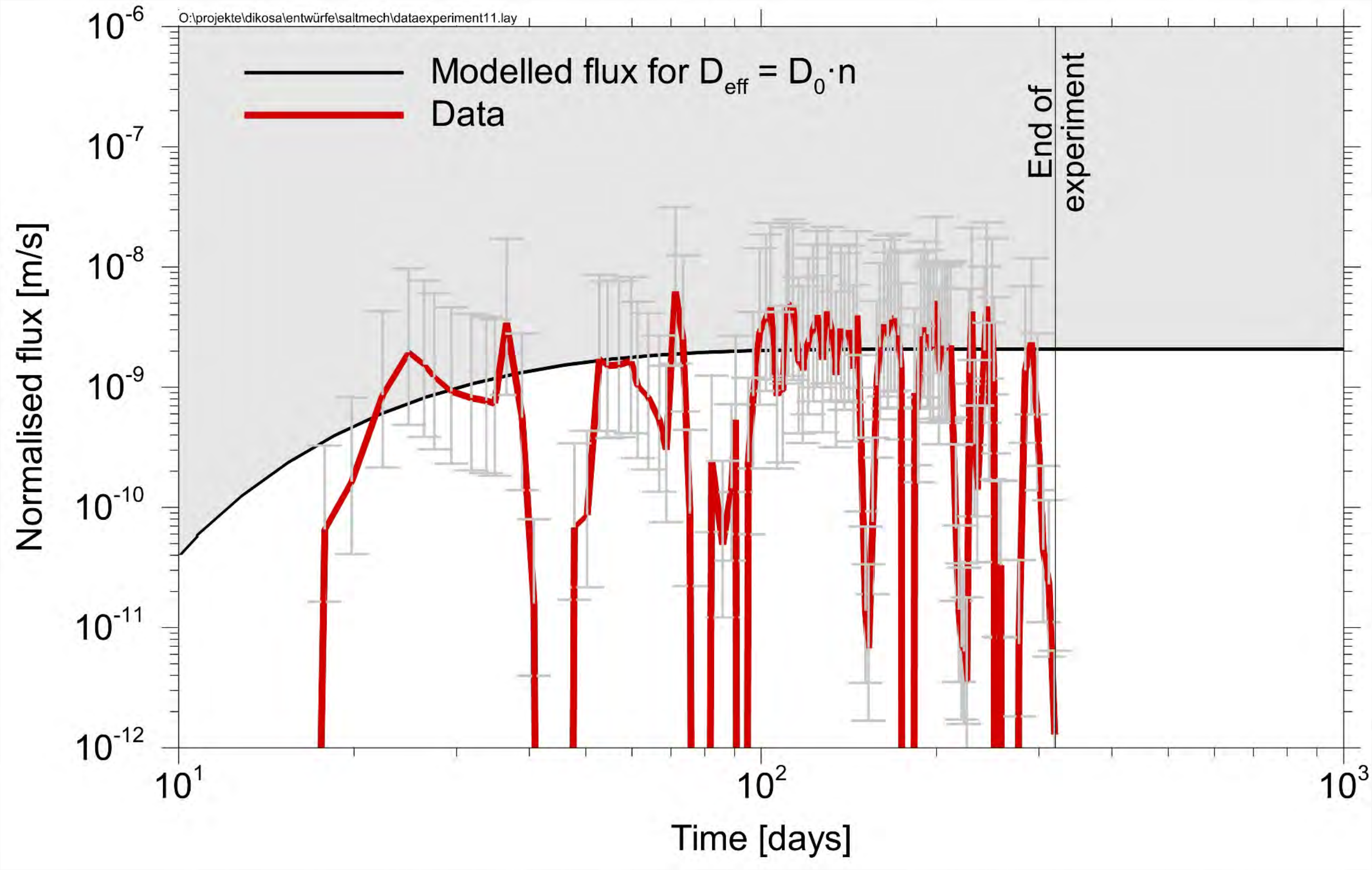
- Recent generic safety assessments show that according to the current model **diffusion** in the pore water of crushed salt is the most relevant transport process



DIKOSA: Compacted crushed salt (n = 2 %, $k = 3 \cdot 10^{-17}$ m²)



DIKOSA: Compacted crushed salt (n = 4 %, k = $1 \cdot 10^{-16}$ m^2)



Implications for long-term safety

- Diffusion of radionuclides in the pore water of the compacted crushed salt used as backfill in the drifts is the expected transport process for a repository in domal salt
  - relevant at late times > 10^5 years
  - pore diffusion coefficient and its dependence on the porosity of the crushed salt was determined experimentally
    - No dependency of the pore diffusion coefficient on the porosity could be observed ($G = 1$, i.e. $D_p = D_0$)
    - The approach used in the long-term safety assessment so far to apply the diffusion coefficient in free water remains valid
  - Release by diffusion does not result in problematic radiological consequences

  - But a comprehensive knowledge of compaction process in crushed salt is required for building confidence in the expected boundary conditions
    - Final porosity / structure
    - Managing uncertainties → assessment of alternative evolutions

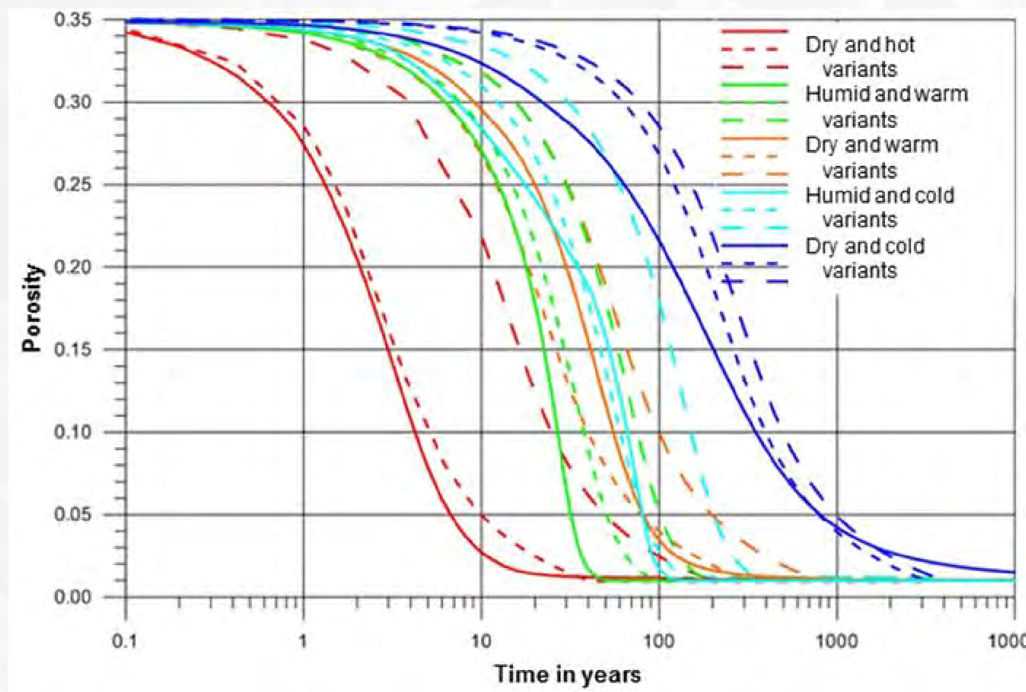
→ KOMPASS

KOMPASS project history

- Reconsolidation/re**<u>compa</u>**ction of Cru<u>s</u>hed **<u>S</u>**alt Backfill

  („<u>Kompa</u>ktion von Salzgrus für den sicheren Einschlu<u>ss</u>“)

- Boundary conditions (VSG)
  - in disposal drifts or boreholes → **hot** (up to 200° C) and **dry**
  - in temperature-affected drifts → **warm** and **dry** or **wetted** (depending on emplacement)
  - in “**cold”** access drifts → temperatures ~35 ° C, **dry** or **wetted**



Porosity evolution prediction in VSG – model not validated, GRS-287

DAEF Initiative

BGE TEC

GRS

Institut für Gebirgsmechanik GmbH Leipzig

TU Clausthal

BGR

http://www.endlagerforschung.de/

DAEF Initiative

Reconsolidation of crushed salt backfill – review of existing experimental database and constitutive models and need for future R&D work

- The DAEF report recaps and assesses
  - the **current understanding** of the mechanisms and influencing factors of crushed salt reconsolidation and the consequences for hydraulic behavior
  - the available **experimental database** and
  - the existing **simulation models**

  and suggestions for completing the database and calibrating and improving the models are made

- For future experiments **sample pre-treatment, suitable testing procedure, and measurement accuracy** are critical

- For model calibration a set of **benchmark tests** should be used

- **International cooperation** is desirable

KOMPASS project objective

- Reconsolidation/re**compa**ction of Cru**s**hed **S**alt Backfill
  („Kompaktion von Salzgrus für den sicheren Einschluss“)

- The overall objective of the project is
  - to **reduce the deficits** in the prediction of crushed salt reconsolidation,
  - thus **creating the prerequisite** for enhancing the safety case for a repository in rock salt.

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

Completion of exp. database

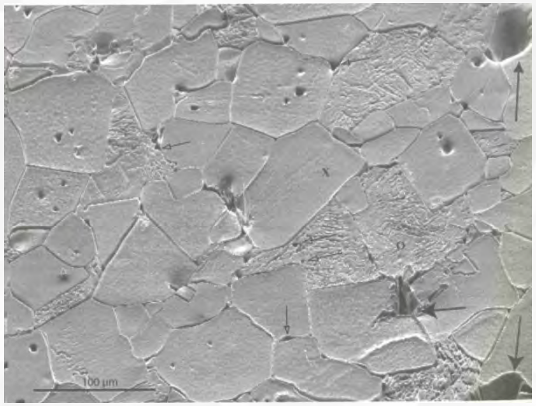
- Investigation of
  - creep compaction of dry crushed salt
  - influence of moisture and saturation
  - grain breakage and dislocation
  - pore size evolution of dry and moist crushed salt
  - influence of stress state (hydrostatic/deviatoric)
  - permeability evolution (dry/moist), influence of grain size
  - two-phase flow
- Experiments in balloon cells (hydrostatic) or Kármán cells (else)
- Accurate **porosity determination**: comparison and combination of measuring techniques
- Development of suitable **pre-compaction methods**

Talk given within the Breakout Session: *Test Sample Conditioning*

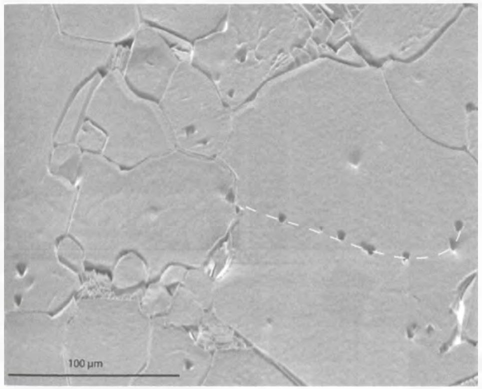
Process understanding

- Relevant mechanisms of salt reconsolidation are known, but
- Which processes are most relevant at which conditions?
  - Porosity range
  - Temperature
  - Dry or moist conditions
  - Saturation state → pore pressure effects
  - Effect on hydraulic behavior
- Systematic investigation program by BGR (additional human resource)

Talk given by Melissa Mills ref. to *“Micromechanical Investigations in R&D projects WEIMOS and KOMPASS”*



Salt powder rapidly compacted to ~ 5% porosity



Salt powder rapidly compacted to ~ 5% porosity – fluid activated grain boundary migration

(**Pennock et al., 2007**)

Model calibration, comparison & improvement

- Calibration of the models in the **porosity range < 5%**
- A **need for improvement** is expected for all models (depending on the respective formulation)
- A model is considered calibrated if it can reproduce **different experiments** (both stress- and deformation-controlled), down to low porosity, **with a single parameter set**
- This should be shown for different types of crushed salt and **different moisture contents**

Talk given by Christian Lerch ref. to *“Realistic modelling in R&D project KOMPASS – generic and/or specific”*

Acknowledgements

- Up-comming workshop in September with special regard to cross-cutting activities within **WEIMOS** and **KOMPASS** projects
- Current investigations presented here are funded by the Federal ministry of economic affairs and energy (**BMWi**) under support code 02E11708. The authors are sincerely thankful for the support.
- The project partners would also like to express their special thanks to our colleagues from **Sandia** for fruitful cooperation

Partners

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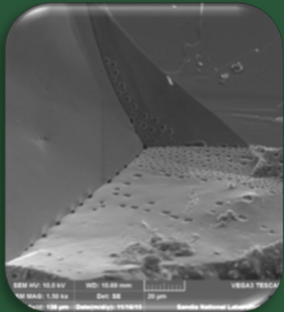
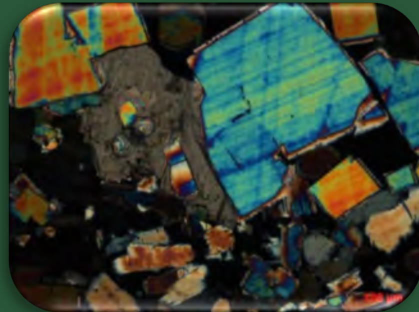
BGR: Johanna Lippmann-Pipke, Ulrich Heemann, Dieter Stührenberg, Kristoff, Svensson
IfG: Christoph Lüdeling, Till Popp
TUC: Uwe Düsterloh, Svetlana Lerche, Juan Zhao
GRS: Larissa Friedenberg, Klaus Wieczorek, Oliver Czaikowski (Coordinator)

PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie

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

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

MgO shotcrete for engineered barrier systems in salt formations - in situ tests with inflow of $MgCl_2$ bearing solution (R&D project MgO-SEAL)

Sandia National Laboratories
BGE TEC
BGE TECHNOLOGY GmbH
PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology
RESPEC
South Dakota School of Mines & Technology
U.S. DEPARTMENT OF ENERGY
Federal Ministry for Economic Affairs and Energy

Daniela Freyer, Matthias Gruner
Technische Universität Bergakademie Freiberg (TU BAF)

Till Popp, Klaus Salzer, Christopher Rölke
Institut für Gebirgsmechanik GmbH (IfG), Leipzig

Rapid City, SD, United States
May 28-30, 2019

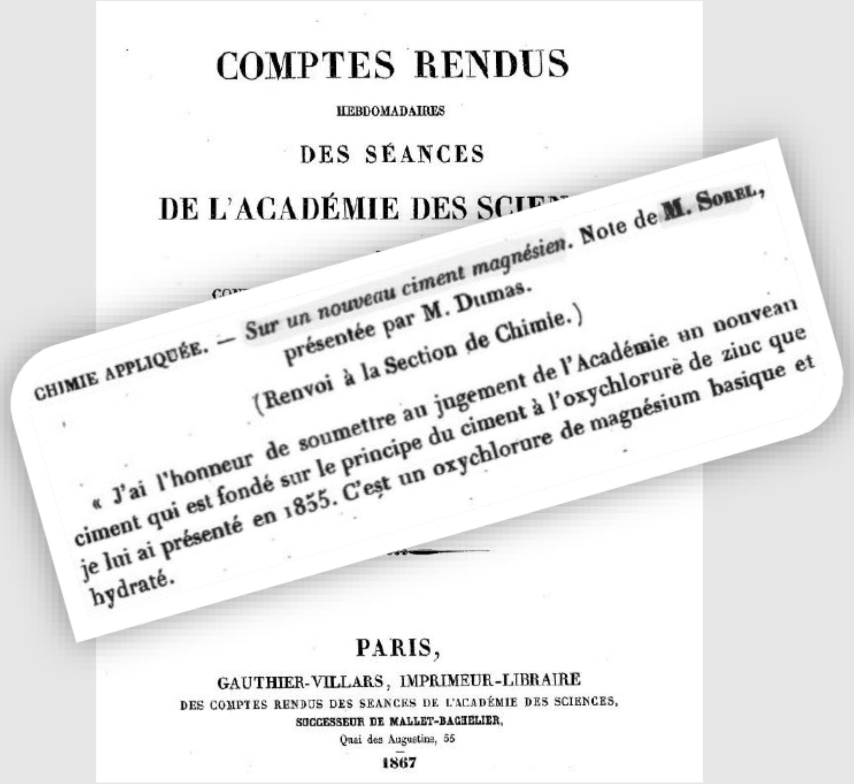
Outline

- **Introduction / Historical backview**
- **Knowledge – Status 2019**
- **Building material formulations**
- **Material Properties**
- **Applications**
- **R&D project MgO-SEAL**
- **Outcome in situ-tests**
- **Conclusions / Outlook**

Sorel Building Material: History

1867

Discovery of a new cement
resulting from MgO and $MgCl_2$-solution
by Stanislas Sorel

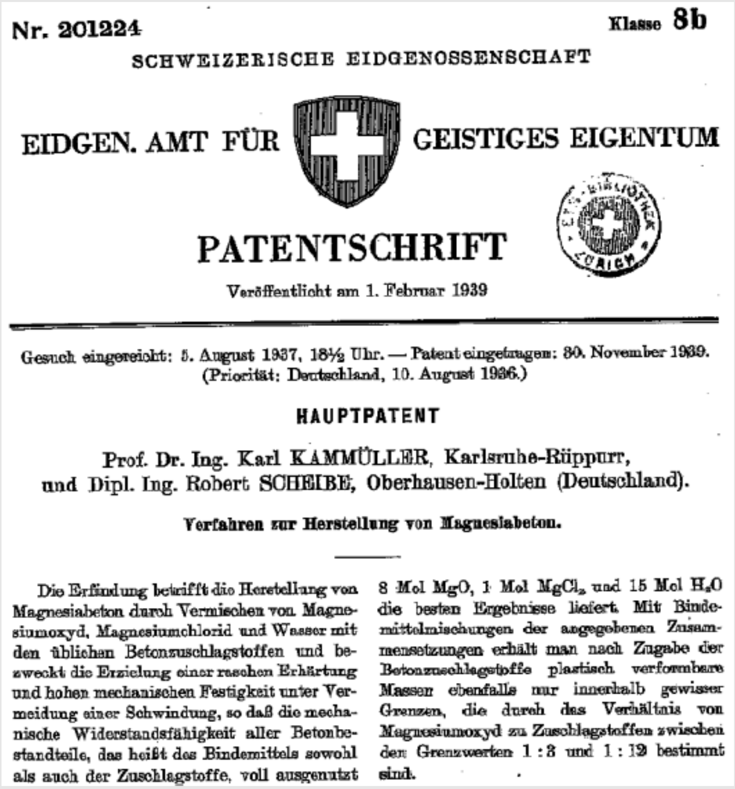

COMPTES RENDUS
HEBDOMADAIRES
DES SÉANCES
DE L'ACADÉMIE DES SCI...

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.

PARIS,
GAUTHIER-VILLARS, IMPRIMEUR-LIBRAIRE
DES COMPTES RENDUS DES SÉANCES DE L'ACADÉMIE DES SCIENCES,
SUCCESSEUR DE MALLET-BACHELIER,
Quai des Augustins, 55
1867

1939

1st patent: MgO-concrete as building material
by Karl Kammüller & Norbert Scheibe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SCHWEIZERISCHE EIDGENOSSENSCHAFT
EIDGEN. AMT FÜR GEISTIGES EIGENTUM
PATENTSCHRIFT
Veröffentlicht am 1. Februar 1939

Gesuch eingereicht: 5. August 1937, 18½ Uhr. — Patent eingetragen: 30. November 1939.
(Priorität: Deutschland, 10. August 1936.)

HAUPTPATENT

Prof. Dr. Ing. Karl KAMMÜLLER, Karlsruhe-Rüppurr,
und Dipl. Ing. Robert SCHEIBE, Oberhausen-Holten (Deutschland).

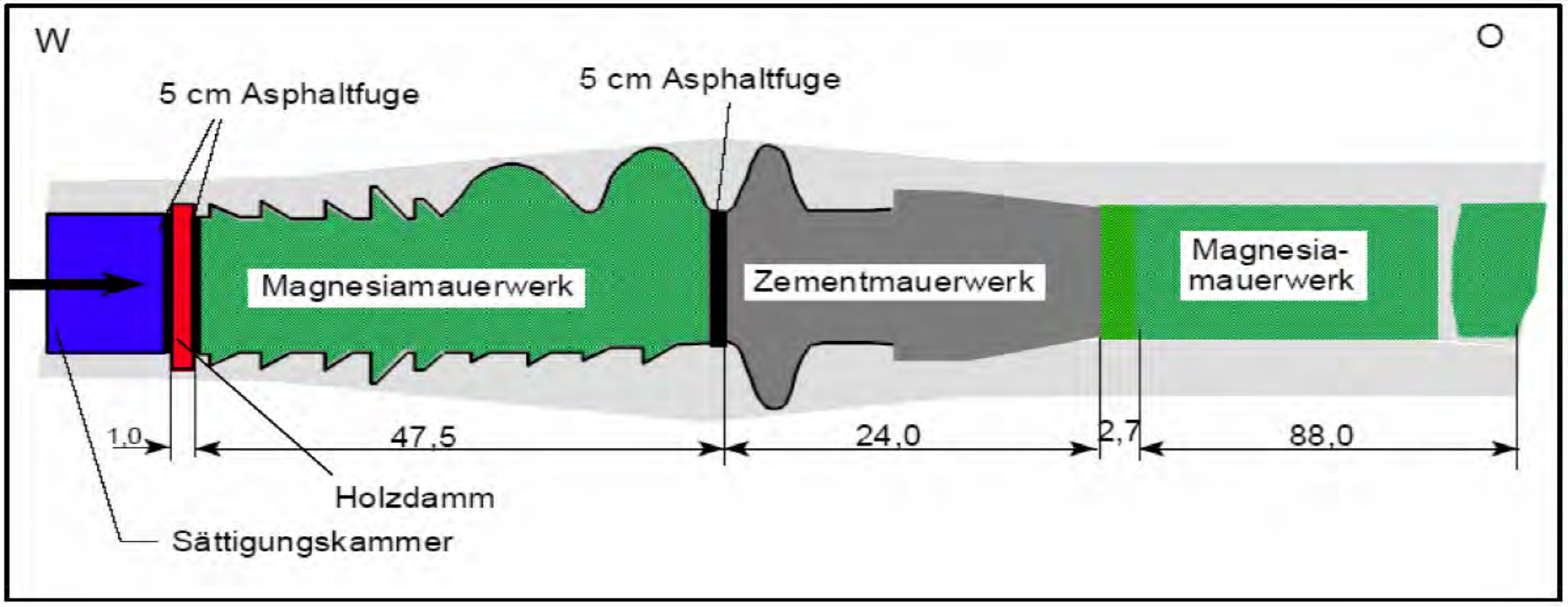
Verfahren zur Herstellung von Magnesiabeton.

Die Erfindung betrifft die Herstellung von Magnesiabeton durch Vermischen von Magnesiumoxyd, Magnesiumchlorid und Wasser mit den üblichen Betonzuschlagstoffen und bezweckt die Erzielung einer raschen Erhärtung und hohen mechanischen Festigkeit unter Vermeidung einer Schwindung, so daß die mechanische Widerstandsfähigkeit aller Betonbestandteile, das heißt des Bindemittels sowohl als auch der Zuschlagstoffe, voll ausgenutzt

8 Mol MgO, 1 Mol $MgCl_2$ und 15 Mol H_2O die besten Ergebnisse liefert. Mit Bindemittelmischungen der angegebenen Zusammensetzungen erhält man nach Zugabe der Betonzuschlagstoffe plastisch verformbare Massen ebenfalls nur innerhalb gewisser Grenzen, die durch das Verhältnis von Magnesiumoxyd zu Zuschlagstoffen zwischen den Grenzwerten 1 : 3 und 1 : 12 bestimmt sind.

Sorel Building Material : 1st application in salt mines

1898: 162 m long drift seal in the salt mine Leopoldshall



Empirically taken by the miners, but ….

fortunately the dam worked!

Why and how does it work ?

Sorel Building Material: What it is ….

Components

MgO + $MgCl_2$-bearing salt solution **= MgO - Building Material**

Binder phase(s):

Basic Mg-Chlorid-Hydrates

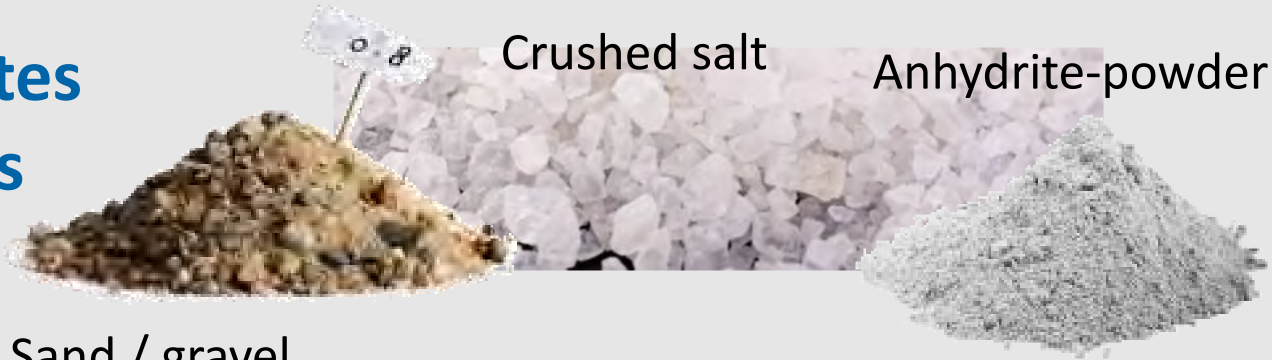
x $Mg(OH)_2 \cdot$ **y** $MgCl_2 \cdot$ **z** H_2O:

x-y-z phase (Sorel phases)

+ Aggregates / Additives

Crushed salt

Anhydrite-powder



Sand / gravel

Progress of knowledge in the last decade

Outcome of recent research projects


Entwicklung eines Grundkonzeptes für langzeitstabile Streckendämme im leichtlöslichen Salzgestein (Carnallitit) für UTD/UTV
Teil 2: Erprobung von Funktionselementen
Abschlussbericht

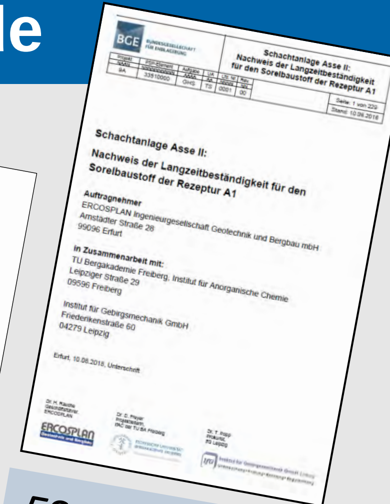
CARLA (2010)
2 Mock-Up-Tests


FREIBERGER FORSCHUNGSHEFTE
Zusammenhang von Chemismus und mechanischen Eigenschaften des MgO-Baustoffs
Daniela Freyer, Matthias Gruner und Till Popp
TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG

MgO-project (2015)
- Development of fundamental understanding


KIT
Endlagerforschung
Fachgespräch
"Verschlusssysteme – In-situ-Bauwerke aus Magnesiabaustoff und dessen chemisch-mechanische Eigenschaften im Hinblick auf HAW-Endlager"
Freiberg, 28.-29.04.2015
- Materialienband -

2015 State of the art workshop


Schachtanlage Asse II:
Nachweis der Langzeitbeständigkeit für den Sorelbaustoff der Rezeptur A1
Auftragnehmer
ERCOSPLAN Ingenieurgesellschaft Geotechnik und Bergbau mbH
Arnstädter Straße 28
99096 Erfurt
In Zusammenarbeit mit:
TU Bergakademie Freiberg, Institut für Anorganische Chemie
Leipziger Straße 29
09596 Freiberg
Institut für Gebirgsmechanik GmbH
Friederikenstraße 60
04279 Leipzig

ESA (2018):
Demonstration of A1 – long term stability

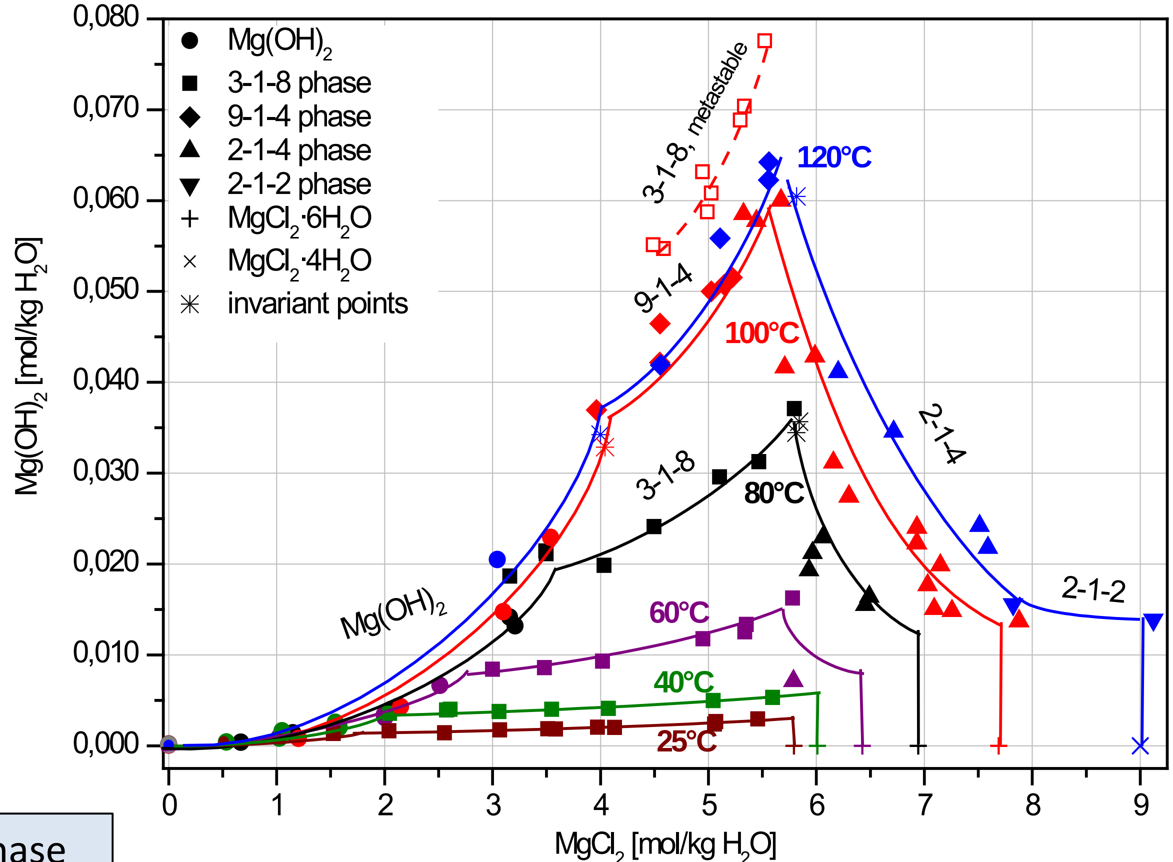
- **A set of different formulations is available**
- **Fundamental understanding on binder phase formation in connection to composition of the formulation and setting temperature development**
- **Comprehensive data base of hydro-mechanical properties**
- **Demonstration of feasibility of drift seals by mock-up tests**
- **Proof of self sealing ➔ indirect long-term stability** in case of 5-1-8 binder phase

Sorel Building Material : Long term stability

→ Binder phase stability at/after brine access

Solubility equlibria in the **System $Mg(OH)_2$ - $MgCl_2$ - 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)



x $Mg(OH)_2$ · **y** $MgCl_2$ · **z** H_2O: **x-y-z** Phase

M. Pannach, S. Bette and D. Freyer: "*Solubility Equilibria in the System $Mg(OH)_2$–$MgCl_2$–H_2O from 298 to 393 K*". Journal of Chemical and Engineering Data (2017) **62,** 1384–1396.

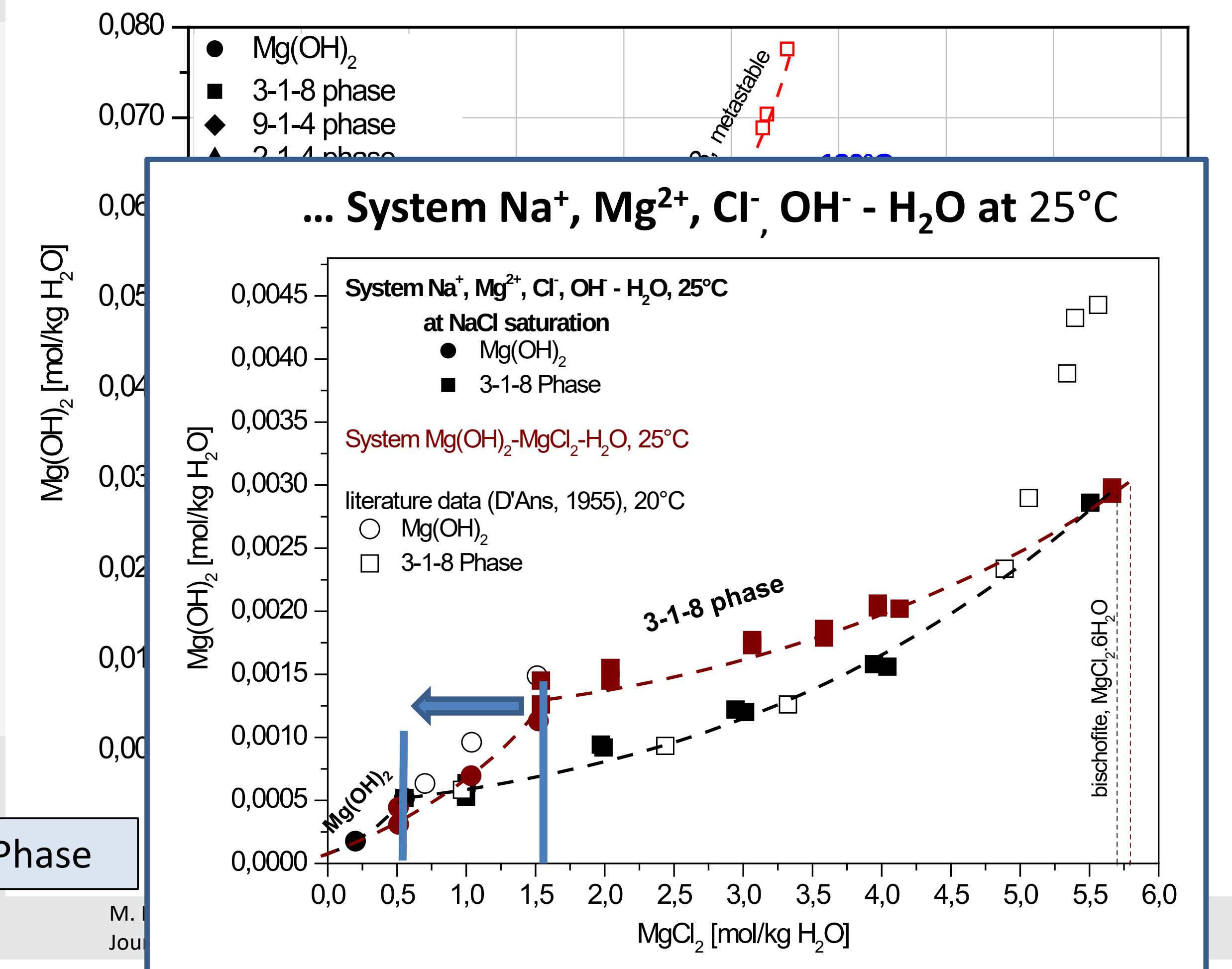
Sorel Building Material : Long term stability

→ Binder phase stability at/after brine access

Solubility equlibria in the **System $Mg(OH)_2$ - $MgCl_2$ - 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

x $Mg(OH)_2$ · **y** $MgCl_2$ · **z** H_2O: **x-y-z** Phase



Sorel Building Material : Long term stability

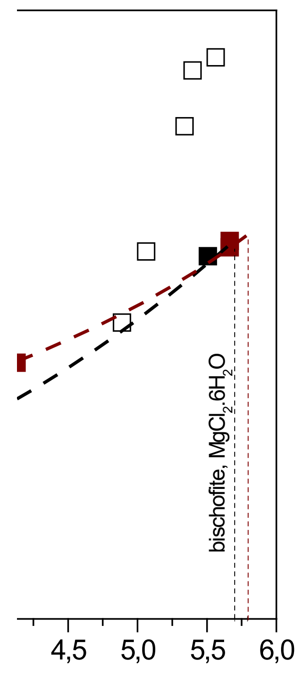
→ Binder phase stability at/after brine access

Solu… …°C - 120°C

- 3-1-8 phas… thermody… stable up t… at higher t… 9-1-4 phas…
- no existing… 5-1-8 phas…
- At NaCl sa… salt "condi… stability fie… is extende… Mg^{2+} / kg …

x $Mg(OH)_2$ · **y** Mg…

…$_2$O at 25°C



Jou…

Thermodynamic modeling *(behavior of MgO building material in contact with brine)* **is now possible!**

Presentation will be held at

KIT Karlsruhe Institute of Technology | Federal Ministry for Economic Affairs and Energy | WIPP Waste Isolation Pilot Plant www.wipp.energy.gov | Los Alamos National Laboratory Est. 1943

ABC-Salt (VI)

Actinide Brine Chemistry in a Salt-Based Repository

25th + 26th June, 2019, Karlsruhe, Germany

→ **"Modeling of solubility equilibria of Sorel phases"**

Melanie Pannach, Daniela Freyer & Wolfgang Voigt

Institute of Inorganic Chemistry, TU Bergakademie Freiberg, Leipziger Str. 29, 09596 Freiberg

Sorel Building Material : Formulation Typs

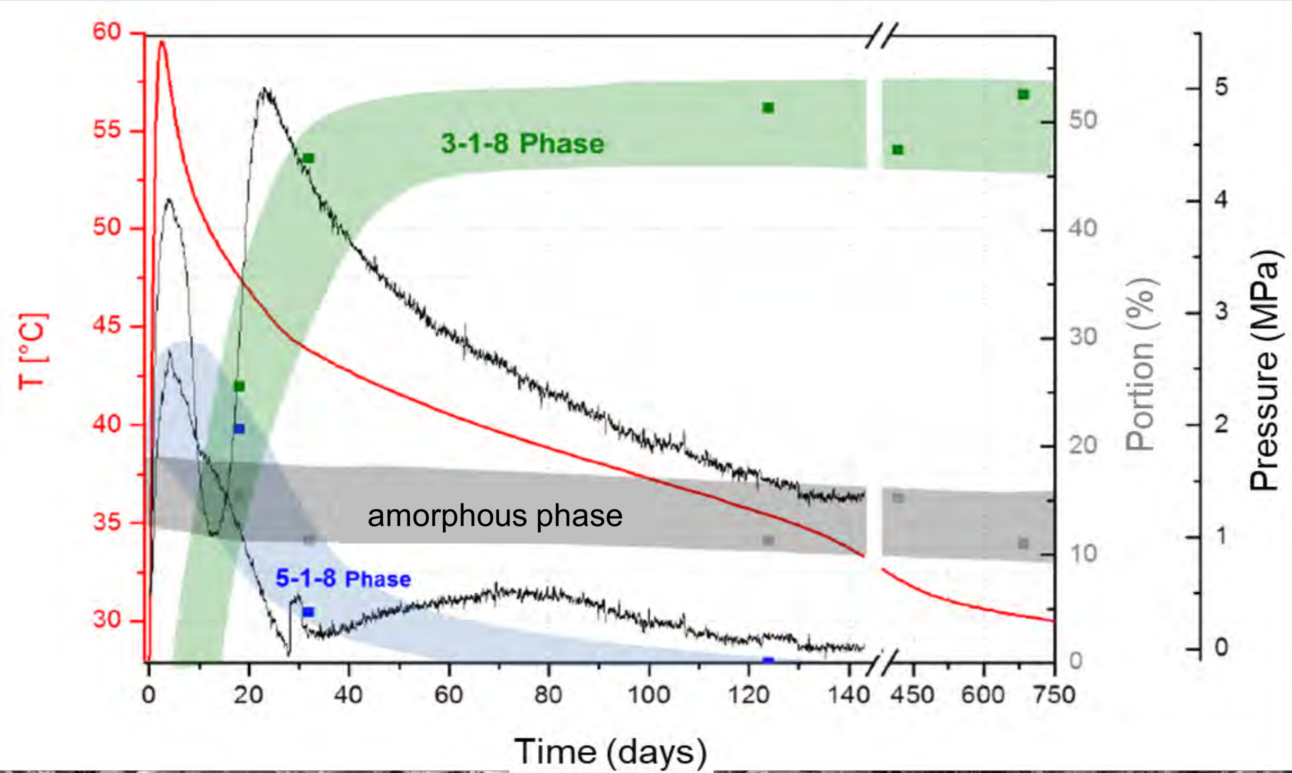
- Currently used building material formulations for sealing measures in German salt mines

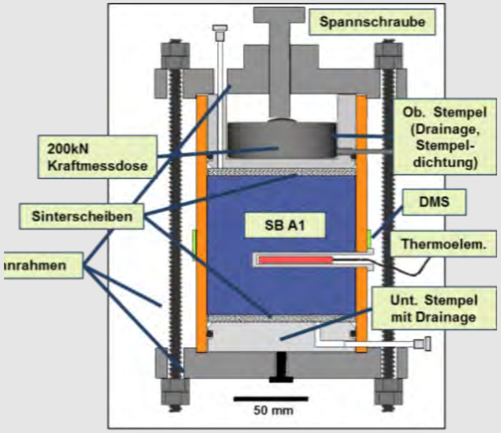
Formulation Type „3-1-8“ — DBM2, A1, C3; Formulation Type „5-1-8“ — D4

Formulation	DBM2	A1	C3	D4
		Site concrete	Site concrete	Site concrete Shotcrete
MgO cav-reactivity [s], pH7	10.5 % MgO 250±50 s	11.3 ±2 % MgO 100-300 s	6.9 ±0.1 % MgO 200±50 s	17 ±2 % MgO 200±50 s
Mixing solution	20.8 % $MgCl_2$-soln. (390-430 g/L, S-30 DEUSA)	25.0 % $MgCl_2$-soln. (ca. 400 g $MgCl_2$/L)	15.8 ±0.5 % $MgCl_2$-soln. (ca. 5 molal)	11.4 …18.3 % $MgCl_2$-soln. (ca. 5 molal)
Additives	34.3 % sand 29.5 % anhydrite 4.5 % microsilica (amorphous SiO_2)	63.7±2 % rock salt	55.6 ±1 % sand/gravel, 0-8 mm 21.5 ±0.5 % quarz powder (SiO_2, kristallin)	63.4 … 73.0 % sand/gravel, 0-8 mm
Mol ratio $MgO : MgCl_2 : H_2O$	**3.5 … 3.7 : 1 : ~11**	**3.1 … 3.3 : 1 : ~11**	**3 … 3.1 : 1 : ~11**	**5 … 8 : 1 : ~10**
→ binder phase(s)	**3-1-8, 5-1-8**	**3-1-8, 5-1-8**	**3-1-8**	**5-1-8, MgO**

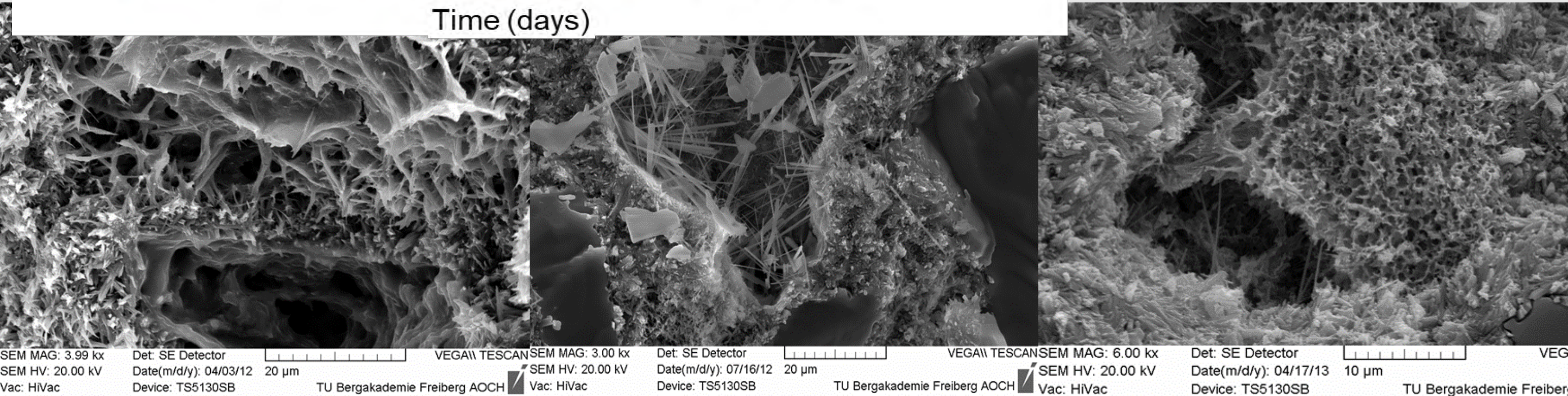
Sorel Building Material : Phase development for 3-1-8 formul. typ

Investigation of the hardening process at simulated in situ conditions



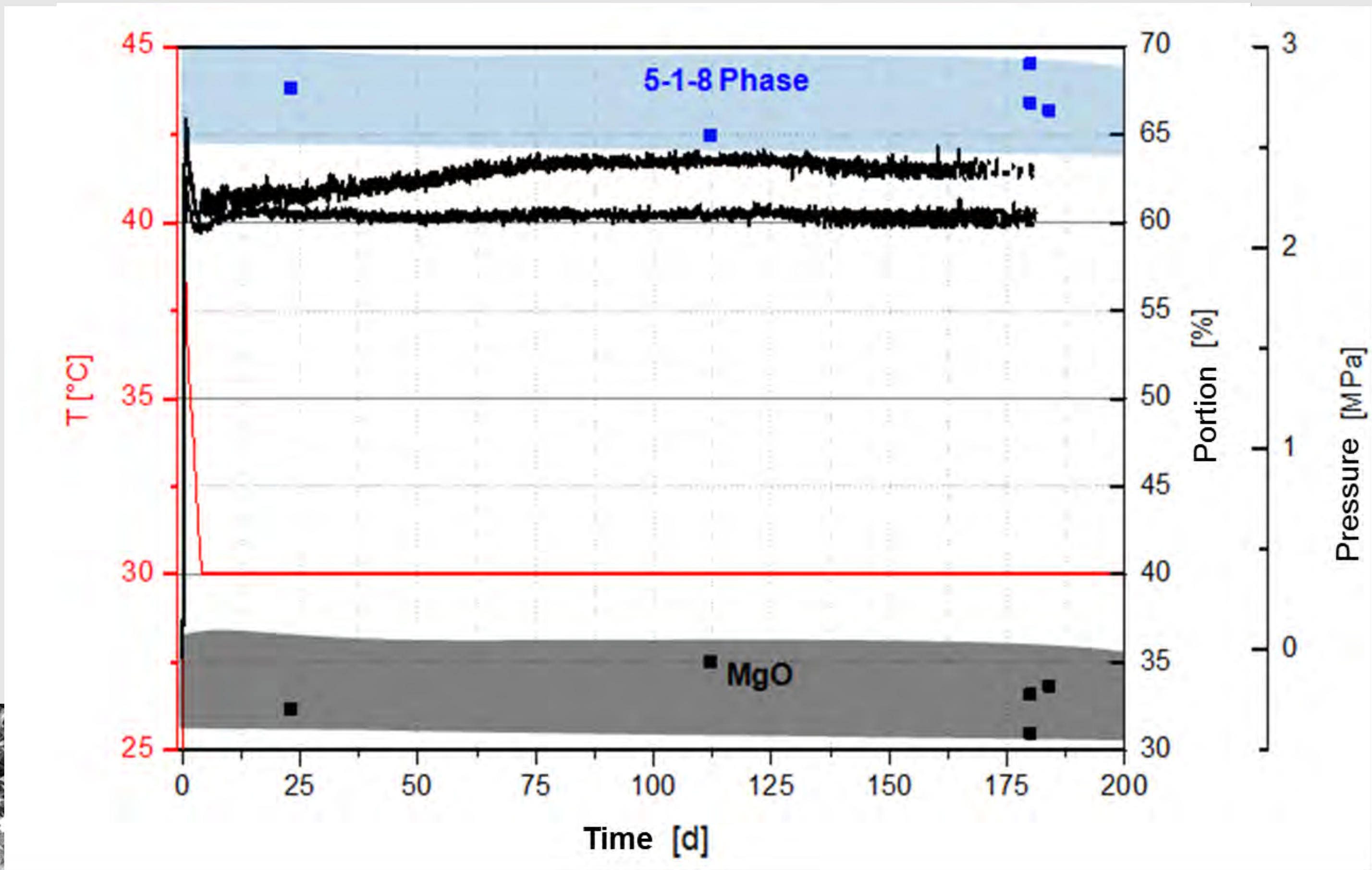


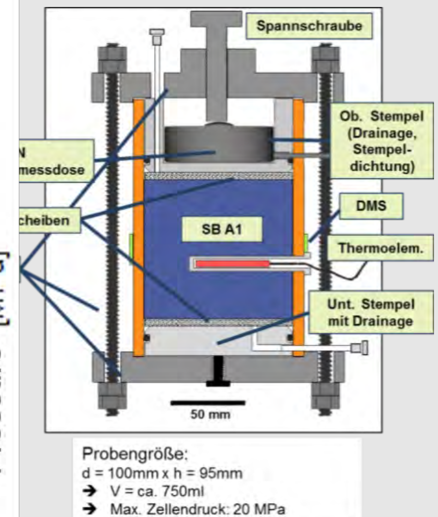
Probengröße:
d = 100mm x h = 95mm
→ V = ca. 750ml
→ Max. Zellendruck: 20 MPa



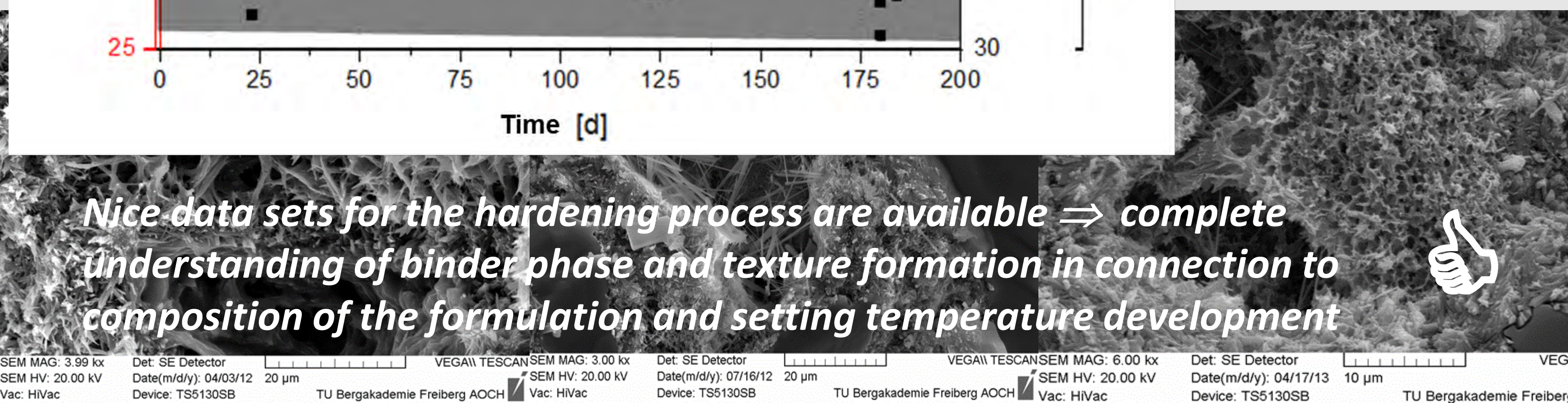
Sorel Building Material : Phase development for 5-1-8 formul. typ

Investigation of the hardening process at simulated in situ conditions



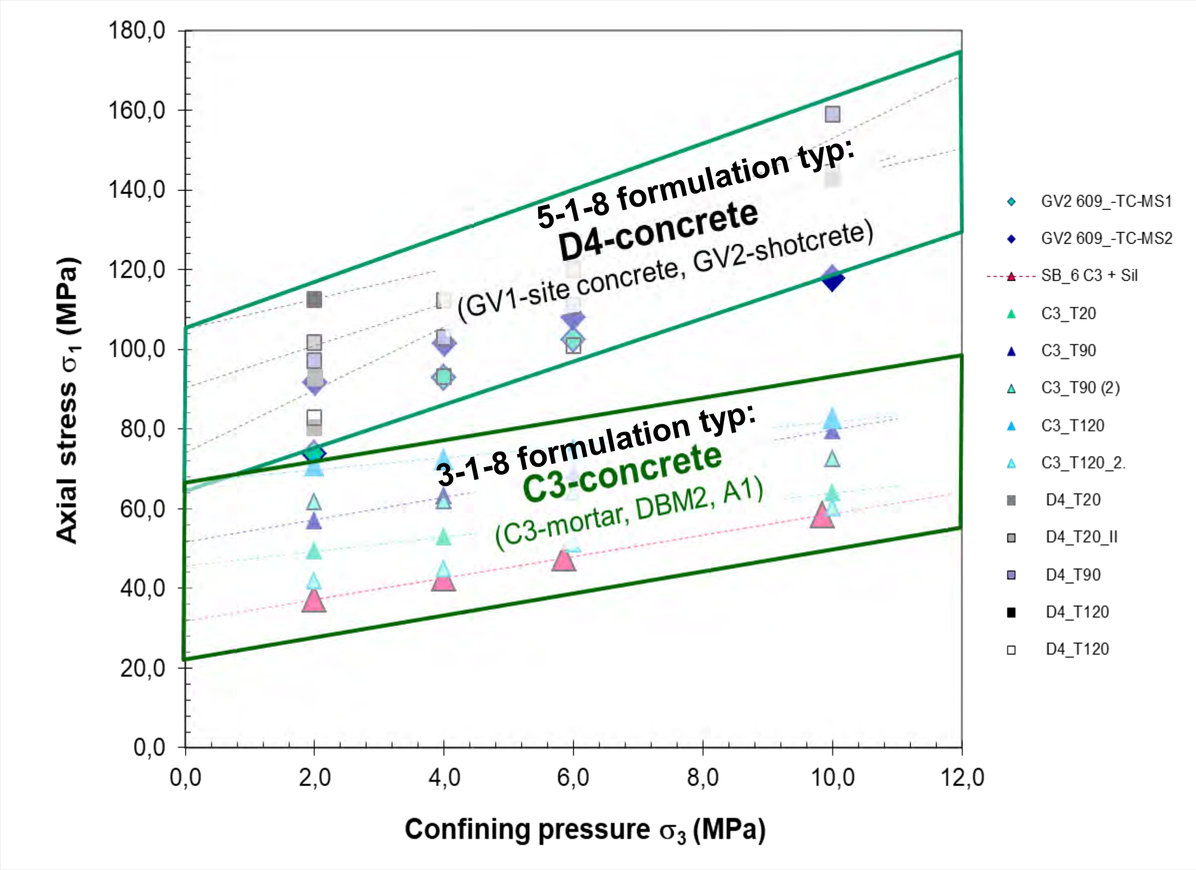


Nice data sets for the hardening process are available ⇒ complete understanding of binder phase and texture formation in connection to composition of the formulation and setting temperature development



Sorel Building Material : Strength properties

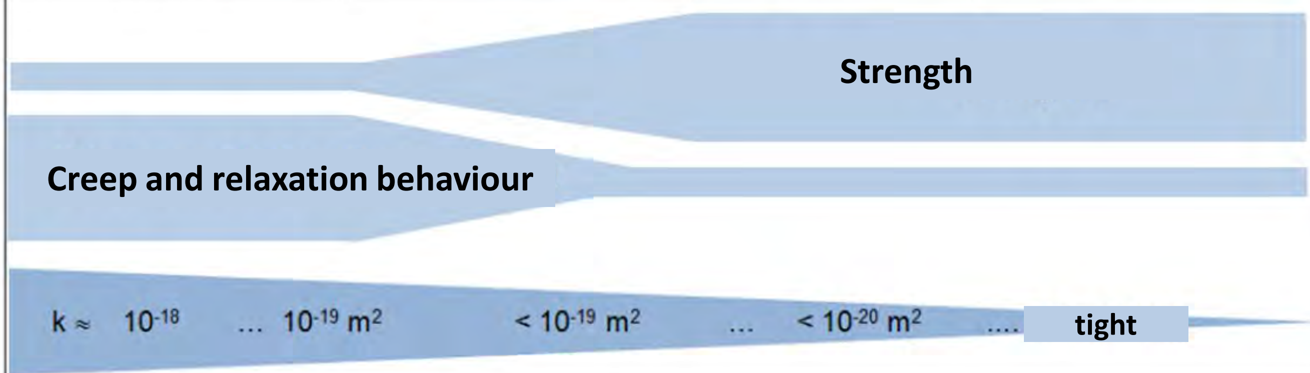
Outcome of multi-step strength tests



Ultra-High strength values, but a moderate decrease is obvious if a transition from 5-1-8 to 3-1-8 formulations occurs.

Sorel Building Material : Tool box of formulations

Depending on the requirements different formulations are available

Formulationtyp	„3-1-8“		„5-1-8“	
Name	C3 DBM2 A1			D4 (MB10)
Ratio of components MgO : $MgCl_2$: H_2O	Name	(3 - 5) : 1 : (11 - 13)	5 : 1 : 13	(>5) : 1 : 13
Geomechanical Properties in relative comparison / **Brine permeability** (repository solution)				
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).			

Depending on the mixture appropriate properties (e.g. strength, permeabilities) can be selected according the requirements

To demand absence of cracks: MgO-dam buildings concepts

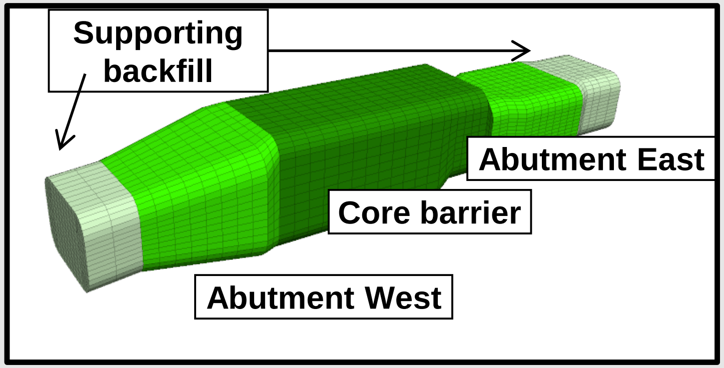
(1) Construction:

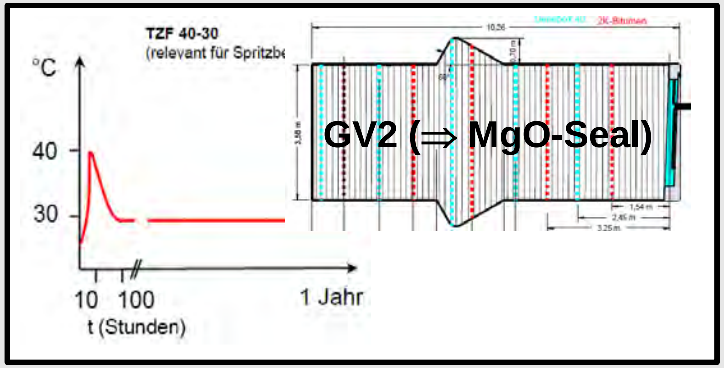
- **Site concrete:**
  - Use of a stiff (and expansive) Sorel concrete, e.g. A1
  - Clamping of the sealing element between massive abutments / development of a suspension pressure
  - ➔ The flow barrier PSB A1 proves the technical feasibility and functionality in terms of the requirements of the Asse repository
- **D4 - shotcrete**
  - Reduction of the temperature development
  - Self sealing during brine inflow (5-1-8 ➔ 3-1-8)
  - ➔ GV2 (⇒ **MgO-SEAL**)

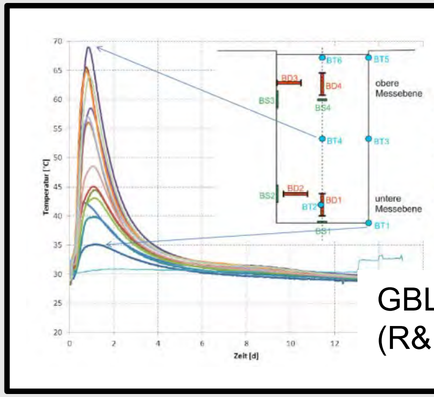
---

(2) Binding behaviour of the MgO-concrete:

- **C3 - Site concrete (3-1-8 formulation type):**
  - Use of a "softer" (and expansive) Sorel concrete (less crack-sensitive?)
  - ➔ Ongoing investigations in ELSA II





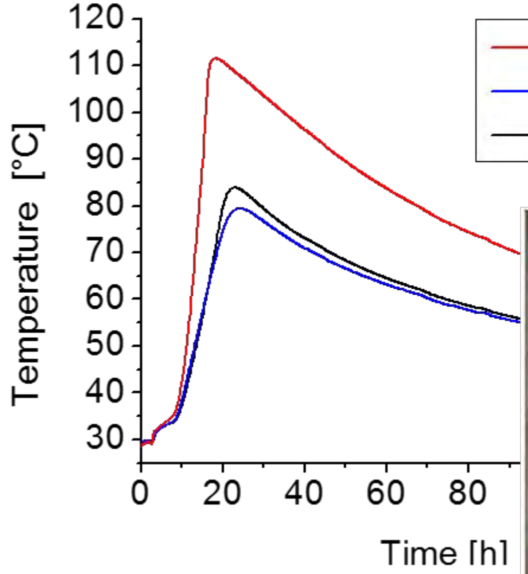


GBL Sonderhausen (R&D project ELSA II)

Sorel Building Material : Temperature development

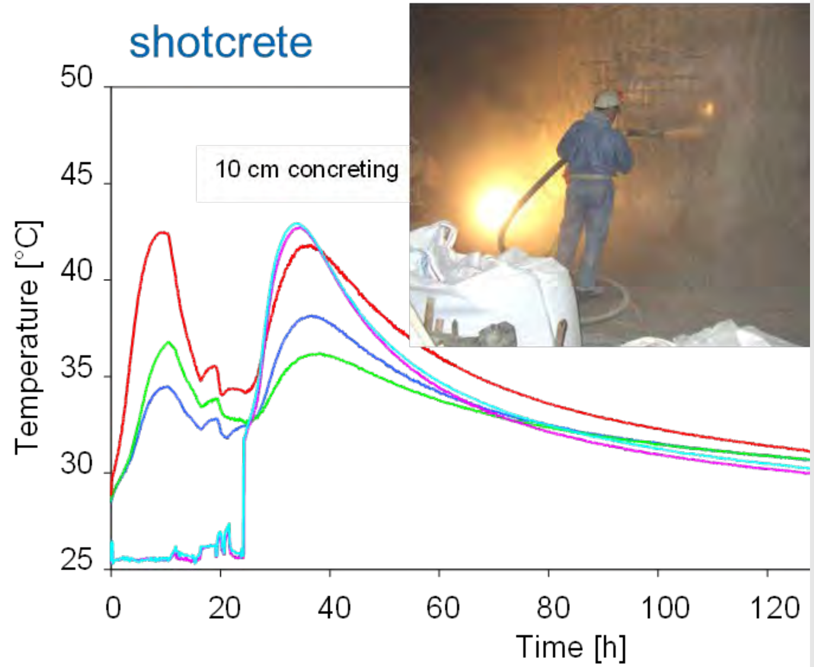
Influence of the technical application

site concrete



3-1-8 formulations
5-1-8 formulations

shotcrete



5-1-8 formulations

- ***Note that the maximum temperature is significantly reduced for shotcrete ?***

R&D project MgO-SEAL (FKZ: 02E11435)

Tasks

(1) Characterisation of the geochemical and hydro-mechanical state of the MgO-shotcrete dam after 7 years of service life

(2) 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:
  - *NaCl-saturated brine + $MgCl_2$ (2 mol Mg^{2+}/kg H_2O)*

and the solution with the strongest impact:

- *Saturated NaCl-brine (Mg^{2+} - free)*

Project partners

TU BA Freiberg
Prof. Kudla: Coordinator
TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
Die Ressourcenuniversität. Seit 1765.

Grube Teutschenthal

IBeWa

TS-Bau, NL Jena

IfG Leipzig
Institut für Gebirgsmechanik GmbH
Untersuchung·Prüfung·Beratung·Begutachtung

MFPA Weimar

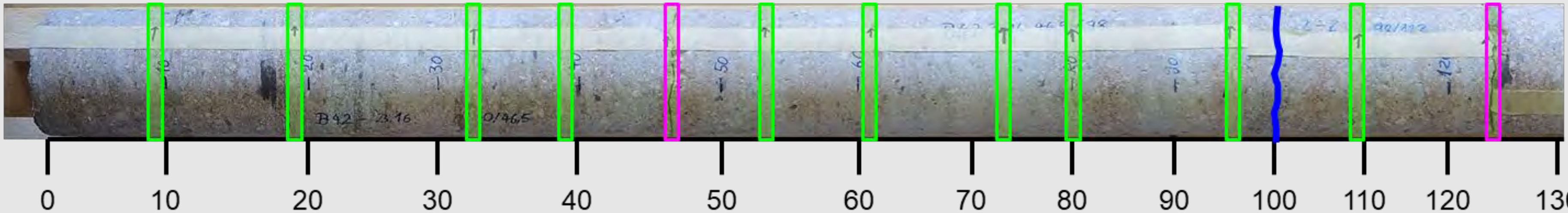
Funding

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

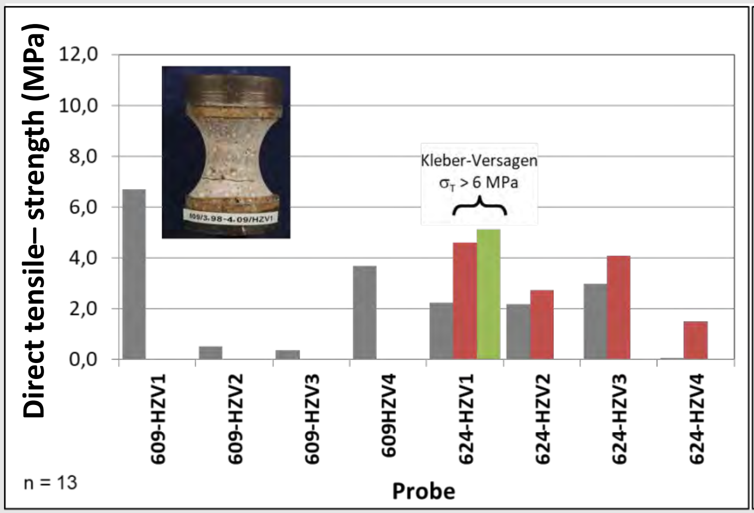
Support

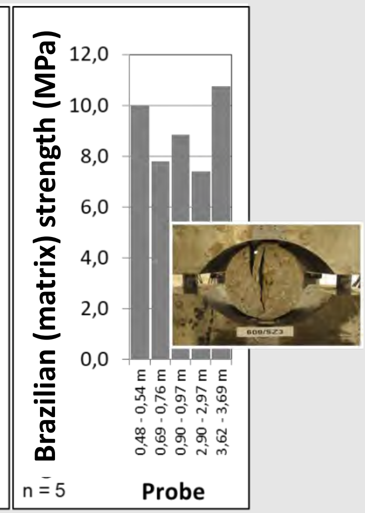
BETREUT VOM
PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie

Shotcrete interface characteristics

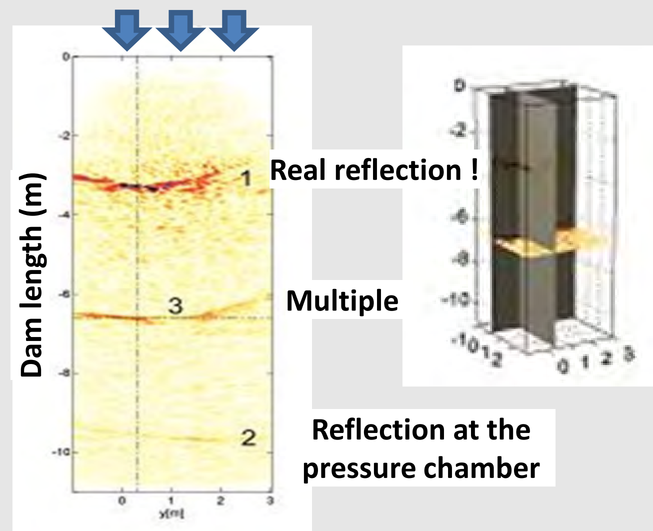


Interfaces exist , but what is there relevancy?





➔ Tensional strength of interfaces varies

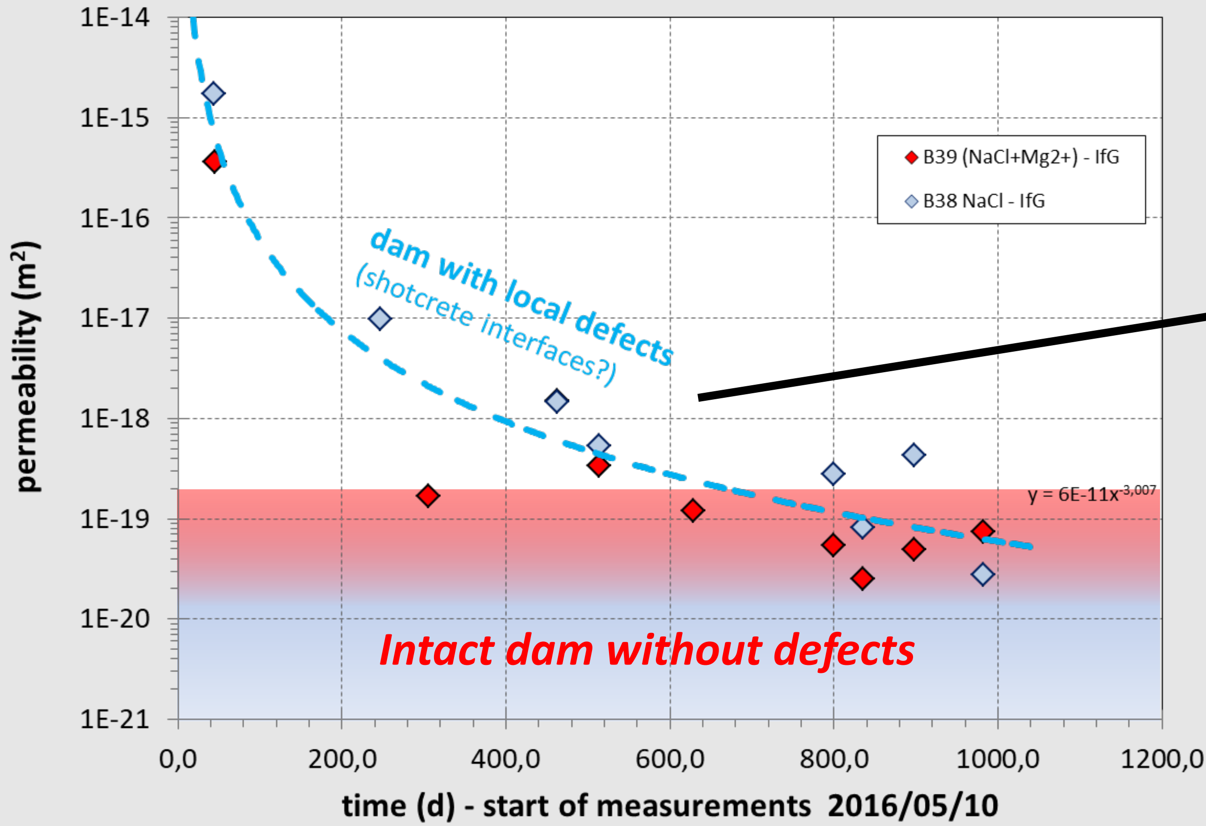


BAM

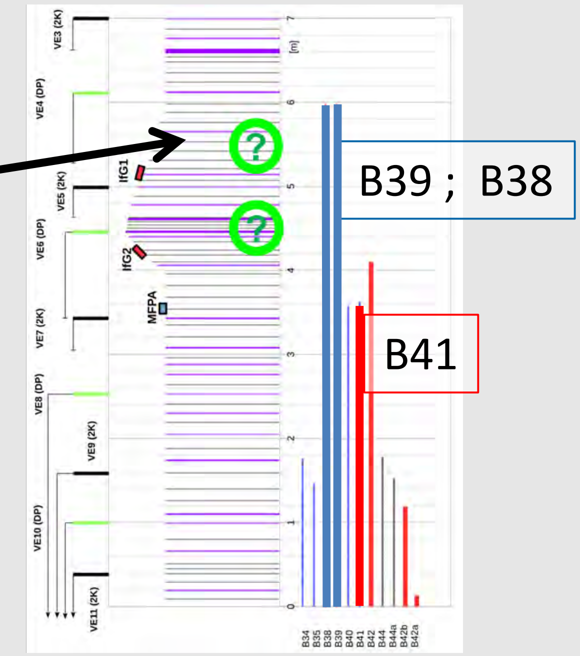
➔ Integral ultrasonic probing (echo-transmission/reflection method), performed by BAM demonstrates only one relevant interface

Bore-hole testing of the GV2-dam

Local interfaces in the shotcrete dam?



Half-Section of the GV2-dam with sprayed segments and Investigation bore holes

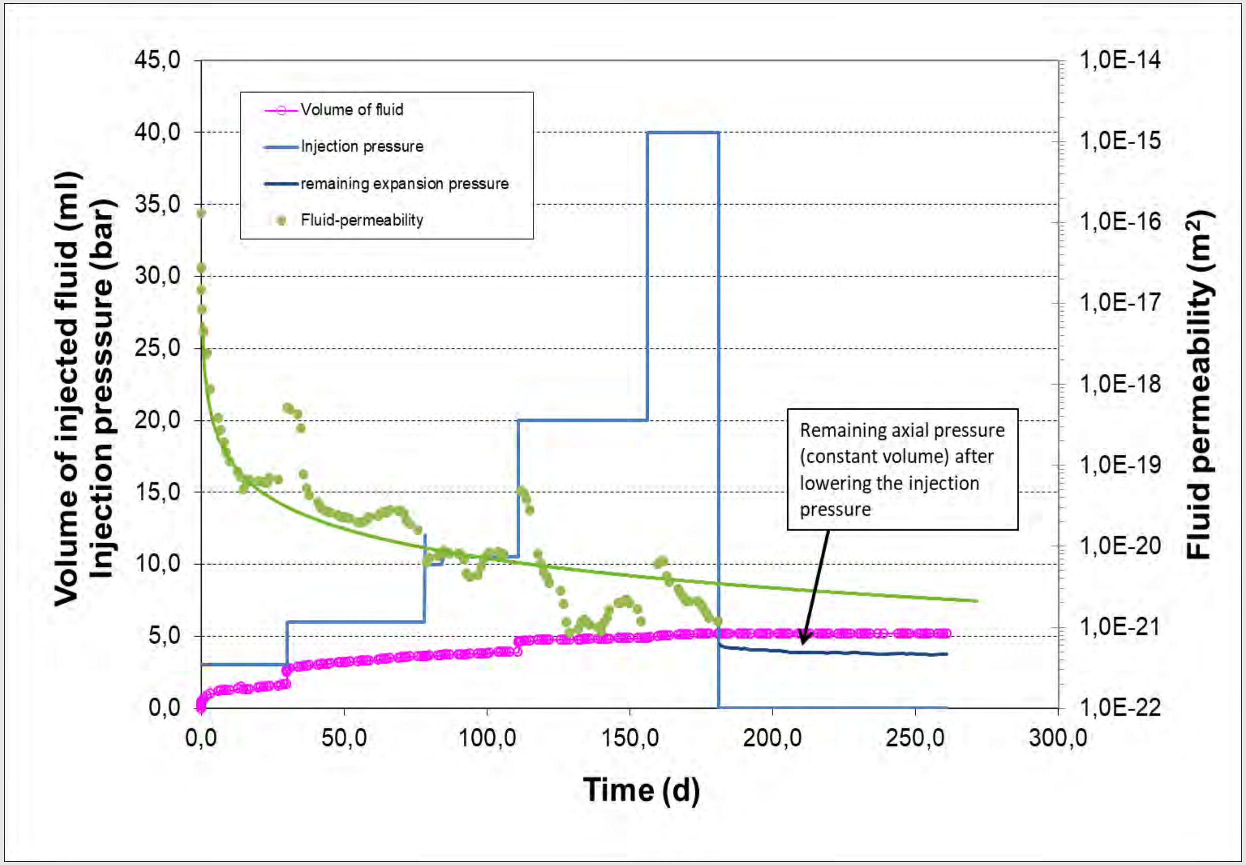


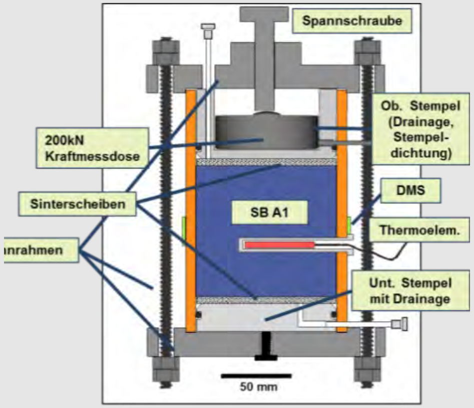
Local defects in the dam exist, but

a time-dependent permeability dcrease occurs for both solutions!

Sorel Building Material : Permeability testing with brine

Long-term injection lab test in an oedometer cell (5-1-8 mixture)





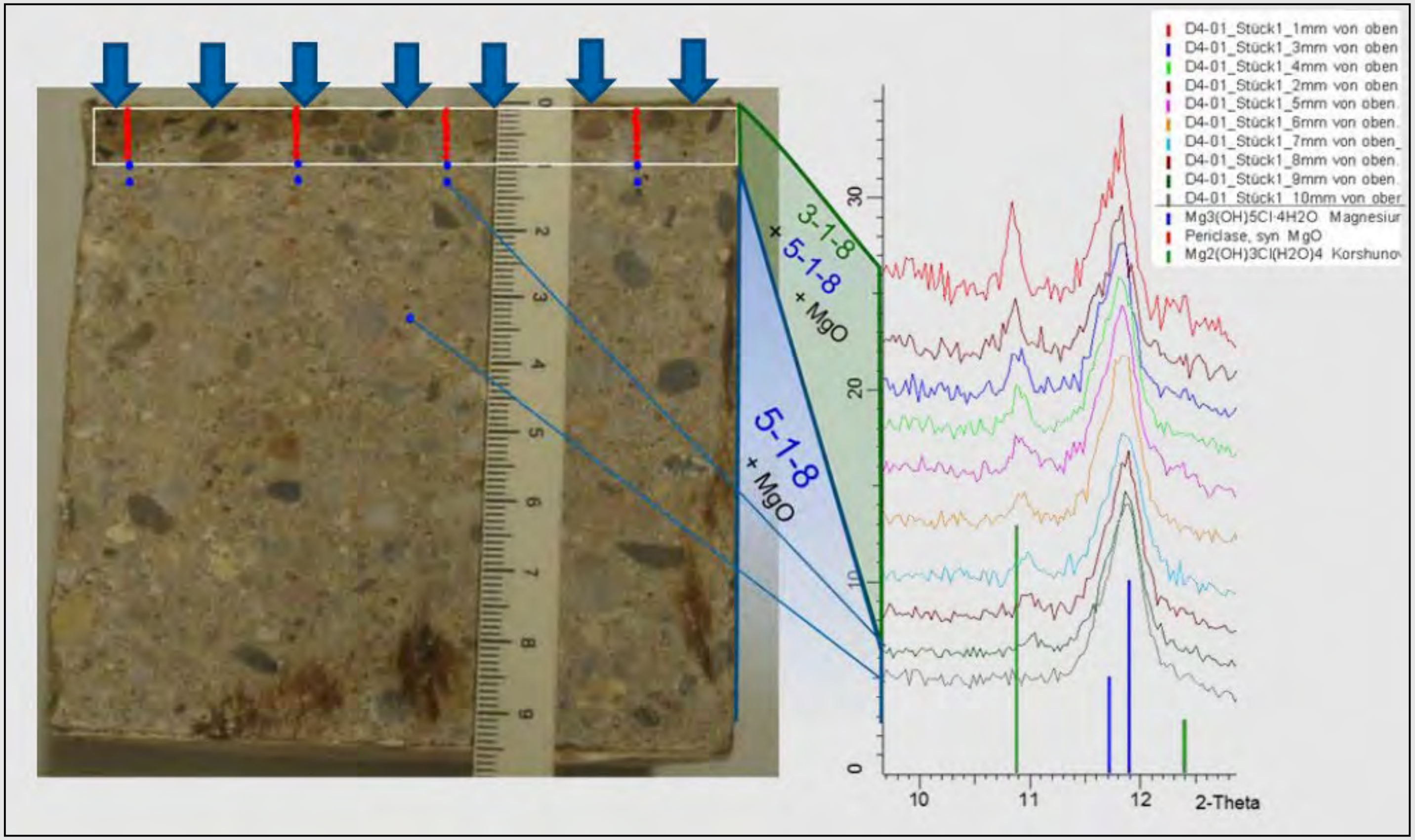
Probengröße:
d = 100mm x h = 95mm
➔ V = ca. 750ml
➔ Max. Zellendruck: 20 MPa

Note that the permeability decreases with inflow of brine = self sealing !

Sorel Building Material : Inflow of brine

Solution access to 5-1-8 based material

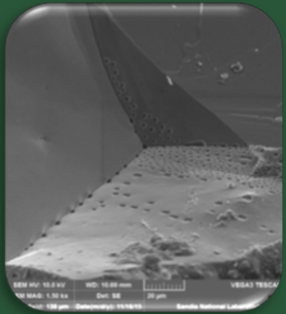
Local resolved x-ray diffraction

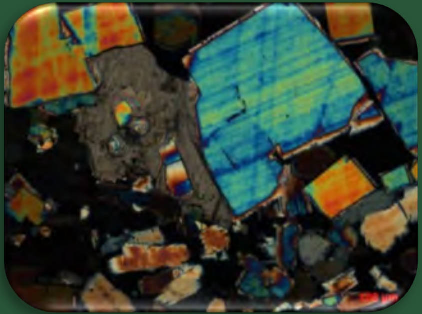


The phase transition from 5-1-8 to 3-1-8 is accompanied with solid phase volume increase = self sealing!

Conclusions and outlook

- **Comprehensive knowledge about MgO-based building materials**
  - Depending on the requirements different formulationtyps are available → "Tool box"
  - Fundamental understanding of geochemical phase relationships related to temperature and composition:
    → *the 3-1-8 phase is thermodynamically stable up to 80°C*
    → *the 5-1-8 phase is metastable*
- **Favorable material properties :**
  - High-strength / low permeability → Comprehensive data base of hydro-mechanical properties of different mixtures
  - Proof of self sealing → indirect long-term stability of the 5-1-8 phase
- **Demonstration of feasibility of drift seals by mock-up tests**
- **Ongoing investigations of the GV2 in the Teutschenthal mine:**
  - **MgO-SEAL** (finished); **MgO- S^3** (just started)





10th US/German Workshop on Salt Repository Research, Design, and Operation

Sandia National Laboratories

BGE TEC
BGE TECHNOLOGY GmbH

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

RESPEC

SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

Stefan Poetzsch (Presenter)
Helmut Mischo (Project Leader)
TU Bergakademie Freiberg

Rapid City, SD, United States
May 28-30, 2019

In-situ Testing of a new Long-term Stable Backfill Material for HAW-Repositories in Saline Formations

Crushed Rock Salt (dry or wet)

- \+ Easily available / characteristic
- \+ Simple backfilling methods
- \- No initial load bearing capacity
- \- High initial porosity

Building Materials (e.g. salt-concrete)

- \+ No settlements
- \+ Low initial porosity
- \- Complex processing methods
- \- Long-term cement stability

GESAV-Material

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

In-situ Testing of a new Long-term Stable Backfill Material for HAW-Repositories in Saline Formations

PROJECT-STRUCTURE

GSES

Glückauf Sondershausen Entwicklungs- und Sicherungsgesellschaft mbH

Active Salt Mine (GSES mbH)

Institute of Inorganic Chemistry

Underground Tests

Lab Tests

Material Design

IfG

Institute of Geomechanics (IfG GmbH, Leipzig)

TU BERGAKADEMIE · FREIBERG ·

Institute of Mining and Special Civil Engineering

Persons involved:

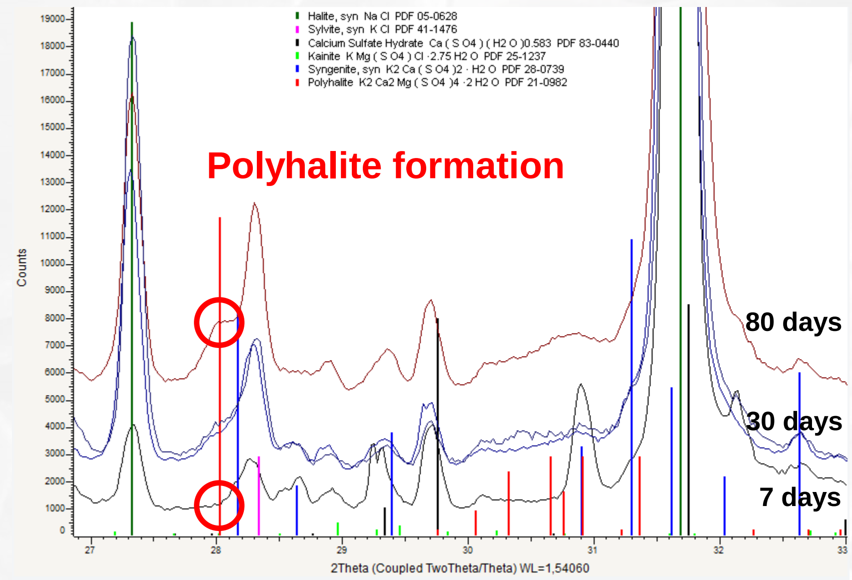
Stefan Pötzsch; Ute Fliege; Ronny Jentzsch; Matthias Gruner; George Barakos; Helmut Mischo; Regina Moßig; Melanie Pannach; Daniela Freyer; Till Popp; Michael Wiedemann; Thomas Kießling; Christian Baum

Granted by: Bundesministerium für Wirtschaft und Energie

Managed by: PTKA Projektträger Karlsruhe, Karlsruher Institut für Technologie

Grant No.: 02E11557

CHEMICAL COMPOSITION OF GESAV-MATERIAL



Rock salt – NaCl: 85 %

Salt binder: 15 %

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

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

➢ Polyhalite is long-term stable (thermodynamically stable) in the hexary oceanic salt system

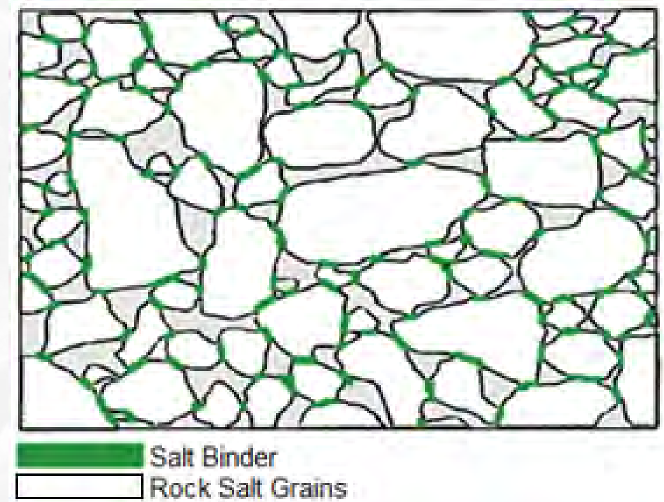
STRUCTURE OF GESAV-MATERIAL

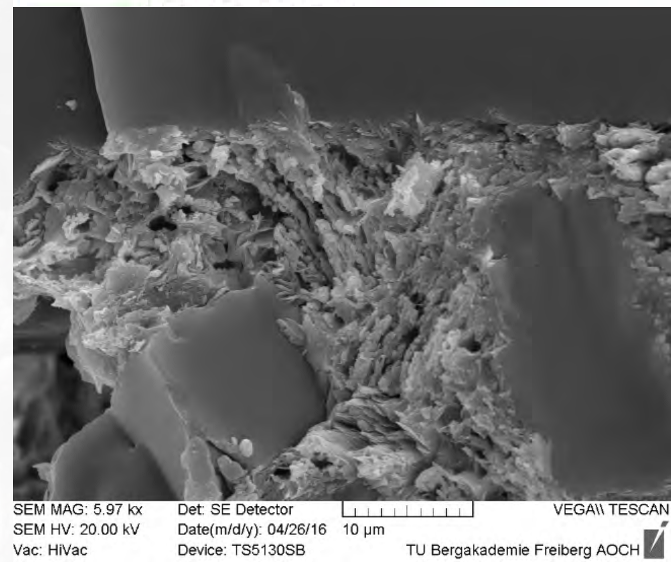
- Optimized crushed rock salt fractions (85 %)
- Max. grain size of 14 mm
- Moisture content 3,75 %

➢ Moist bulk material

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

➢ Matrix-stabilization, no gap filling





LOCATION OF THE TEST SITE

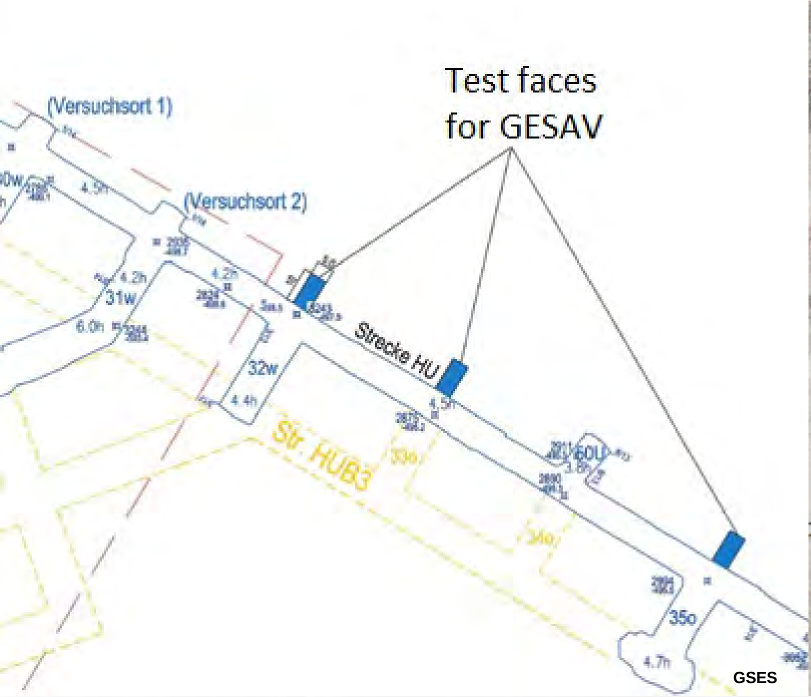
Salt Mine “Glückauf” Sondershausen

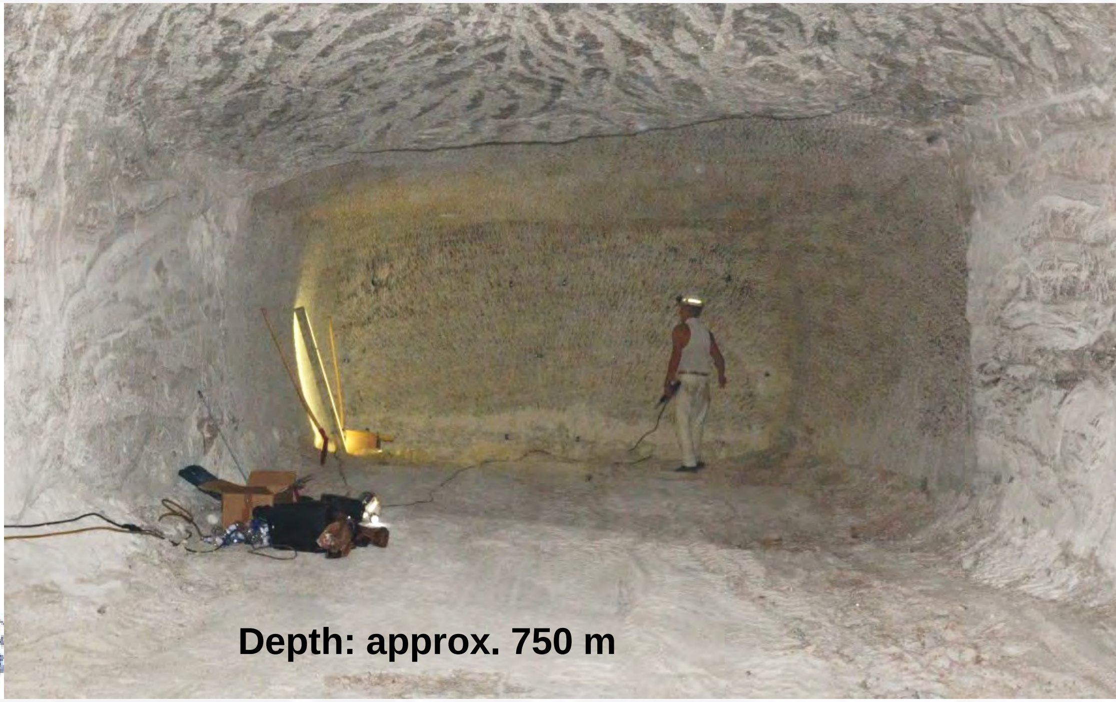
- ➢ Diversified mining company
- Rock salt exploitation, although potash
- Broad backfill activities and various methods:
    - Hydraulic (flush & paste fill)
    - Mechanical (slinger & stack fill)
- Disposal of chemo-toxic waste
- Visitor mine

➢ **Ideal test site for applied backfill research**

In-situ Testing of a new Long-term Stable Backfill Material for HAW-Repositories in Saline Formations

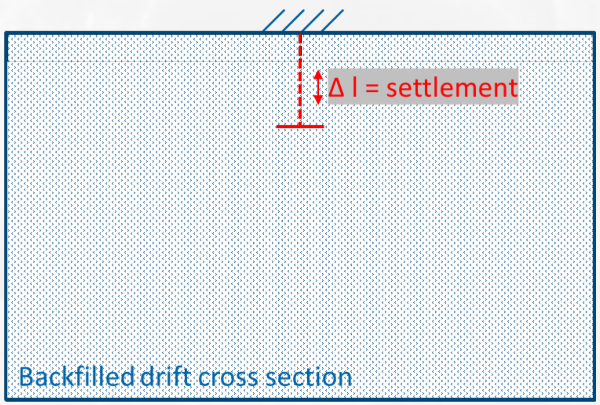
UNDERGROUND TEST SITE



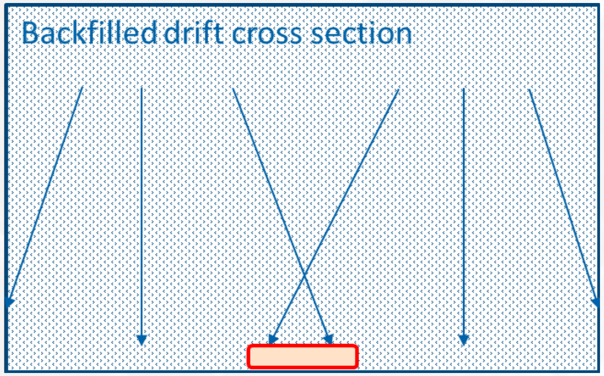


EXPERIMENTAL APPROACH

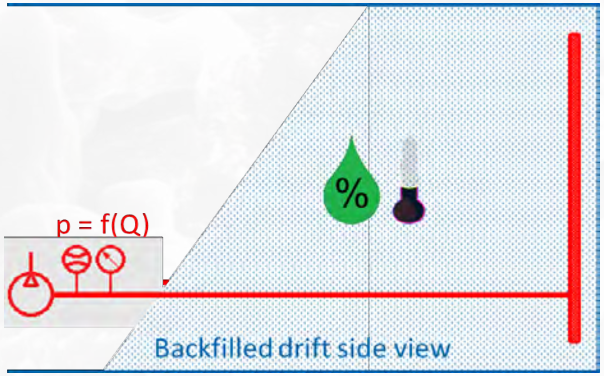
Time dependent settlement



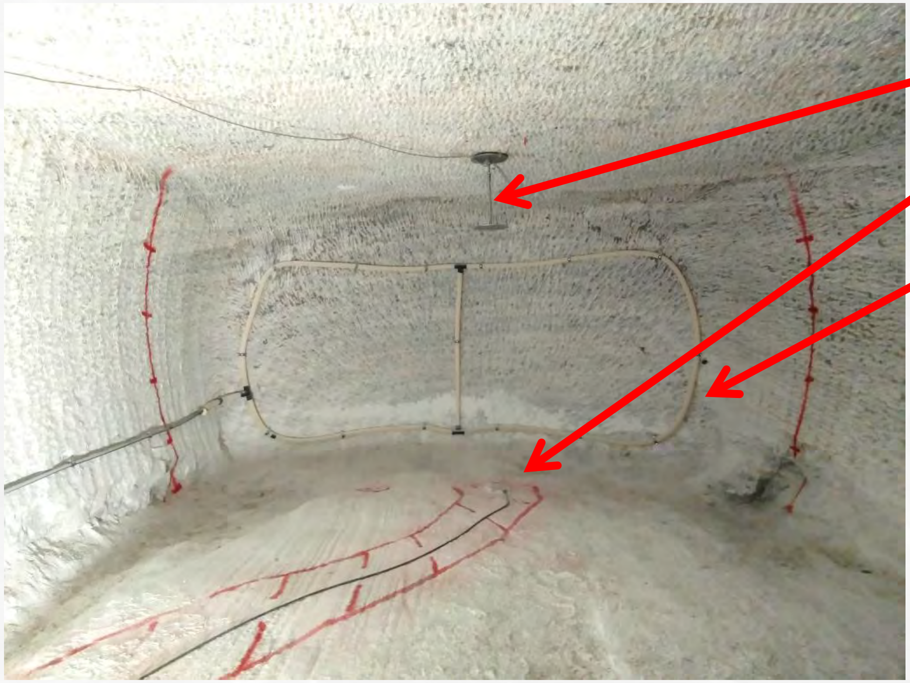
Load bearing capacity



Integral permeability



IN-SITU MEASUREMENT SYSTEMS



Settlement sensor

Earth pressure sensor

Flow-through installation

<u>Not visible:</u>

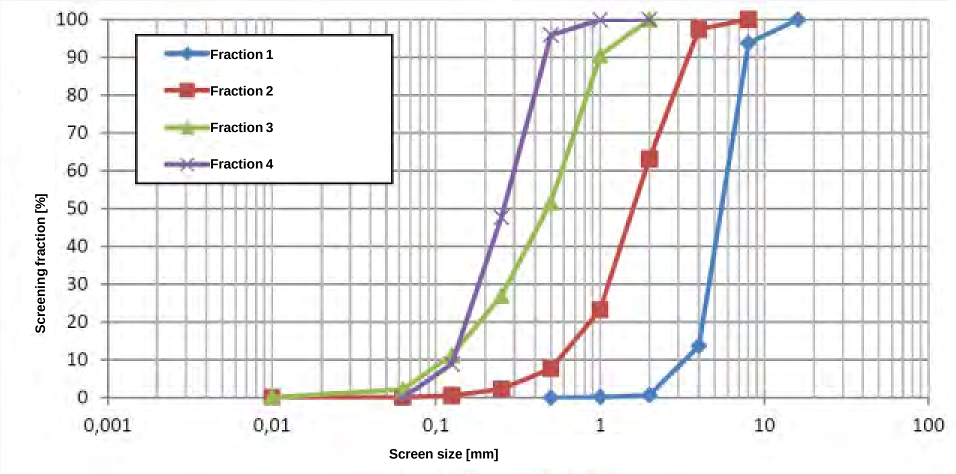
- Moisture & temperature sensors
- 3D-Laserscans
- Convergence measurements

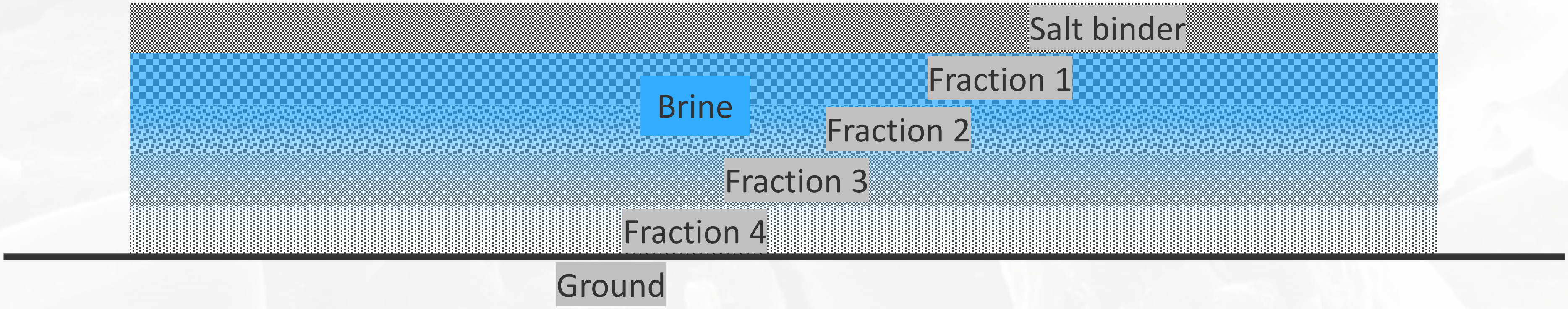
THREE-STAGED MIXING PROCESS

- Salt binder
- Salt aggregates
- GESAV-Material

THREE-STAGED MIXING PROCESS

→ approx. **80 t** for each test face required





APPLICATION OF BACKFILL METHODS

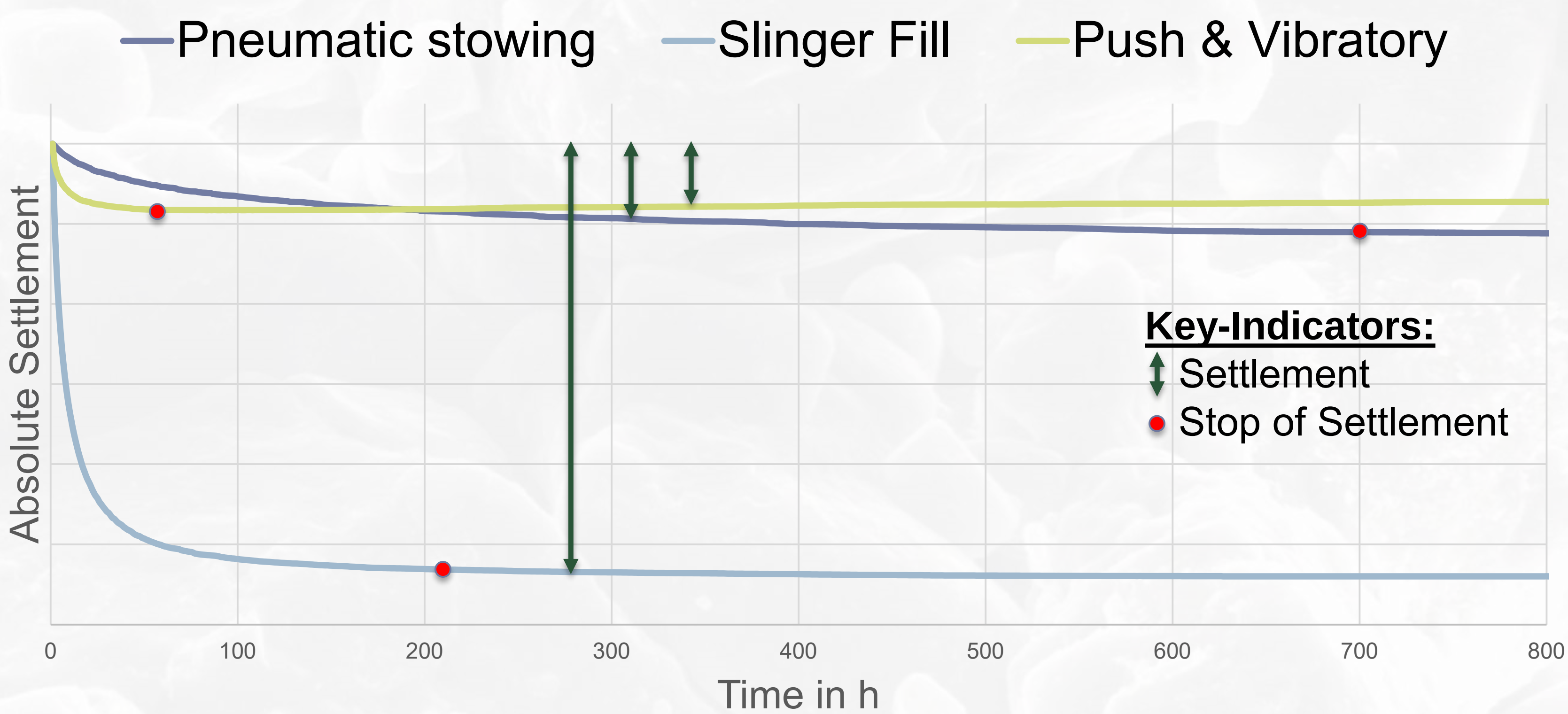
Pneumatic stowing

Slinger fill

Push fill & vibratory compaction fill

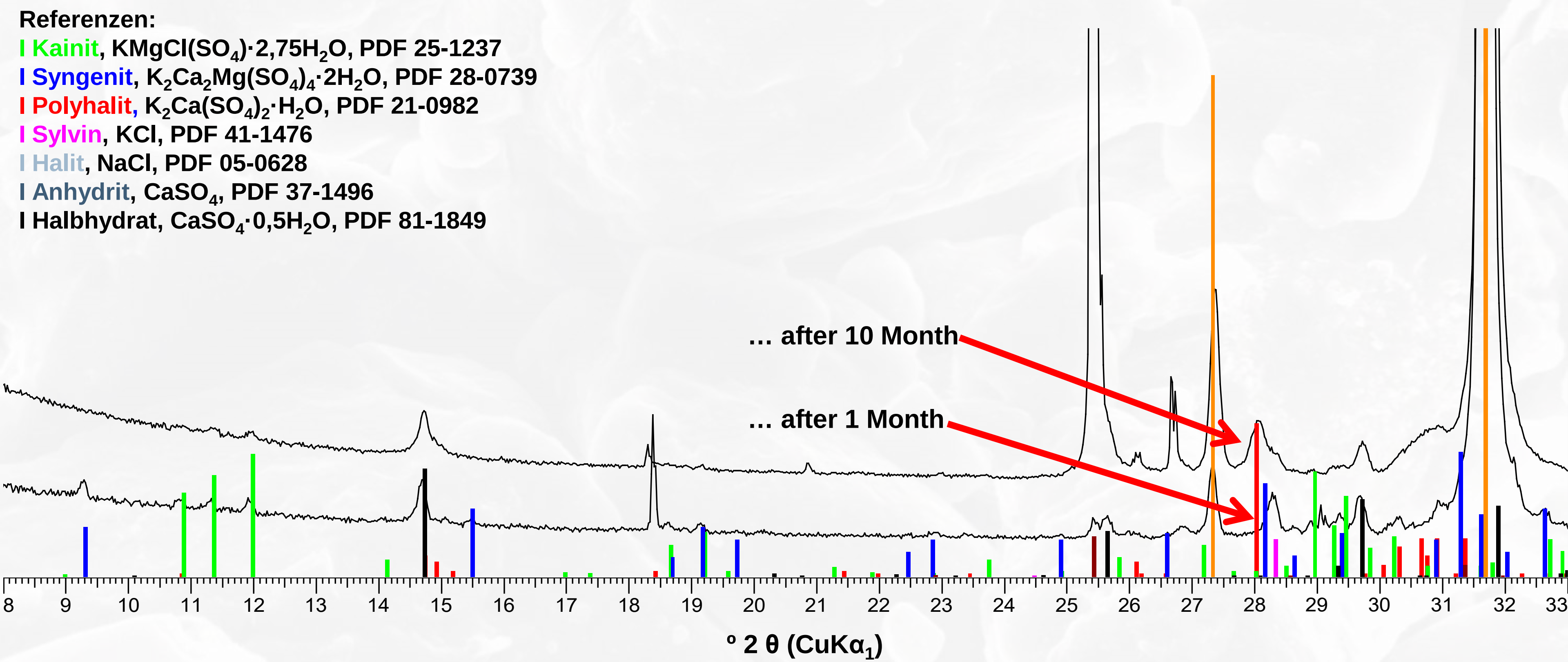
In-situ Testing of a new Long-term Stable Backfill Material for HAW-Repositories in Saline Formations

SETTLEMENT



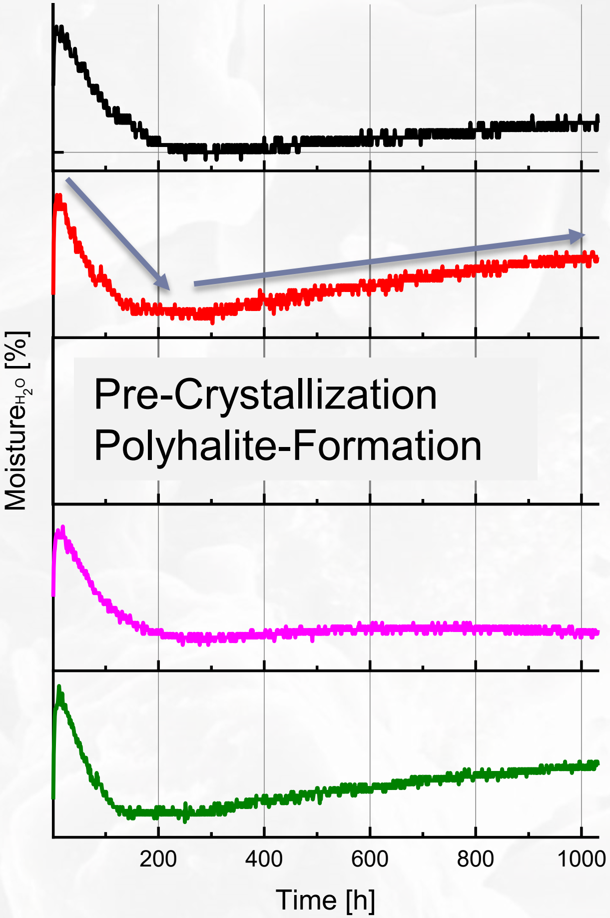
In-situ Testing of a new Long-term Stable Backfill Material for HAW-Repositories in Saline Formations

IN-SITU POLYHALITE-FORMATION



In-situ Testing of a new Long-term Stable Backfill Material for HAW-Repositories in Saline Formations

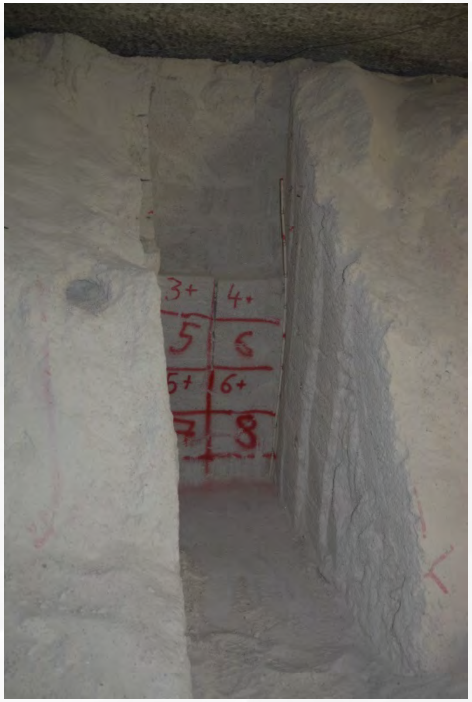
TIME-DEPENDENT MOISTURE CONTENT



SAMPLING METHOD

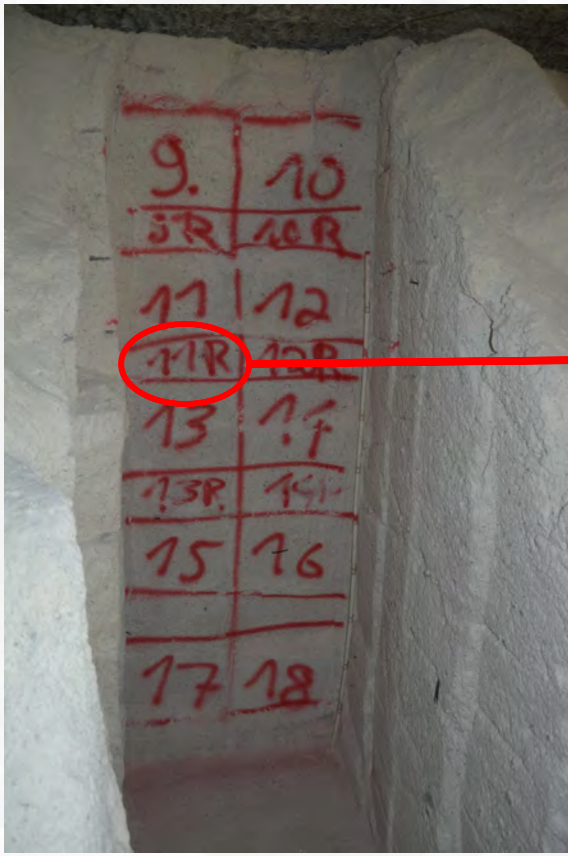
Gaining access to the inner part of the backfill body

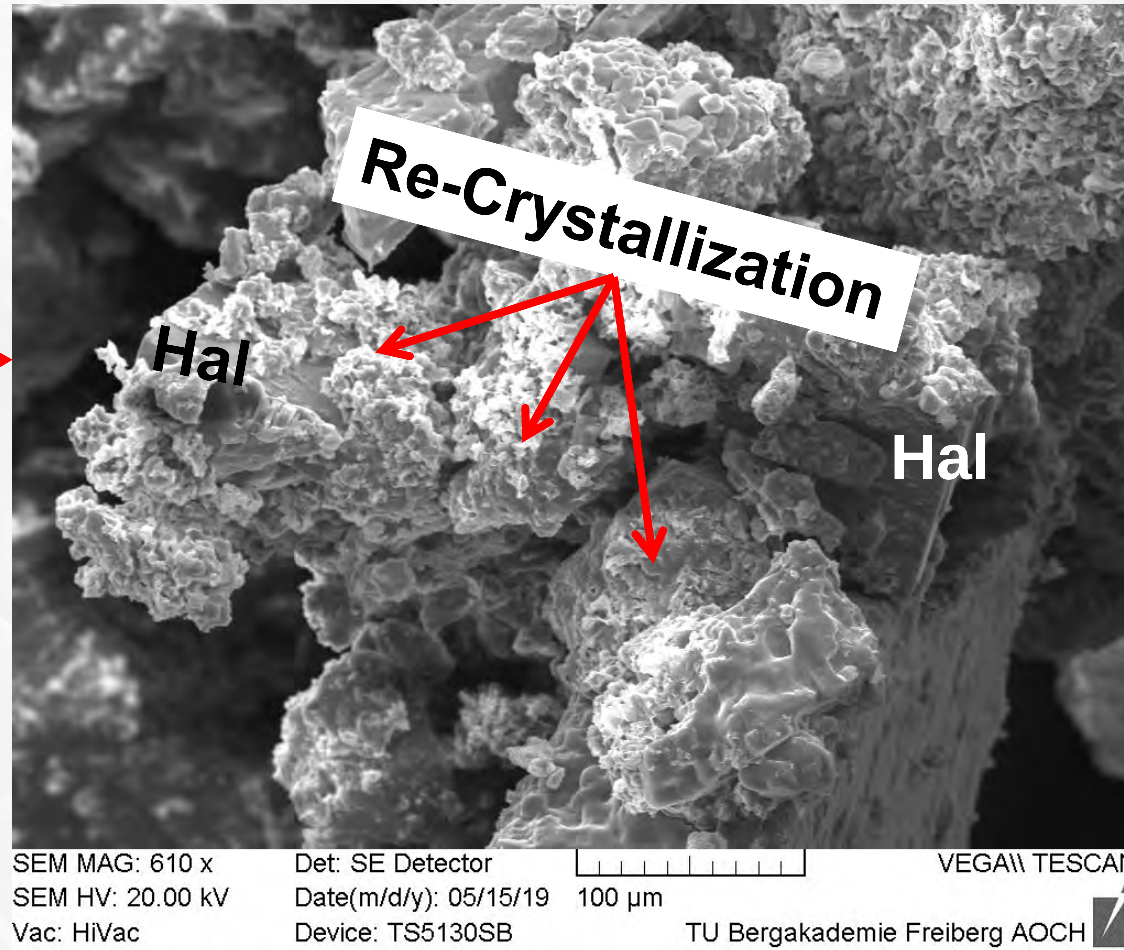
Samples



Measurement layer inside the backfill body

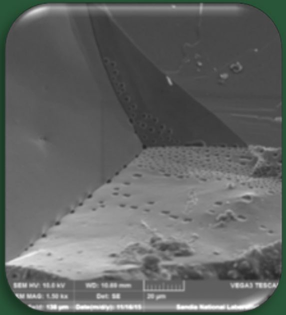
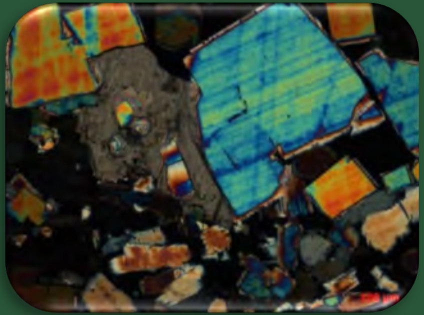
SEM MICROGRAPH OF UNDERGROUND SAMPLES





THANK YOU FOR YOUR ATTENTION.

GLÜCKAUF!

10th US/German Workshop on Salt Repository Research, Design, and Operation

Dr Amy Shelton
Radioactive Waste Management

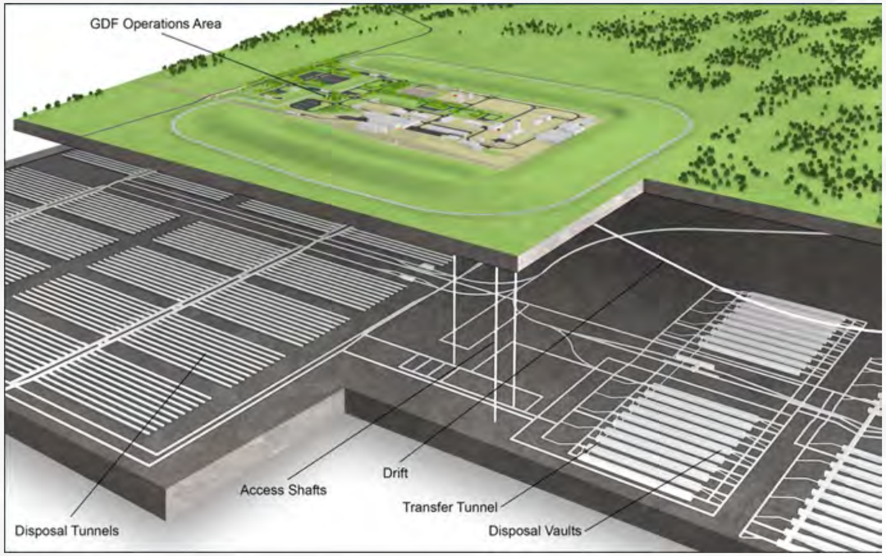
Rapid City, SD, United States
May 28-30, 2019

Integrated project to develop backfill materials for the range of geological environments and waste types.

Our GDF delivery programme

GDF programme vision:

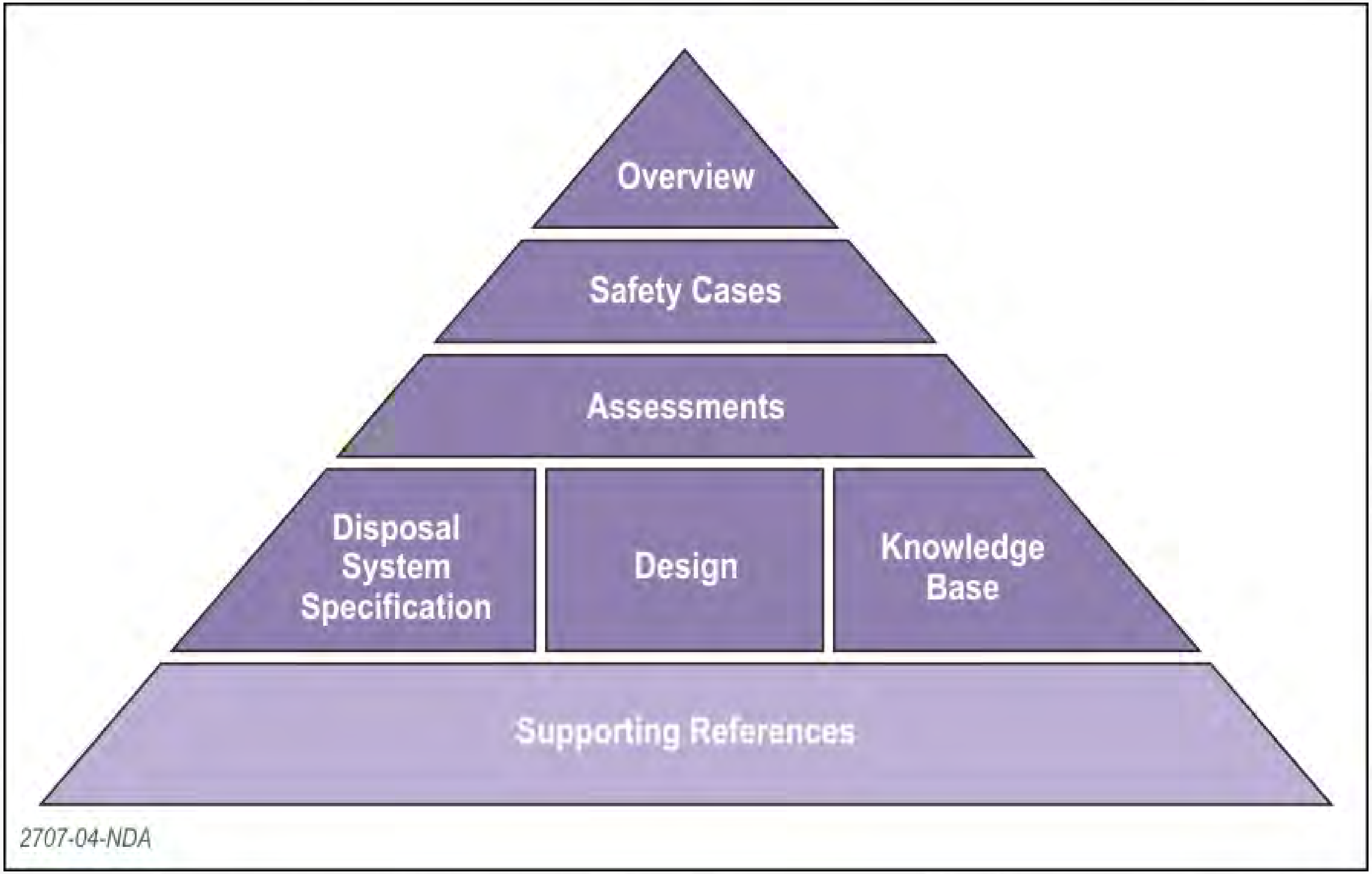
The safe, secure and cost effective disposal of radioactive waste in a geological disposal facility (GDF), to protect people and the environment



Scope:

- design and safety case
- waste acceptance criteria for GDF
- suitable site with a willing community

Generic Disposal System Safety Case



Multi-barrier system

Containment

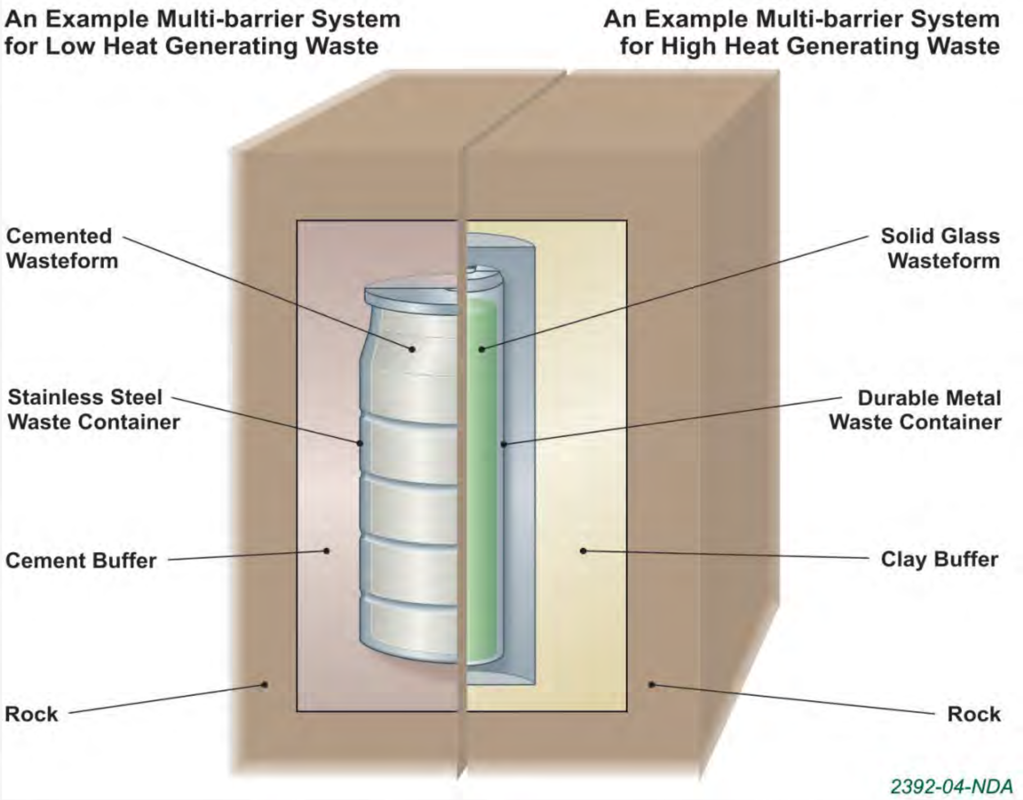
Contain waste in multi-barrier package

Place package in engineered underground facility

Isolation

200-1000m underground to protect from future glaciations

As packages decay, engineered barriers and surrounding rock provides long-term protective barrier



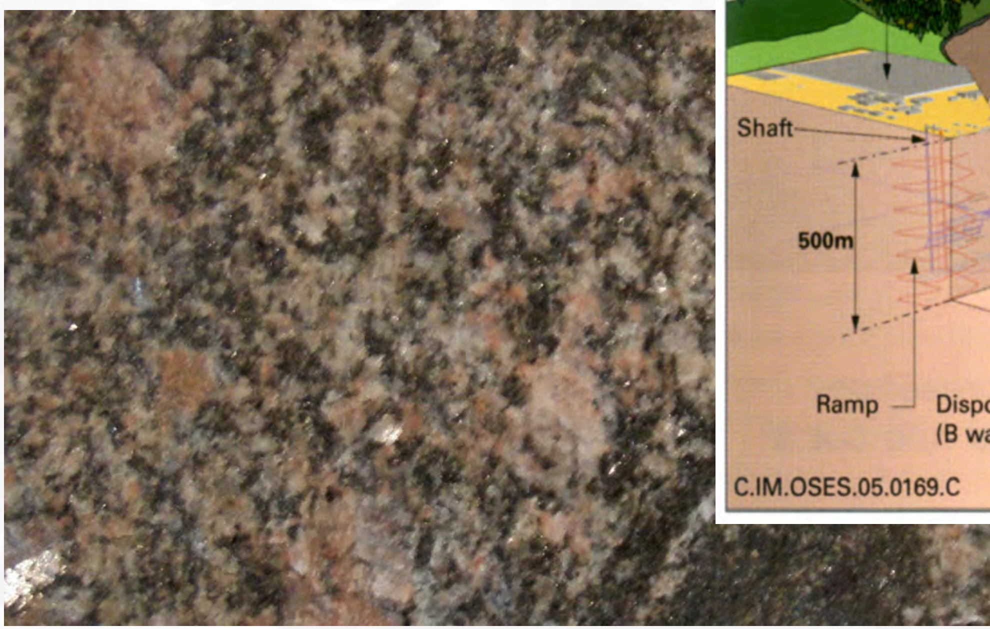
Potentially suitable host rock types:

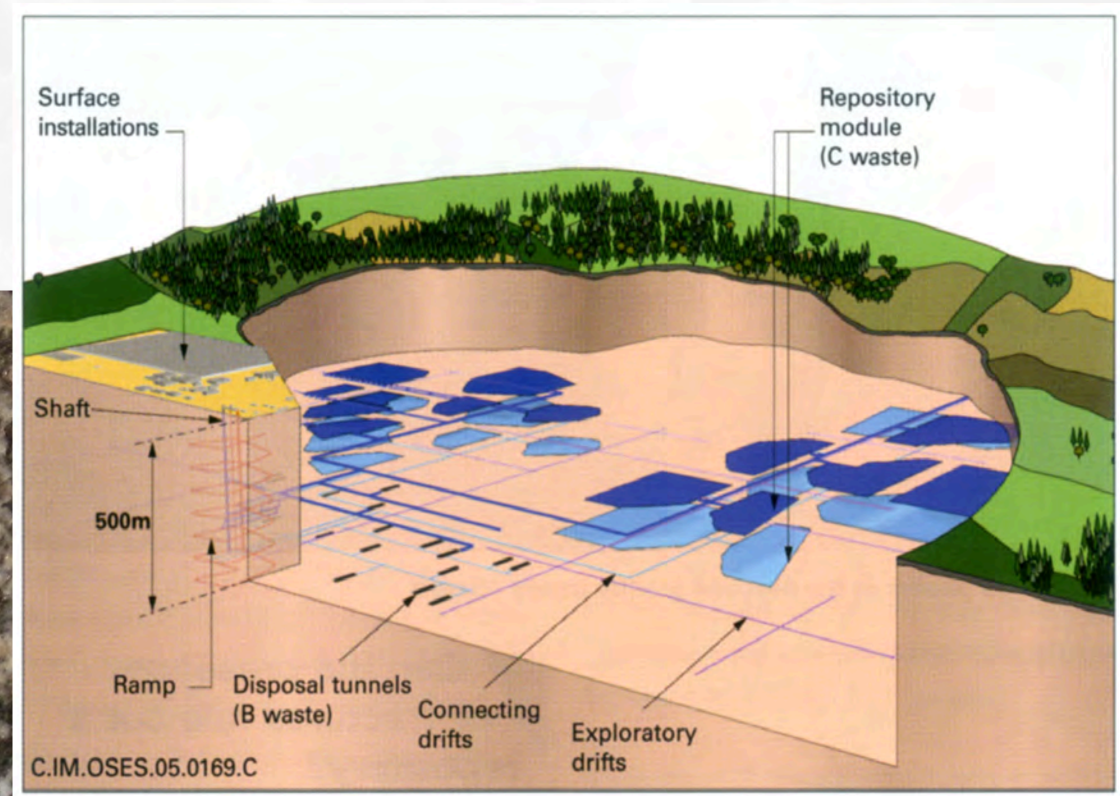
Lower Strength Sedimentary Rocks (e.g. clays, mudstones)

e.g. Jurassic mudstone c.450 m: Bure, France

Potentially suitable rock types:

Higher Strength Rocks (e.g. granite, slate)

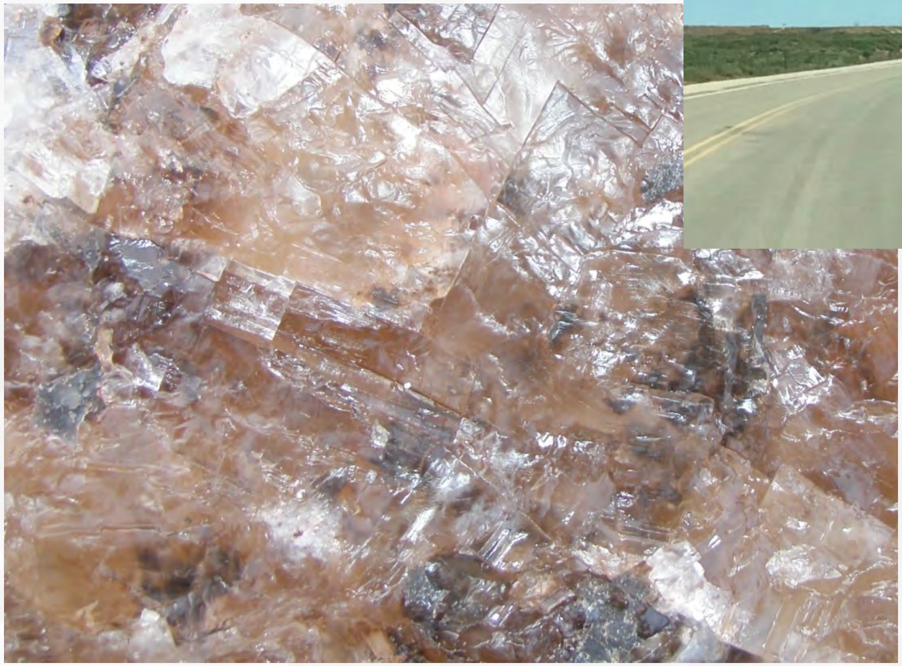




e.g. Granite, Sweden

Potentially suitable rock types:

Evaporite



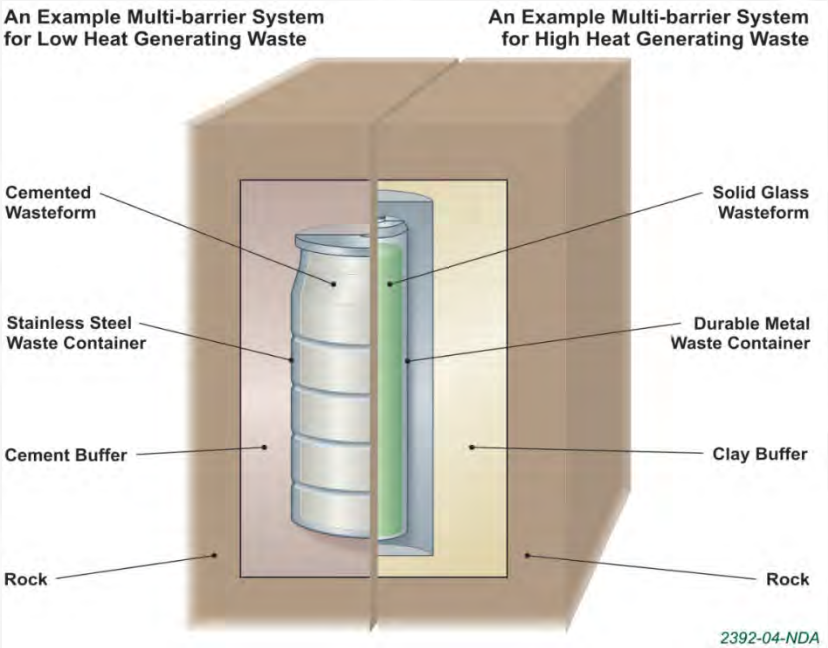
e.g. WIPP Site: Permian basin, USA

Background and Project Context

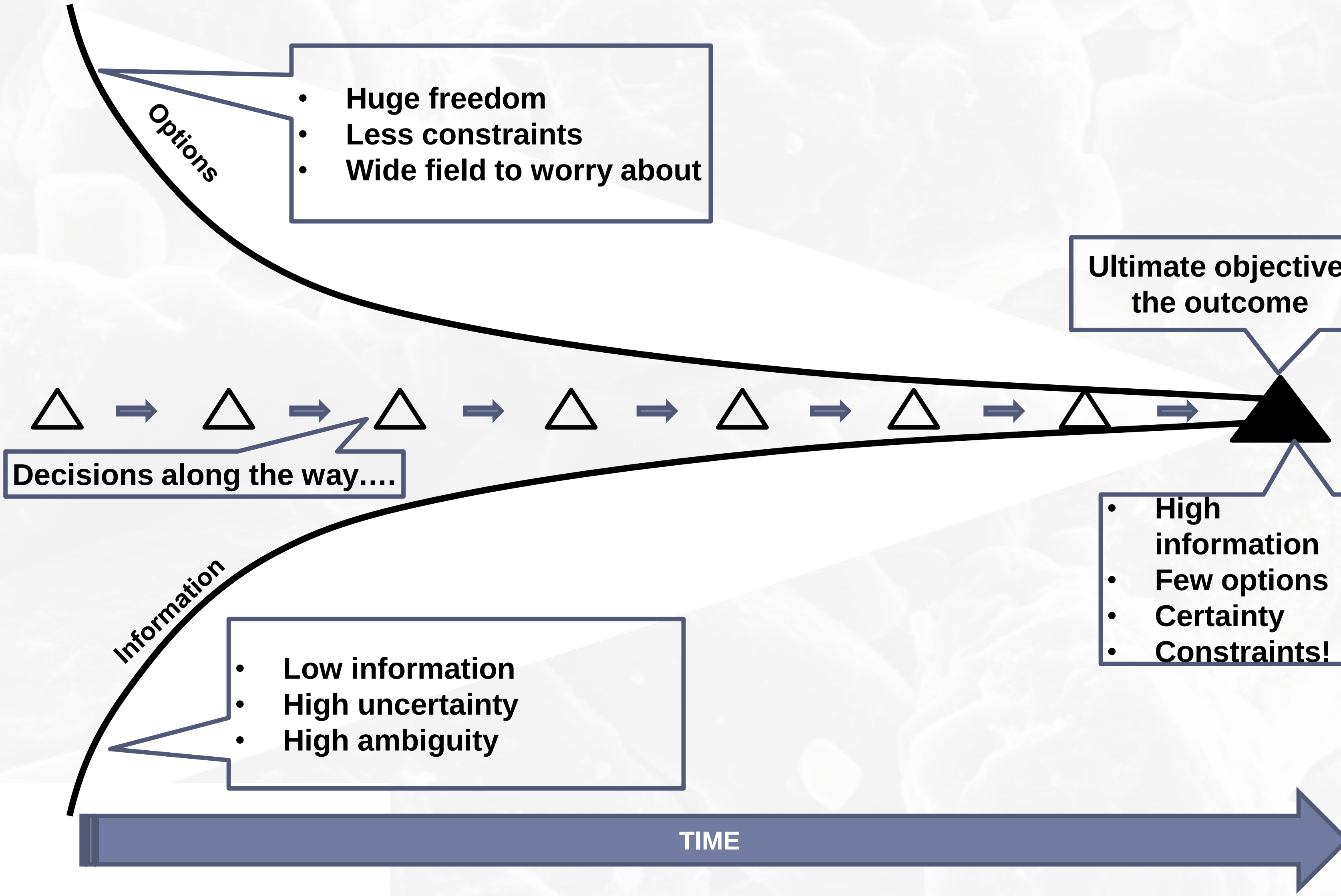
In LHGW concepts, the *backfill* is the material that immediately surrounds the waste packages. *Mass backfill* is the material used to fill GDF accessways.

The backfill material is one of the multiple barriers that contribute to ISOLATION and CONTAINMENT of the waste

The way in which the backfill is required to contribute to isolation and containment will depend on the *geochemistry*, the *groundwater flow regime*, the *mechanical stability* and the *thermal properties* of the selected geological environment



The art of decision making…



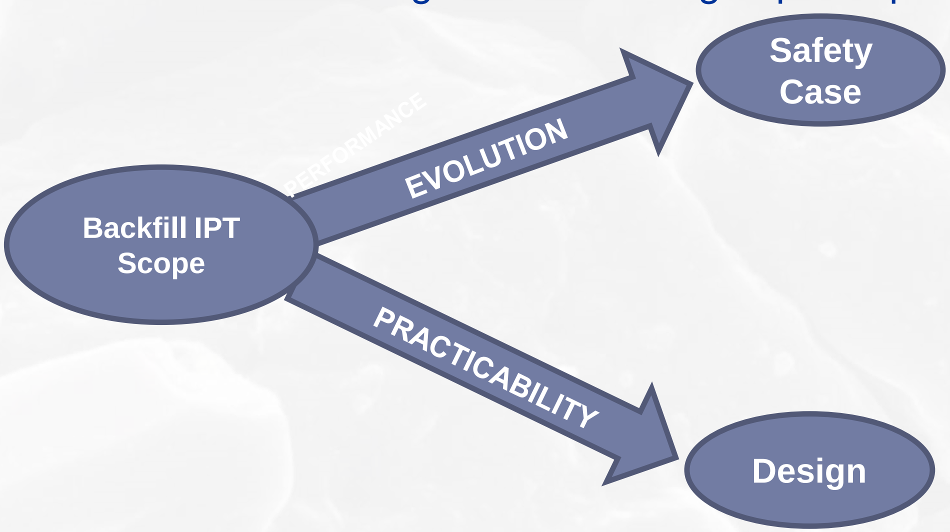
Shifting the focus to DELIVERY

In establishing the GDTP18, the scope to deliver an EBS for LHGW and its numerous interfaces and dependencies have been identified and documented

To *deliver* the GDTP, there is a need for a gated, integrated approach to the EBS technical scope to manage the extensive inputs, needs and handshakes across RWM throughout the duration of the programme

We need to understand the resource needs (people, supply chain and surface and underground facilities)

Why now? Assess the level of technology maturity required to support key decisions and where we are against that through upfront planning.



05/08/2019

Outcomes

The overall objective of the project is based around delivery of the following **OUTCOMES**:

Phase 1

- A fully integrated and justified ROADMAP for delivery of technically feasible and scientifically underpinned backfill materials that meets the long term safety requirements.
- A justified Business Case for the next phase of technical work detailing links to key decisions and interfaces within the geological disposal technical programme.

Phase 2

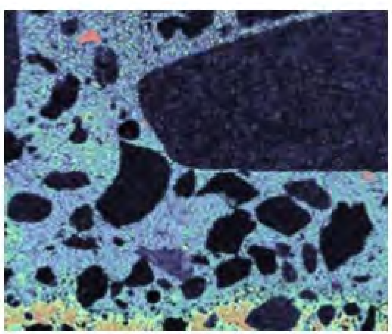
- Implementation and delivery of Roadmap Issue 1

The Project Team

A-INSINÖÖRIT
Phil Bamforth Consulting Ltd
Clay Technology AB
BGE TEC
Studsvik
nagra
mcm
SKB
University of Leeds
wood.

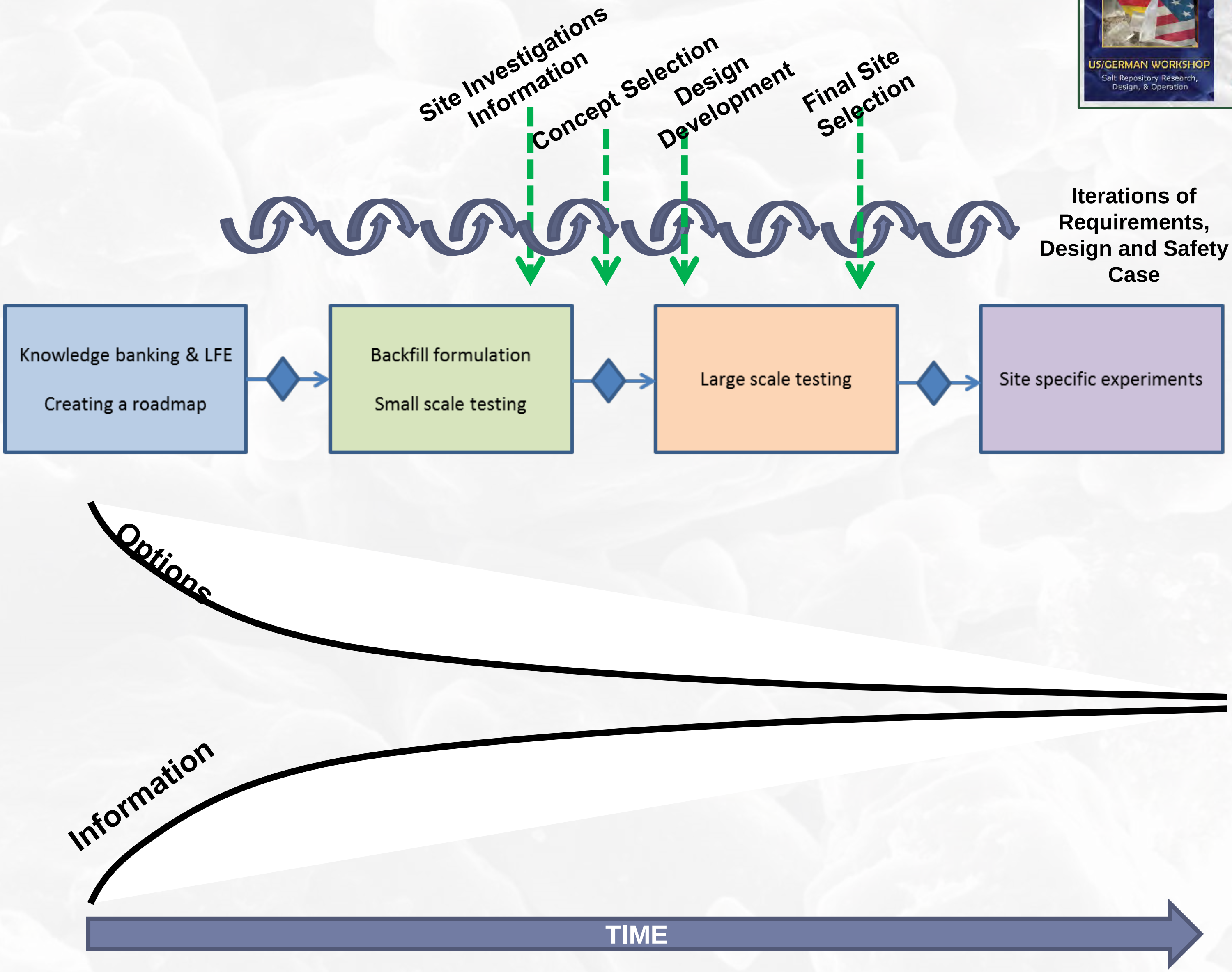
Backfill Development Integrated Project Consortium

From science | ...and technology development | to solution



...underpinned by safety | ...guided by requirements

05/08/2019



Site Investigations Information
Concept Selection
Design Development
Final Site Selection
Iterations of Requirements, Design and Safety Case
Knowledge banking & LFE
Creating a roadmap
Backfill formulation
Small scale testing
Large scale testing
Site specific experiments
Options
Information
TIME

Phase 1

- Task 1 – Knowledge banking
- Task 2 – Influences on backfill formulation
- Task 3 – Development of a future work programme
- Task 4 – Production of the Backfill IPT Roadmap
- Task 5 – Production of the Phase 2 Business Case

Photocredit:<ahref="http://payload181.cargocollective.com/1/5/188088/5920782/DUmap1.png">Cargocollective.com

05/08/2019

Summary

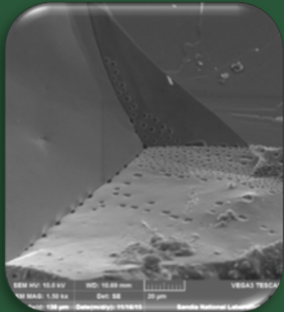
- A phased, gated project to deliver a technically feasible and scientifically underpinned backfill material for the range of geological environments and waste types
- A key focus on alignment with RWM's developing Programme Management approach– setting out the roadmap for delivery with the near-term plans defined in greater detail
- A key focus on integration and communication within RWM
- Bank the knowledge we have developed ourselves and can learn from other WMOs/other industries and use that to define the way forward
- Analysis of options and demonstration of decision making
- Measurements of scientific and technical maturity against information needs/ key decisions within the technical programme. Where are we now, and where do we need to be, by when?

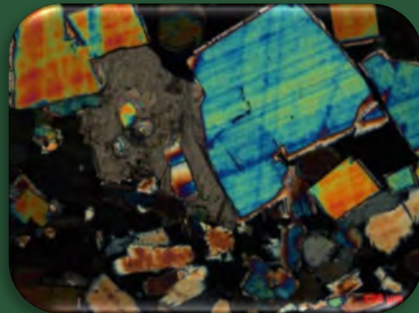
Keeping in touch…

You can contact GDFenquiries@nda.gov.uk or you can reach me directly at: amy.shelton@nda.gov.uk

You can visit our website at: www.nda.gov.uk/rwm

For regular updates please subscribe to our e-bulletin news alerts at: http://www.nda.gov.uk/rwm/subscribe





10th US/German Workshop on Salt Repository Research, Design, and Operation

Topical Session – Sample Conditioning

Sandia National Laboratories

BGE TEC
BGE TECHNOLOGY GmbH

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

RESPEC

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

Stuart Buchholz
RESPEC

Rapid City, SD, United States
May 28-30, 2019

Introduction

- Purpose
  - To identify and discuss influences of sample conditioning on the mechanical behavior of salt
- Goal
  - Summarize standard procedures and best practices for:
    - Handling core in the field
    - Preparing and shipping core from the field
    - Sample preparation and pre-conditioning
    - Preparing core for long-term storage

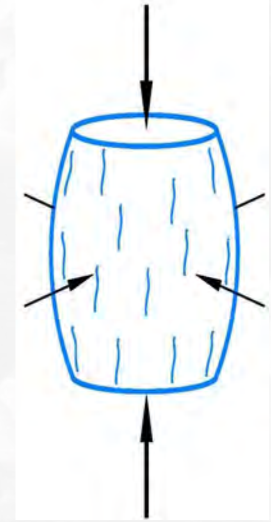
Pre-Conditioning Research Overview

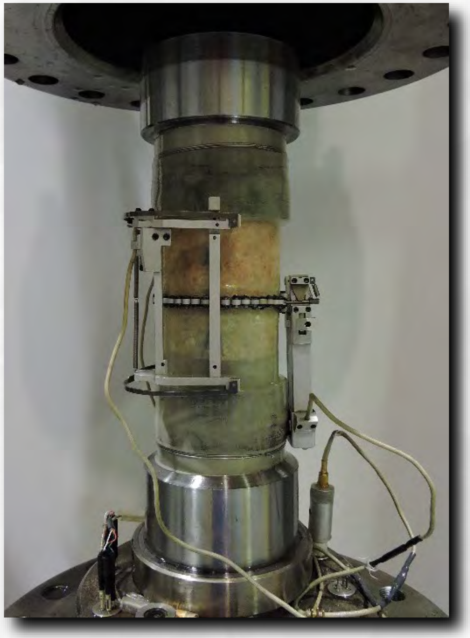
- Purpose
  - Testing for the dilation strength of salt and the influence of pre-conditioning

- Testing Details
  - 27 102mm-diameter by 204mm-length samples were prepared from core obtained from a Gulf Coast salt dome
  - Samples were homogenous clean halite with densities of 2.16 g/cc
  - Samples were pre-conditioned at 20 MPa and room temperature
  - Pre-conditioning times ranged from 0 to 40 days
  - Constant mean stress tests were conducted at 15 MPa mean stress for all 27 tests

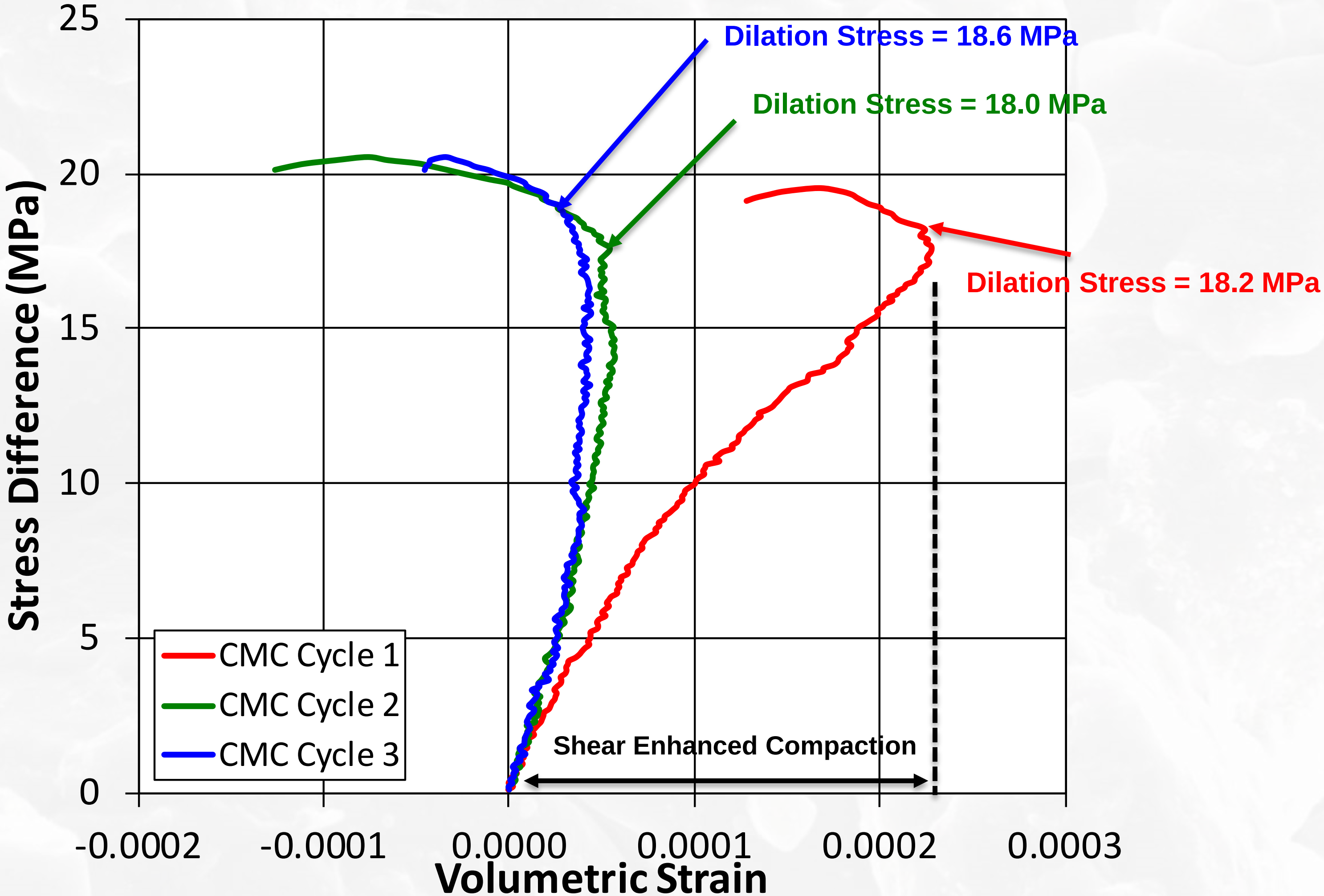
What is a CMS Test?

- Triaxial compression test where the mean stress (average stress) remains constant throughout the entire test
- Mean stress is held constant by applying an axial load at twice the rate the confining pressure is reduced
- Volumetric strain is calculated using the measured axial and radial strains
- Dilation is indicated where the volumetric strain goes negative – indicating an increase in volume (micro-fracturing, creation of void space)

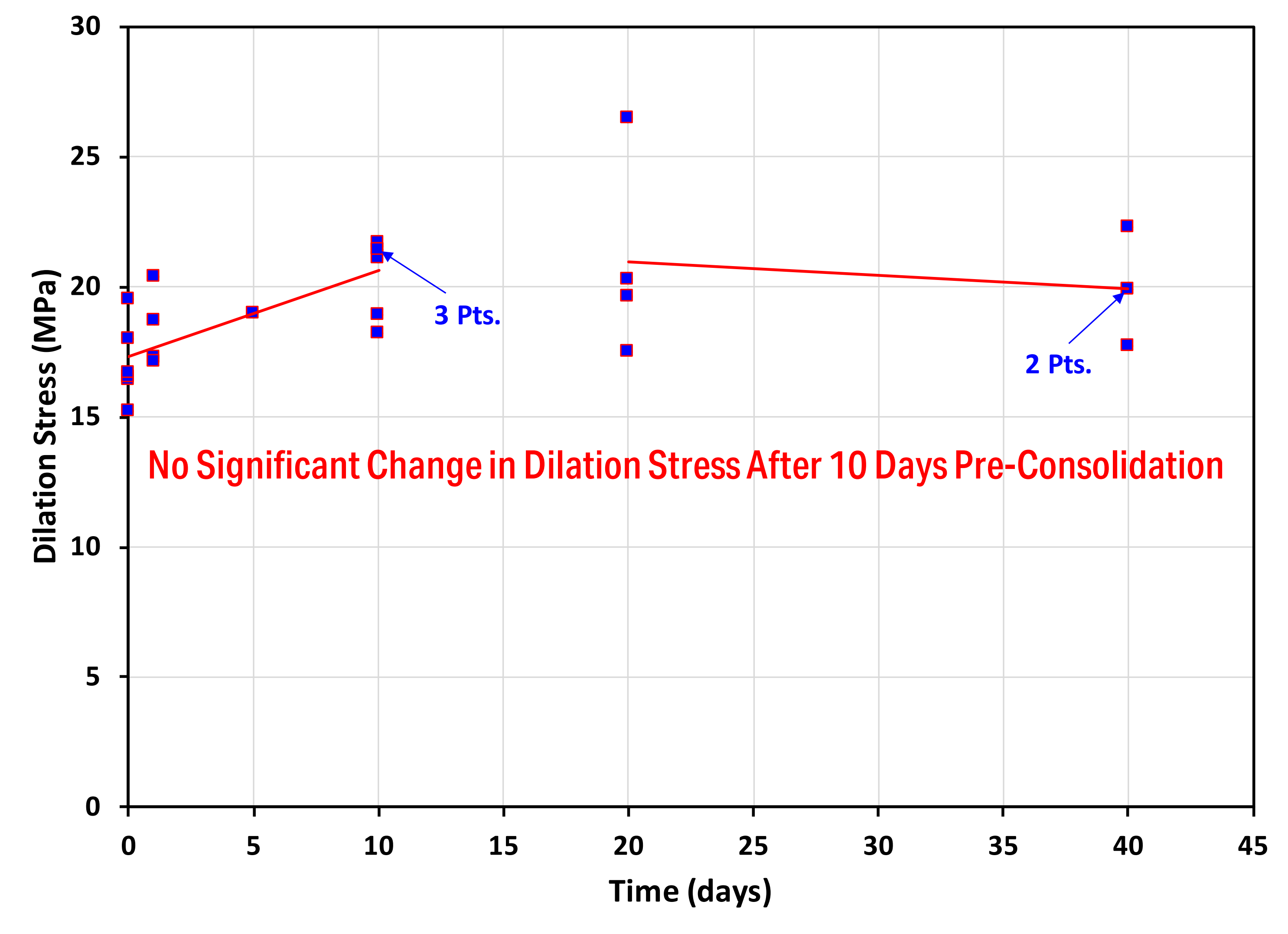




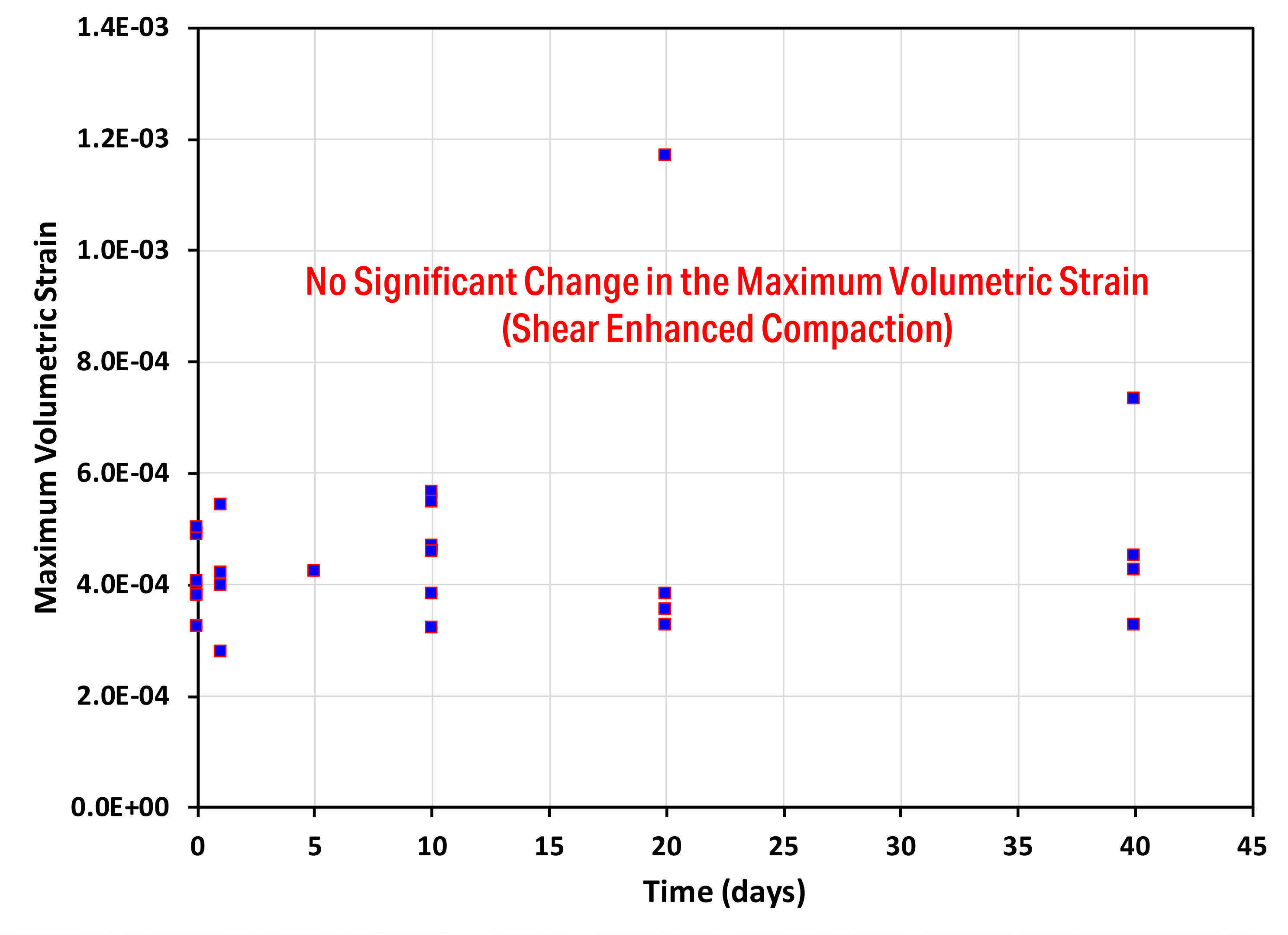
Typical CMS Data Plot



Dilation Stress Vs Pre-Consolidation Time



Dilation Stress Vs Max Volumetric Strain

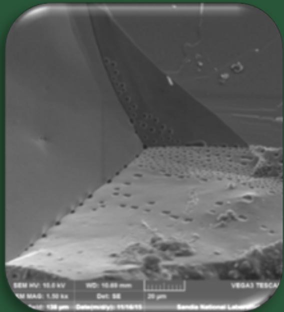
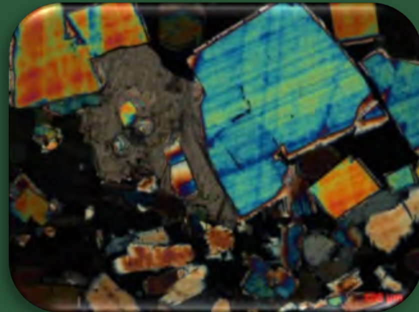


Avery Island Research Core

- Avery Island salt is fine grained, homogeneous, highly pure domal salt used in research for 40 years
- RESPEC collected 30 36cm-diameter by 61cm-long cores, 14 102-mm diameter subcores can be made from each core
- Core is available to Solution Mining Research Institute members for research projects
- Contact myself or Fritz Wilke (DEEP & SMRI) for details

QUESTIONS?

- Jake Hladysz – core shipping, handling, consolidation, long-term storage
- Till Popp / Uwe Dusterloh – sample preparation, influence of sample conditioning on mechanical behavior of salt, scaling effects
- Andres Hampel – influence of temperature during consolidation

10th US/German Workshop on Salt Repository Research, Design, and Operation

Sandia National Laboratories

BGE TEC BGE TECHNOLOGY GmbH

PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology

RESPEC

SOUTH DAKOTA M SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

Author
Affiliation

Rapid City, SD, United States
May 28-30, 2019

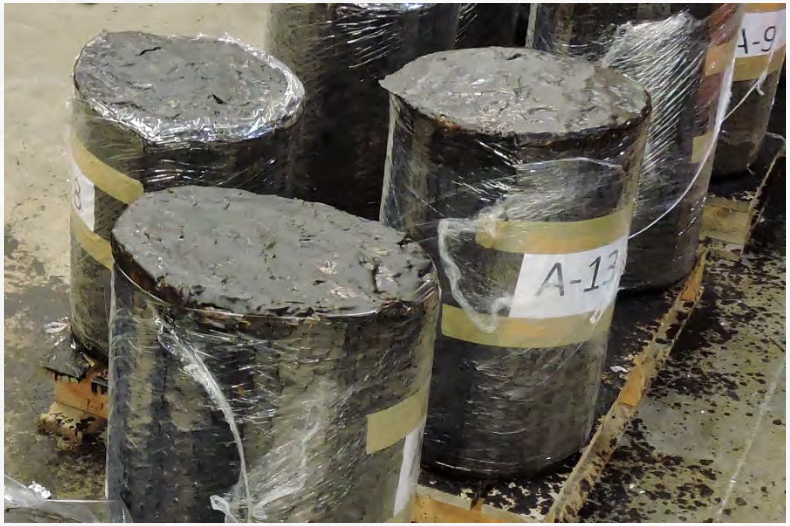
Core Handling

- Extract
- Wash
    - Saturated Brine
    - Degreaser

- Place in Box

Storage

- Boxes
- Plastic Bags in boxes
- Waxed – Long Term
  - Plastic Wrap
  - Aluminum foil
  - Wax



Storage and Shipping

- Boxes on Pallets
- Core Vaults
- PVC tubes on Pallets
- Wood Crates

Consolidation

- Jacket
- Lock Wire
- End Cap and Platen
- Vented
- Pressure Vessel
- 20 MPa for 10-14 days

Test Sample Conditioning

- **Purpose:** **Influence of sample conditioning on mechanical behavior**
- **Goal:** **Procedures and best practices**

10th US/German Workshop on Salt Repository Research, Design and Operation
Rapid City (SD), USA – 29th May 2019

apl. Prof. Dr.-Ing. habil. U. Düsterloh – Clausthal University of Technology - Chair for Waste Disposal Technologies and Geomechanics

standard procedure – sample preparation

(1) Prior mechanical tests

-using a lathe to create cylindrical samples with coplanar end faces and a flat surface

→ no shear loading / no punctual surface loading

- avoid as far as possible breakouts by convenient depth of cut and rim speed

→ healing of small breakouts by Kalloplast (2 component glue)

- check sample quality by unencumbered ultrasonic wave velocity measuring

→ detecting of microfissures inside the samples

(2) Prior mechanical tests (UC, TC, TE, TCc, TEc)

- recompaction and tempering phase at isotropic stress level belonging to σ/T at site

→ duration 1 to 2 day

(3) Prior tests regarding permeability, healing, infiltration, breaktrough of gas

- recompaction and tempering phase at isotropic stress level belonging to σ/T at site

→ duration 1 to 2 weeks

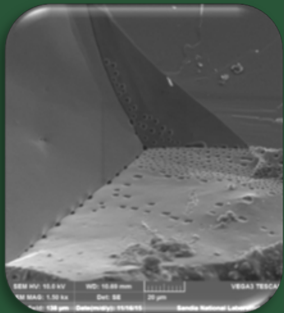
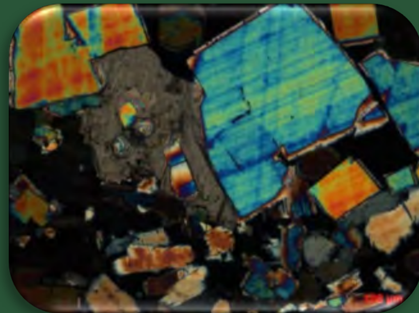
experience – influence of sample conditioning on mechanical behavior

(1) UC, TC, TE, TCc, TEc

- scatter band of results, especially in case of minor confining pressure becomes reduced in case of including a recompaction phase prior starting the tests
- reaching demanded temperature takes 1h to 2h for the confining oil (depending on heating power and demanded temperature level), but reaching demanded temperature inside the sample takes 4h to 5h

(2) tests regarding healing, permeability, infiltration, breakthrough of gas

- lastly from healing tests it is known, that recreation of microfissures takes weeks to months. That is, in case of tests reflecting on the material properties of the undamaged rock salt a significant increasing of the duration of recompaction is recommended (→ question of test costs)
- samples taken from mine in general are less damaged than samples taken from deep boreholes

Is the outcome of geomechanical laboratory tests at all representative for in situ rock properties?

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RESPEC
SOUTH DAKOTA M SCHOOL OF MINES & TECHNOLOGY
U.S. DEPARTMENT OF ENERGY
Federal Ministry for Economic Affairs and Energy

Till Popp, Dieter Brückner
Institut für Gebirgsmechanik GmbH (IfG), Leipzig

Rapid City, SD, United States
May 28-30, 2019

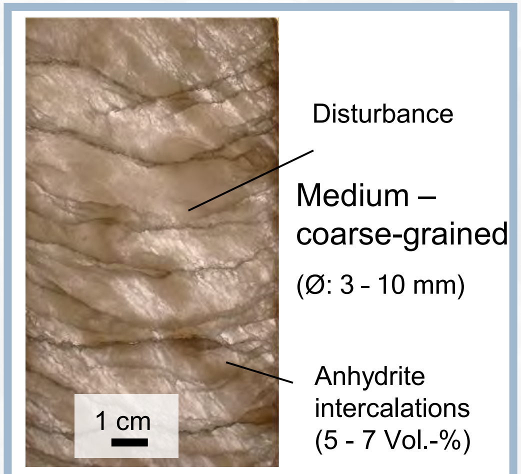
The scale of investigation

(1) From small to big ….

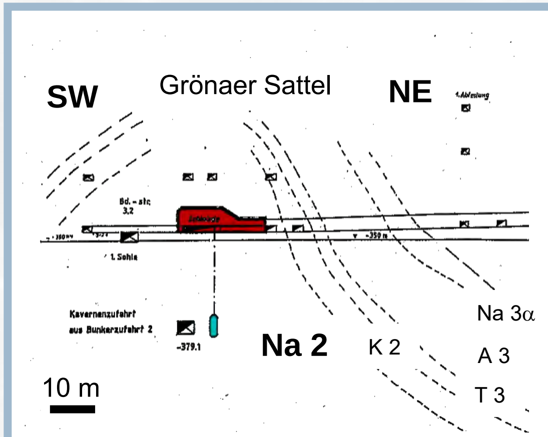
Is the lab sample size sufficient?

(2) From short term tests to long term predictions

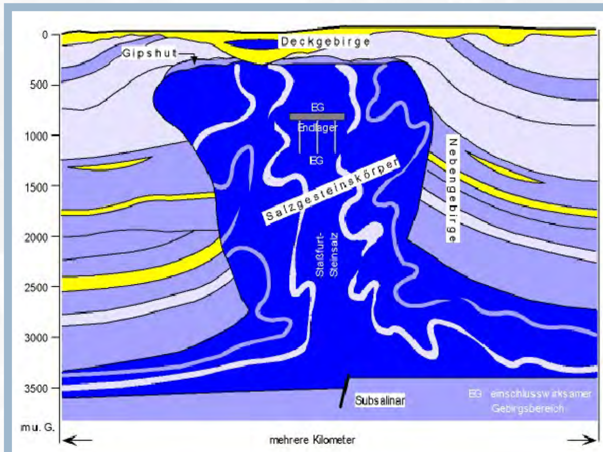
Are extrapolations allowed, i.e. is the investigation time sufficient?



Lab investigations - Single specimens (10 - 25 cm)



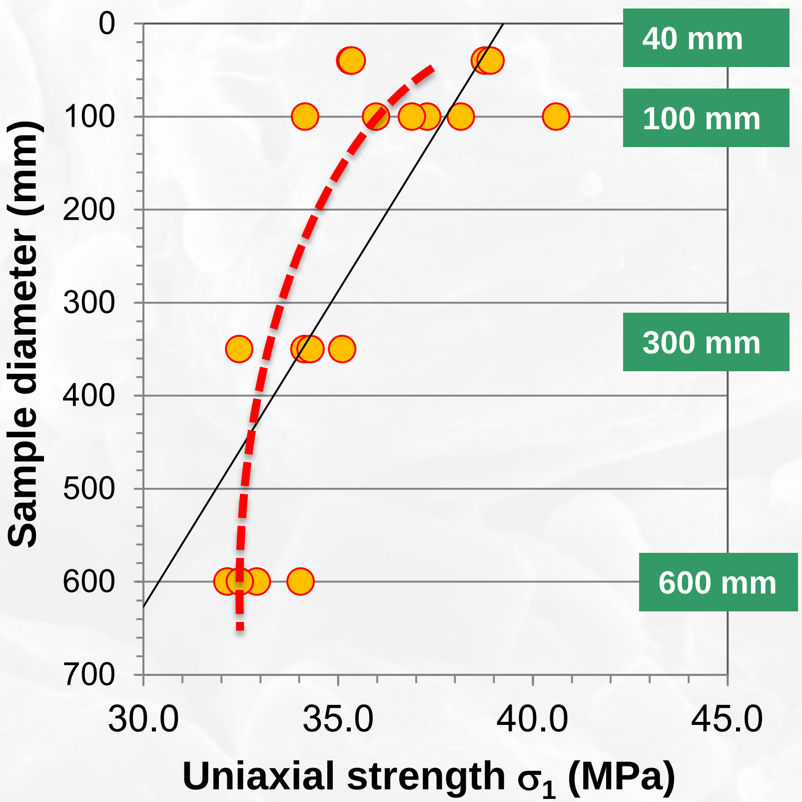
In-situ-Investigations – Field scales (10 - 25 m)



Modelling – Forecast

(10 cm - 10 m - 100 m)

Uniaxial strength testing

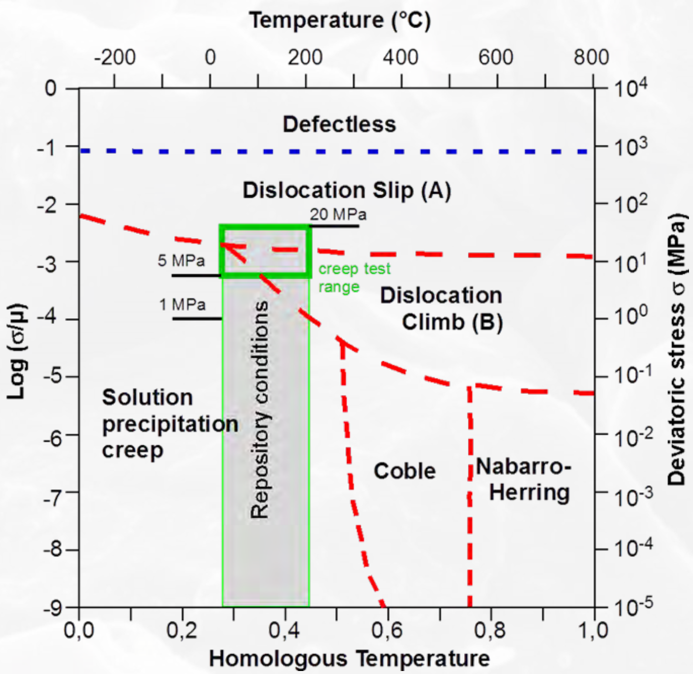


- A small size effect is still visible, due to coarse grained rock portions

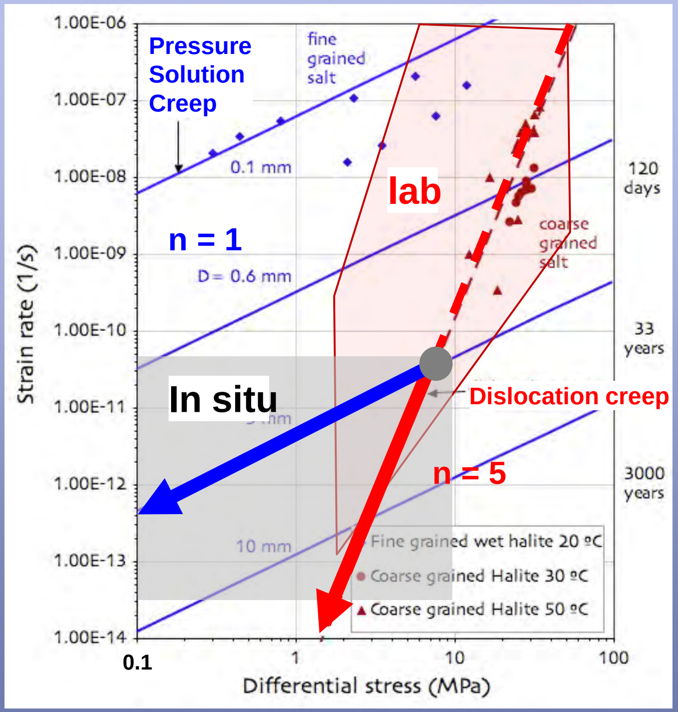
Time scale and load conditions

From short term creep tests to long term predictions

- Is the bandwith and length of lab tests sufficient for extrapolations?
- What happens in the low-stress region?



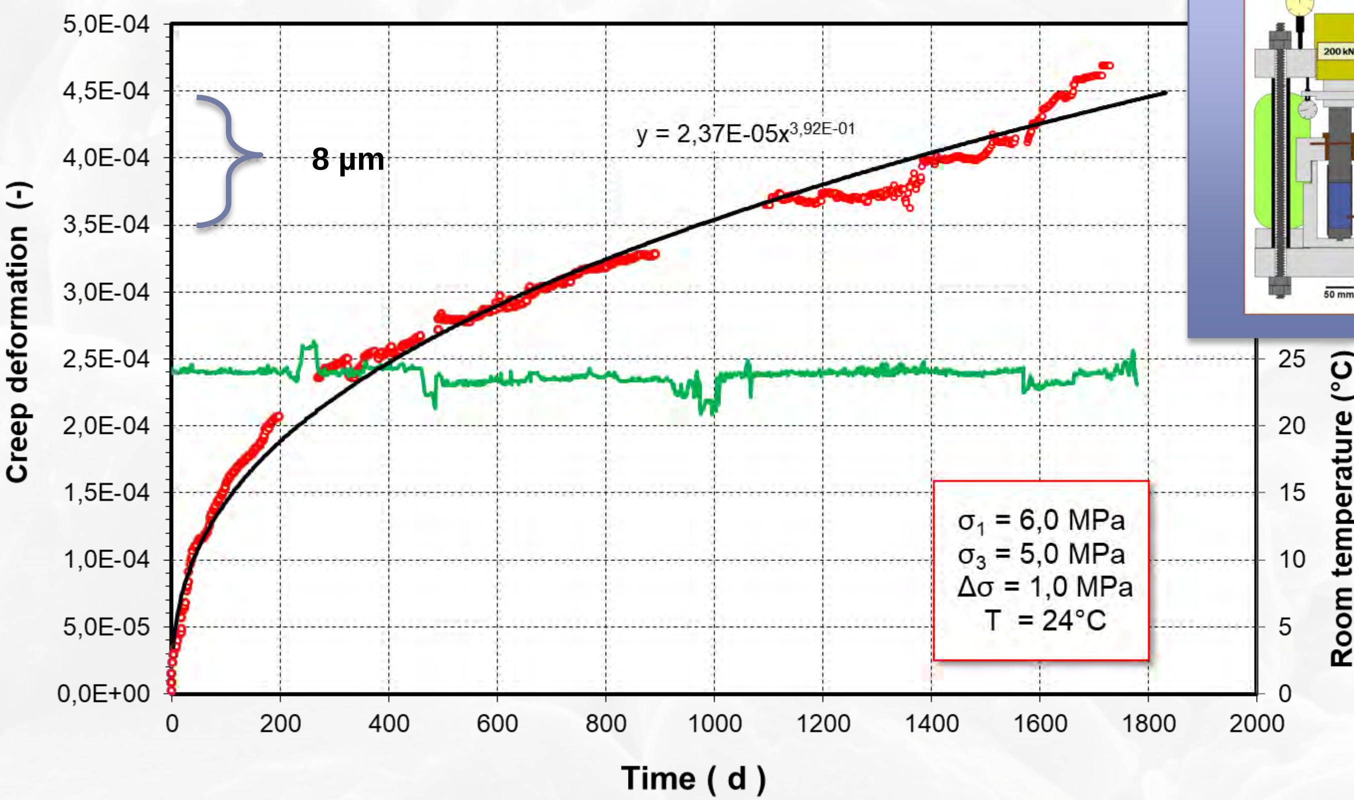
Deformation mechanism map for rock salt

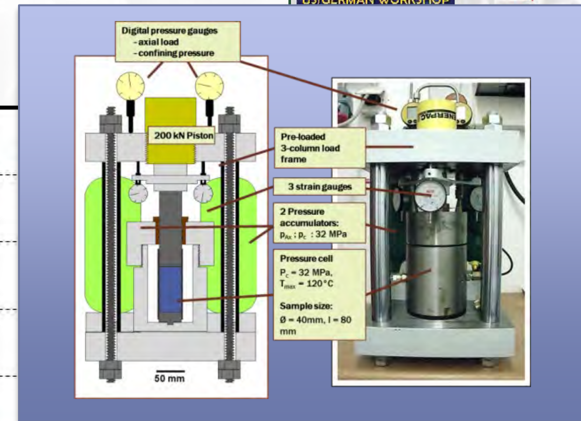


modified after Urai, 2012

Uncertainity of standard creep tests

Long-lasting IfG - creep test





Projekt: xxx - Probe: 411/3/45/17K/TCC rock salt

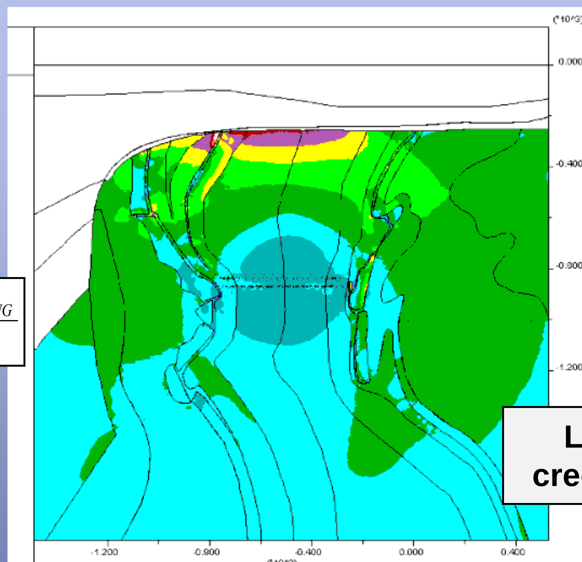
- Room temperature effects are obvious
- Due to the low deformation the measuring resolution is limited
- At $\Delta\sigma$ = 1 MPa (after around 1800 days) the sample is still in the hardening phase

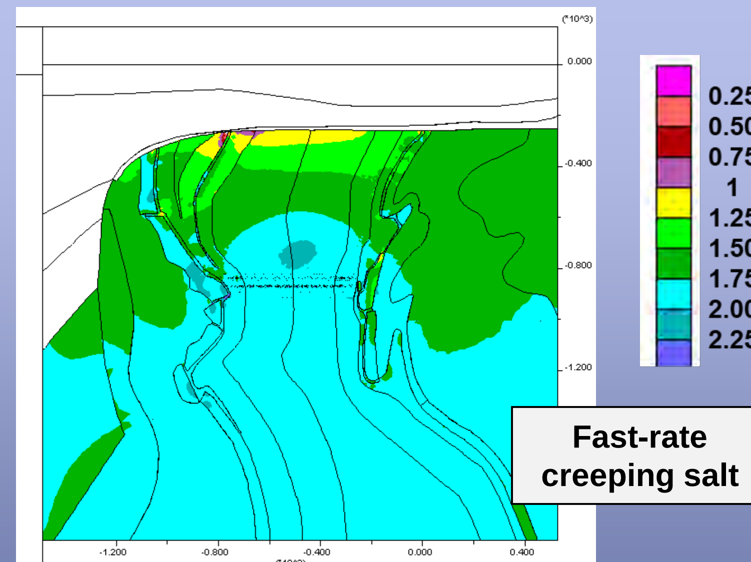
➢ **Technical improvement is required** (➔ WEIMOS)

➢ **How long we have to wait?**

Consequences of „under-estimated creep

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

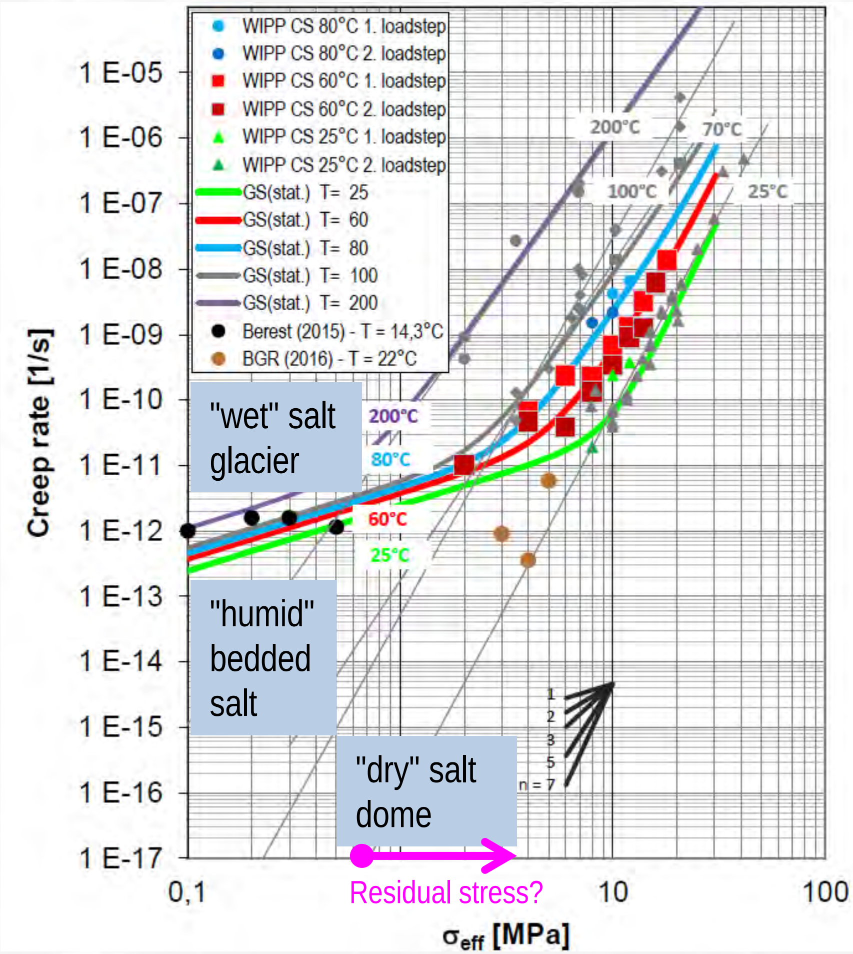




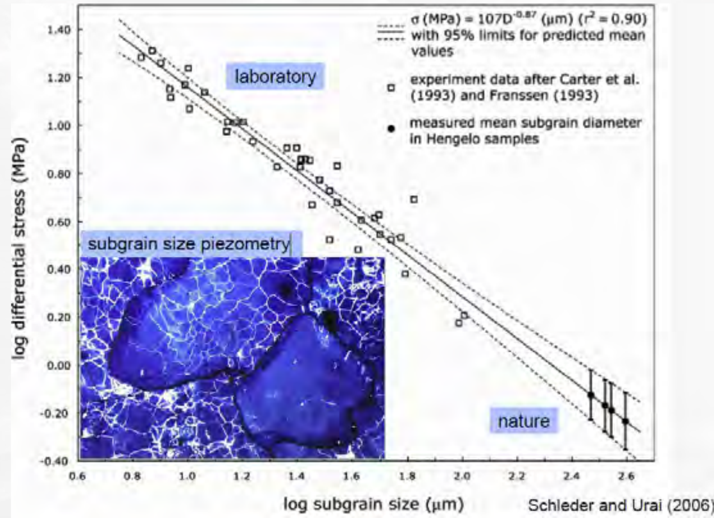
Violation of minimum stress criterion due to the heat impact of the HAW-repository (100 years after emplacement) (source: VSG)

- Uncertainity of knowledge
  - execution of well-defined and –prepared creep tests ➔ Weimos-project)
  - Identification of the acting deformation processes: Microstructural investigations
- Underestimation of creep rate behaviour at low deviatoric stresses is from the safety point conservative

Creep mechanism uncertainity

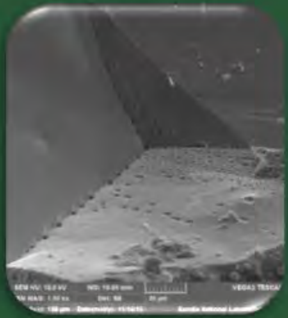


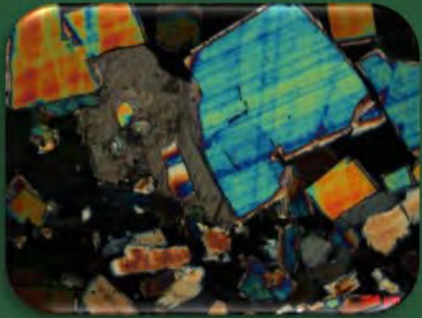
What are the consequences, if the creep rates are over-estimated?



Subgrain – paleostress analysis

- In different salt structures deformation mechanisms and rheology may be different.
- Microstructure analysis is required to study deformation mechanisms, paleostress and paleorheology.
- Numerical modelling allows a proof





10th US/German Workshop on Salt Repository Research, Design, and Operation

Test Sample Conditioning

A. Hampel, Hampel Consulting

Rapid City, SD, USA
May 28-30, 2019

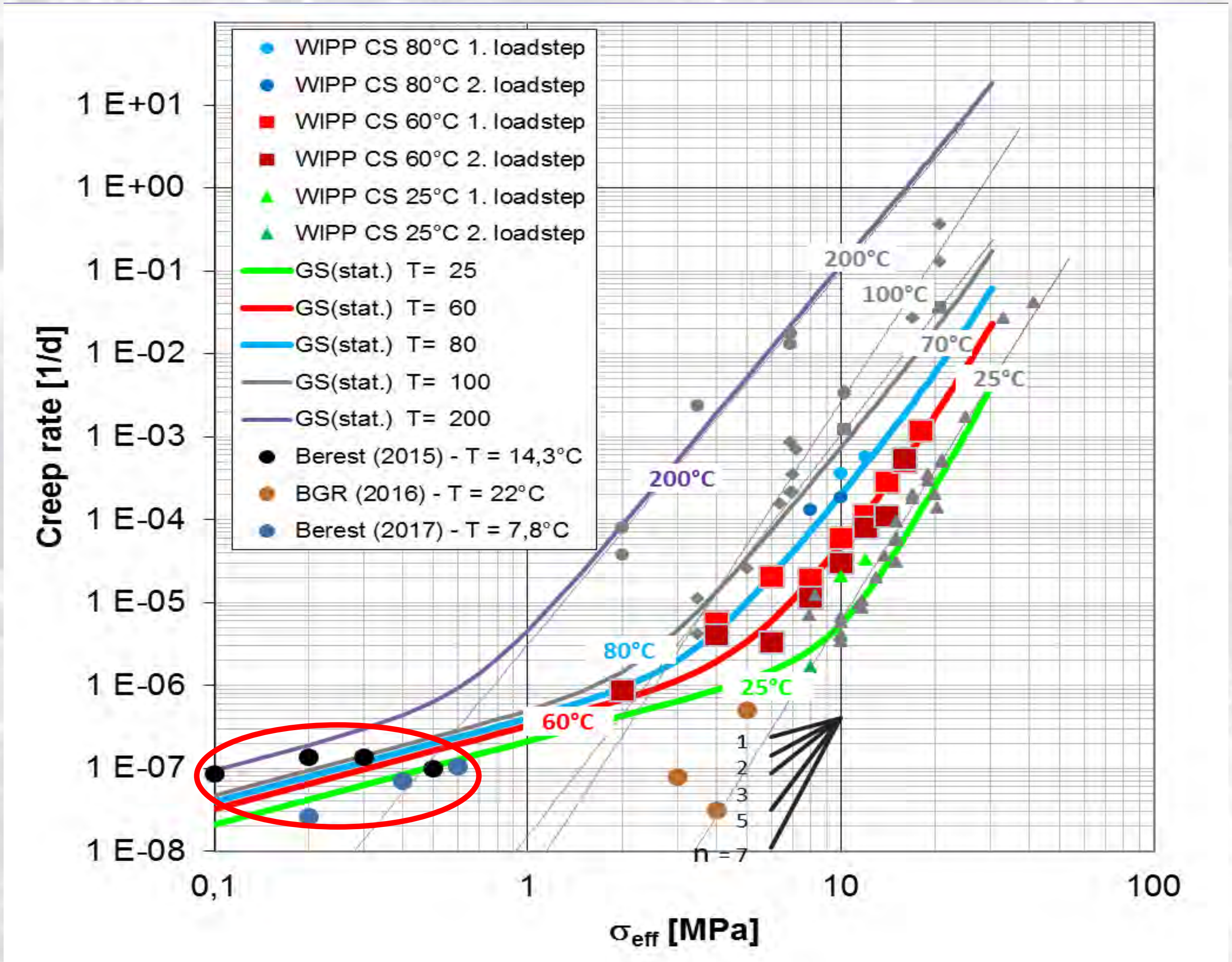
Deformation behavior at small deviatoric stresses

Bérest's uniaxial tests with Avery Island salt and Hauterives salt

Dead weight setup

Sample size:

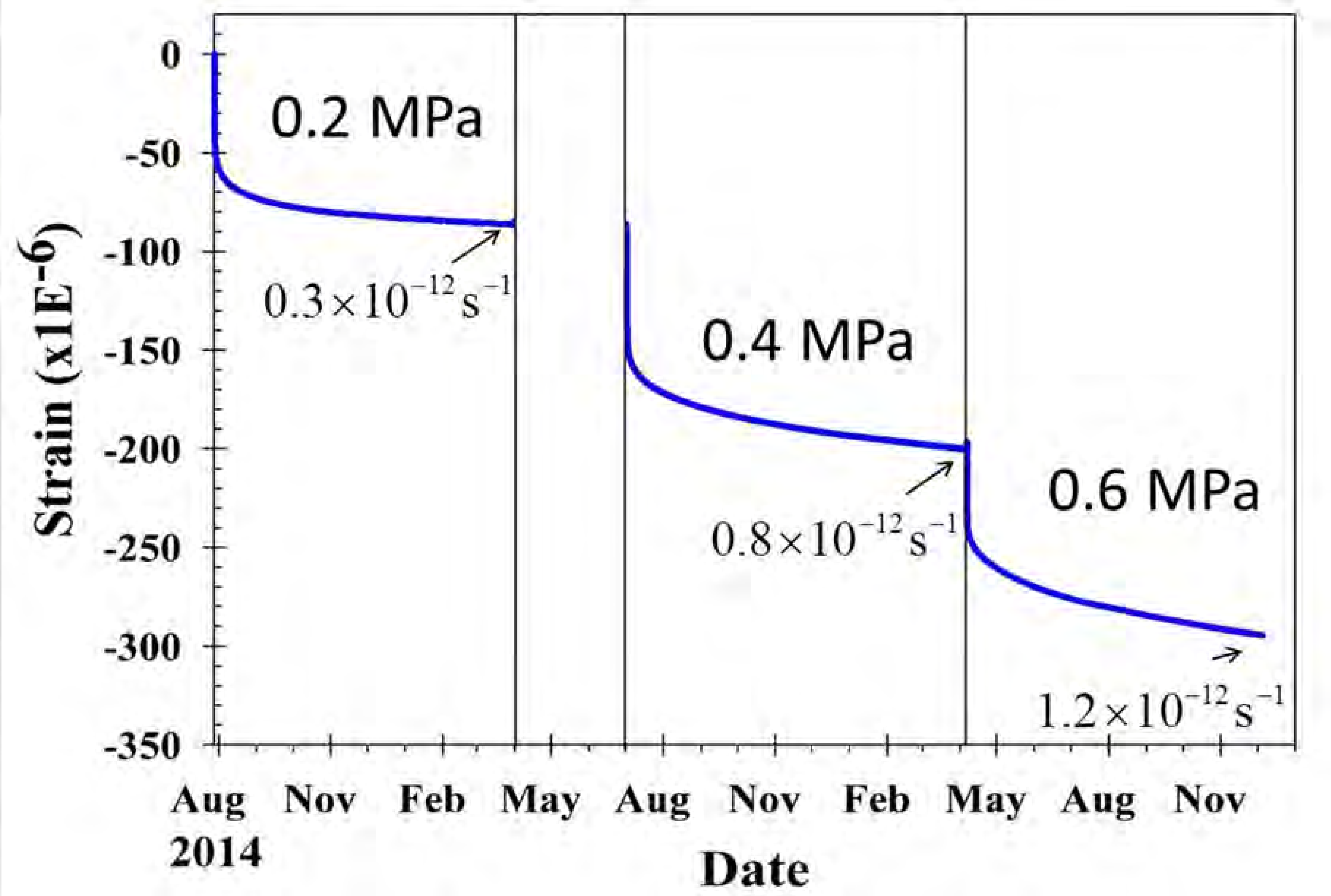
Ø=70 mm L = 140 m



Varangeville - Bérest et al. (2015): Avery Island salt, Ø=70 mm L = 140 m, < 1.5 a
Altaussee – Bérest et al. (2017): Hauterives ≈ 2 a

Deformation behavior at small deviatoric stresses

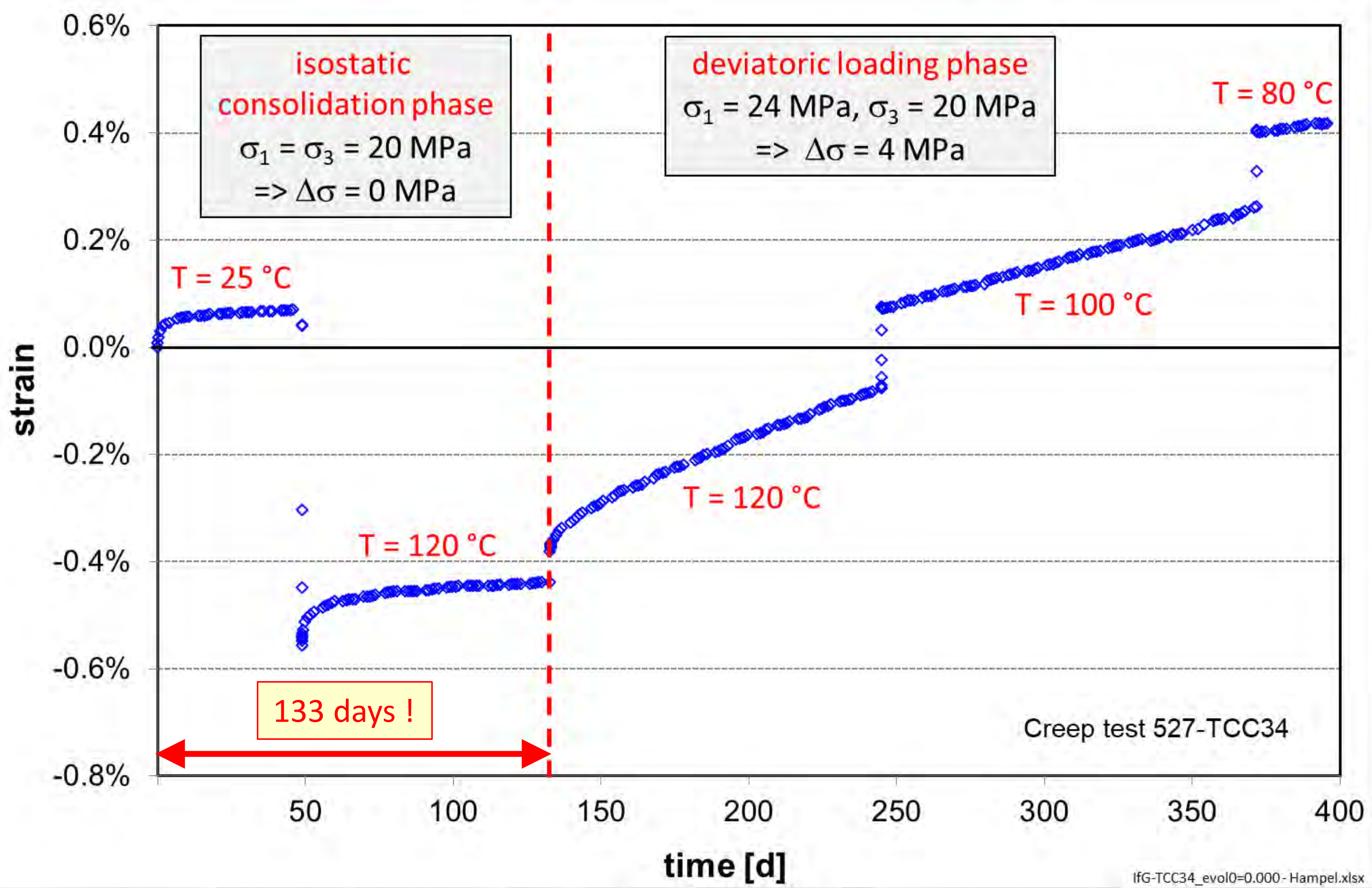
Bérest's uniaxial test with Hauterives salt in the Altaussee mine, Austria



Hauterives sample. Strain as a function of time and strain rate at the end of each stage. The load was increased from 0.2 to 0.4 MPa at the beginning of stage 2 and from 0.4 MPa to 0.6 MPa at the beginning of stage 3 [Bérest et al., 2017].

WP 1: Deformation behavior at small deviatoric stresses

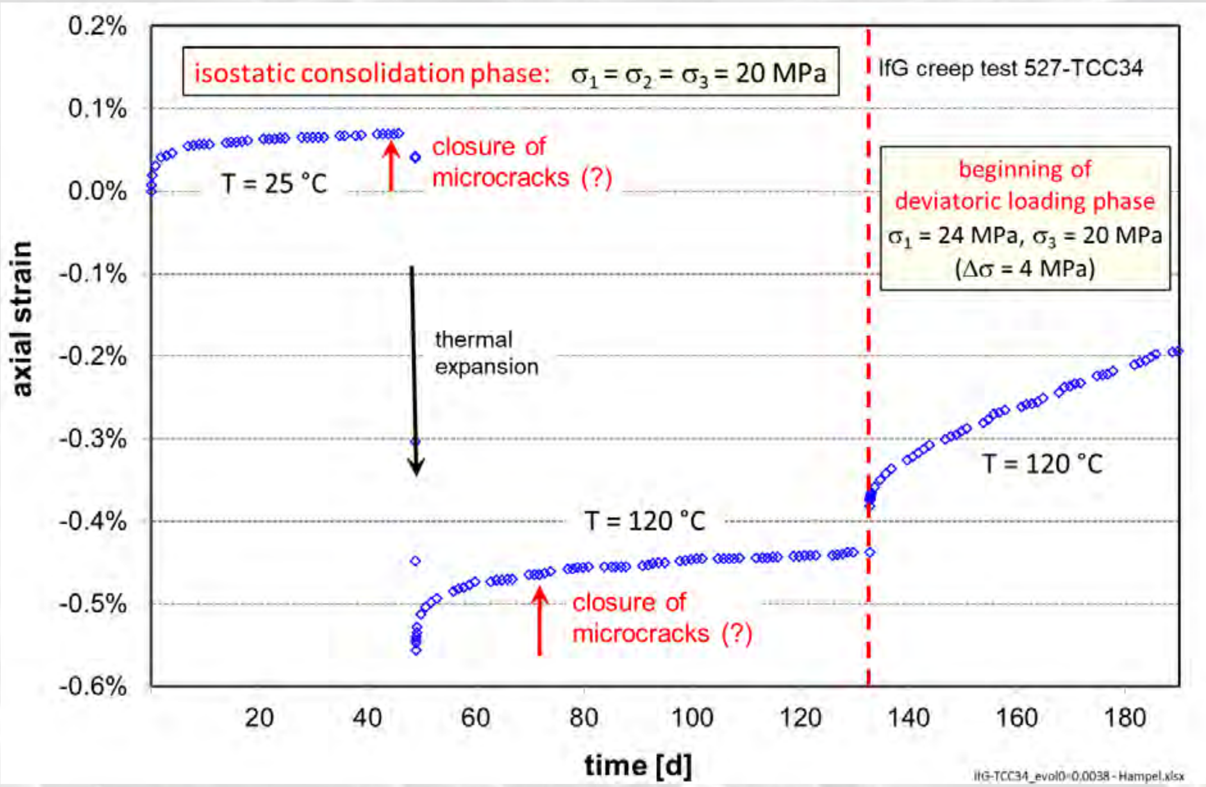
IfG pre-test TCC34 with clean salt from WIPP



Basis for further development of the modeling: extended lab test program

WP 1: IfG: **Triaxial creep test series** with WIPP salt in 3 new test rigs

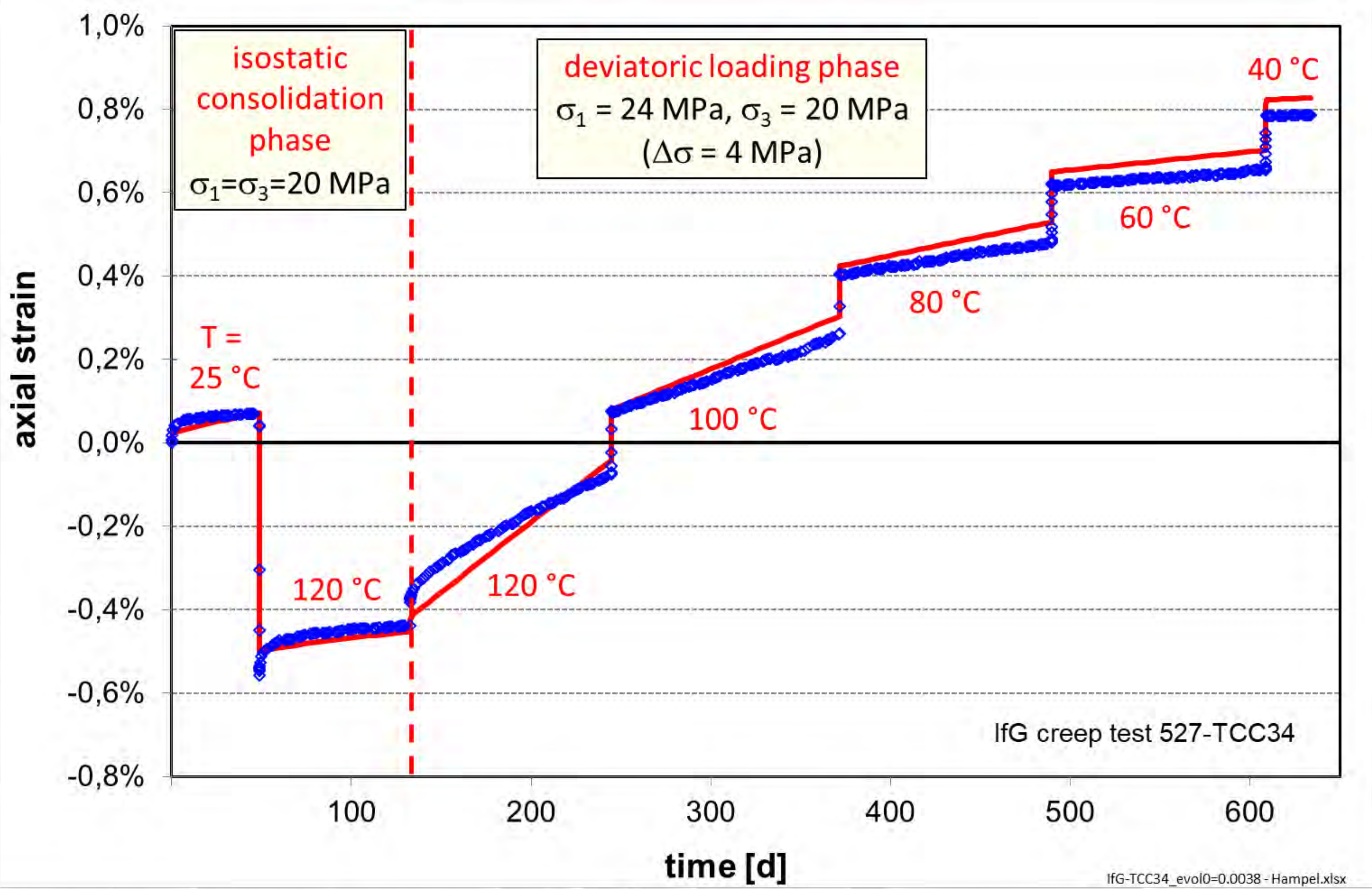
- Long (~ 100 days) initial consolidation phase at T = 120 °C, $\sigma_{1,2,3}$ = 20 MPa ($\Delta\sigma$ = 0)
- Series 1: $\Delta\sigma$ = 2 / 4 / 6 MPa, Series 2: $\Delta\sigma$ = 1 / 3 / 5 MPa, both at T = 80 - 60 - 30 °C (each stage: 100 d)
- Accompanying microscopic investigations (Melissa Mills, Sandia)

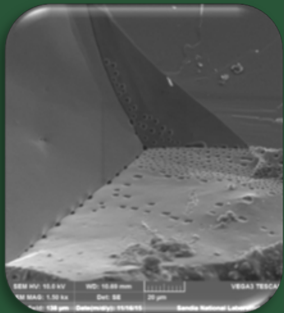


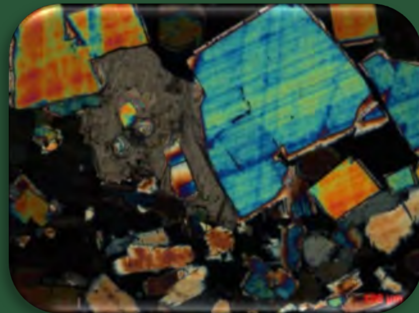
WP 1: Deformation behavior at small deviatoric stresses

Recalculation of IfG pre-test TCC34 with clean salt from WIPP:

Initial consolidation phase calculated with CDM healing module and assumed $\varepsilon_{vol,0}$ = 0.38 %







10th US/German Workshop on Salt Research Activities in Bedded Rock Salt in Germany

Sandia National Laboratories

BGE TEC
BGE TECHNOLOGY GmbH

PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

RESPEC

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

Federal Ministry for Economic Affairs and Energy

J. Hesser, A. Haase, W. Gräsle, M. Pusch,
J. Lippmann-Pipke

Federal Institute for Geosciences
and Natural Resources

Rapid City, SD, United States

May 28-30, 2019

Background

- Historically the exploration of repository sites in Germany was restricted to *salt domes*

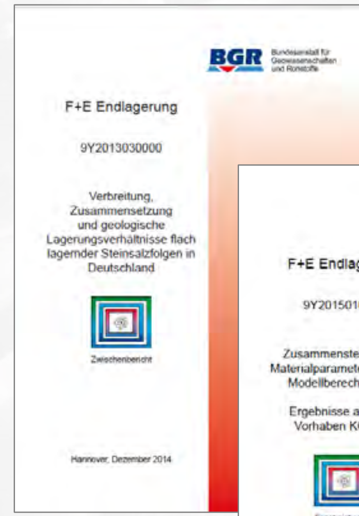
- Since 2017 the new German site-selection law has taken effect (Standortauswahlgesetz):
  Search, exploration and decision of a repository site is *independent* of host rock → (clay, salt and crystalline formations)

- Federal Ministry for Economic Affairs and Energy enacted:
  Geoscientific investigations also of *bedded deposits* in Germany have to be conducted regarding their suitability as final repositories for HLW

Accompanying Tasks

BASAL → Geological Investigation

Reinhold, K. Hammer, J. & Pusch, M. (2014): Verbreitung, Zusammensetzung und geologische Lagerungsverhältnisse flach lagernder Steinsalzfolgen in Deutschland


BGR
F+E Endlagerung
9Y2013030000
Verbreitung, Zusammensetzung und geologische Lagerungsverhältnisse flach lagernder Steinsalzfolgen in Deutschland
Zwischenbericht
Hannover, Dezember 2014

KOSINA → Numerical Analysis

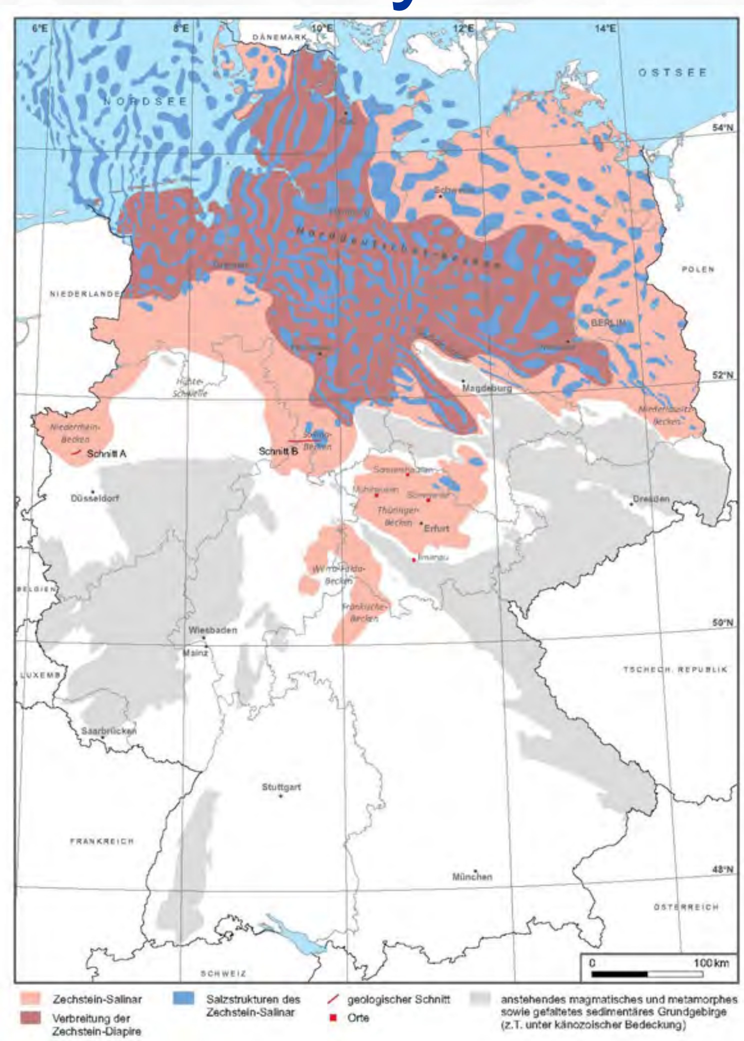
Liu, W.; Völkner, E.; Minkley, W. & Popp, T. (2017): Zusammenstellung der Materialparameter für THM-Modellberechnungen

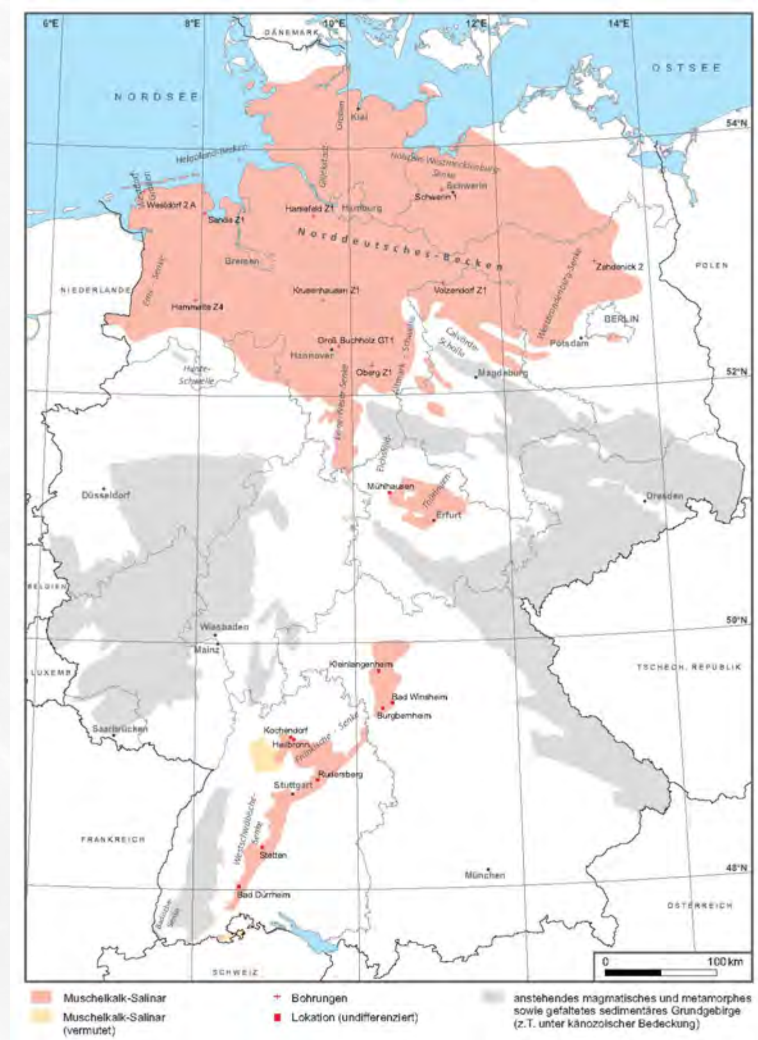

BGR
F+E Endlagerung
9Y2015010000
Zusammenstellung der Materialparameter für THM-Modellberechnungen
Ergebnisse aus dem Vorhaben KOSINA
Ergebnisbericht
Hannover, Dezember 2017

Only few parameters originate from bedded deposits.
Most parameters have been deduced from salt domes.

→ Further measurements in situ and in laboratory are necessary

Bedded salt deposits in Germany





Reinhold, K. Hammer, J. & Pusch, M. (2014): Verbreitung, Zusammensetzung und geologische Lagerungsverhältnisse flach lagernder Steinsalzfolgen in Deutschland; BGR-Report, Hannover

Aims of investigation

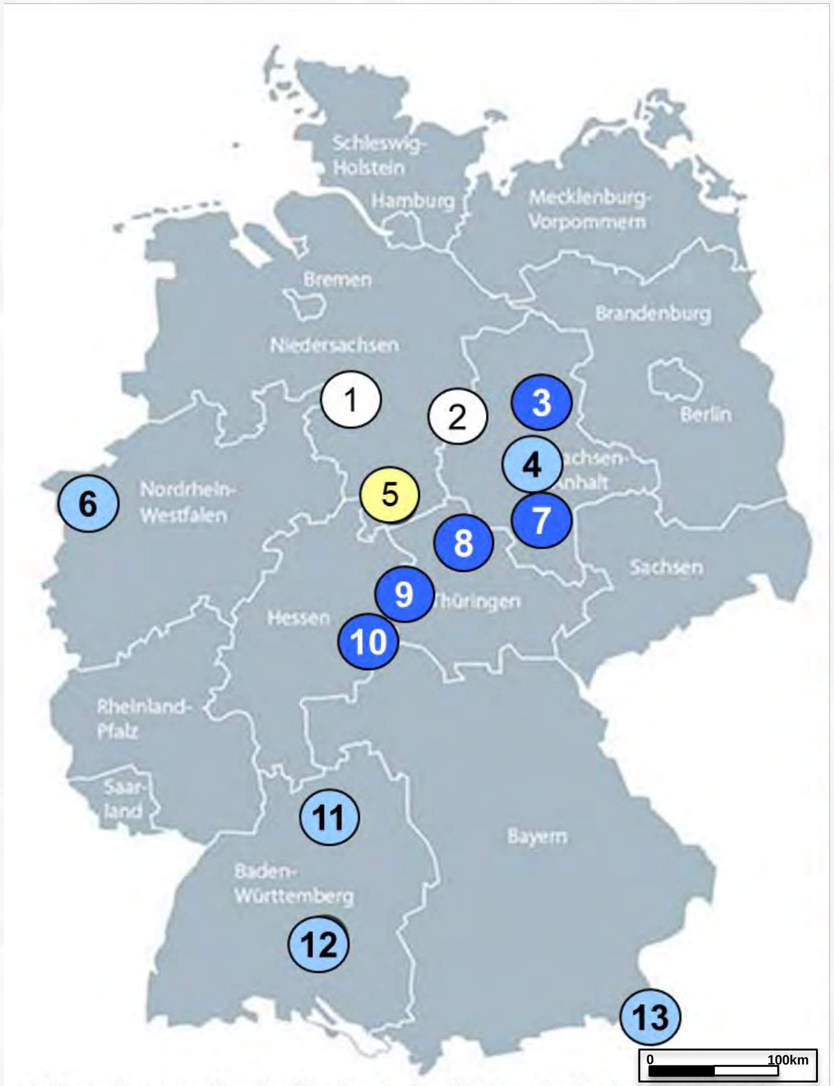
Characterization of bedded salt deposits in Germany

- Determination of mechanical and hydraulic parameters with their bandwidth
- Identification and quantification of possible influences caused by composition, geological age, formation
  → Creation of database for bedded deposits in Germany
- Comparison with results of salt dome studies

In more detail…

- Evaluation of existing measurement data
- Core sampling
- Mechanical In-situ experiments (deformation modulus, rock stresses)
- Hydraulic In-situ experiments (permeability)
- Microstructural investigations
- Rock mechanical lab tests (strength, creeping)

Bedded salt deposits in Germany



https://www.vks-kalisalz.de/kali/standorte-in-deutschland/

Rock Salt Mines

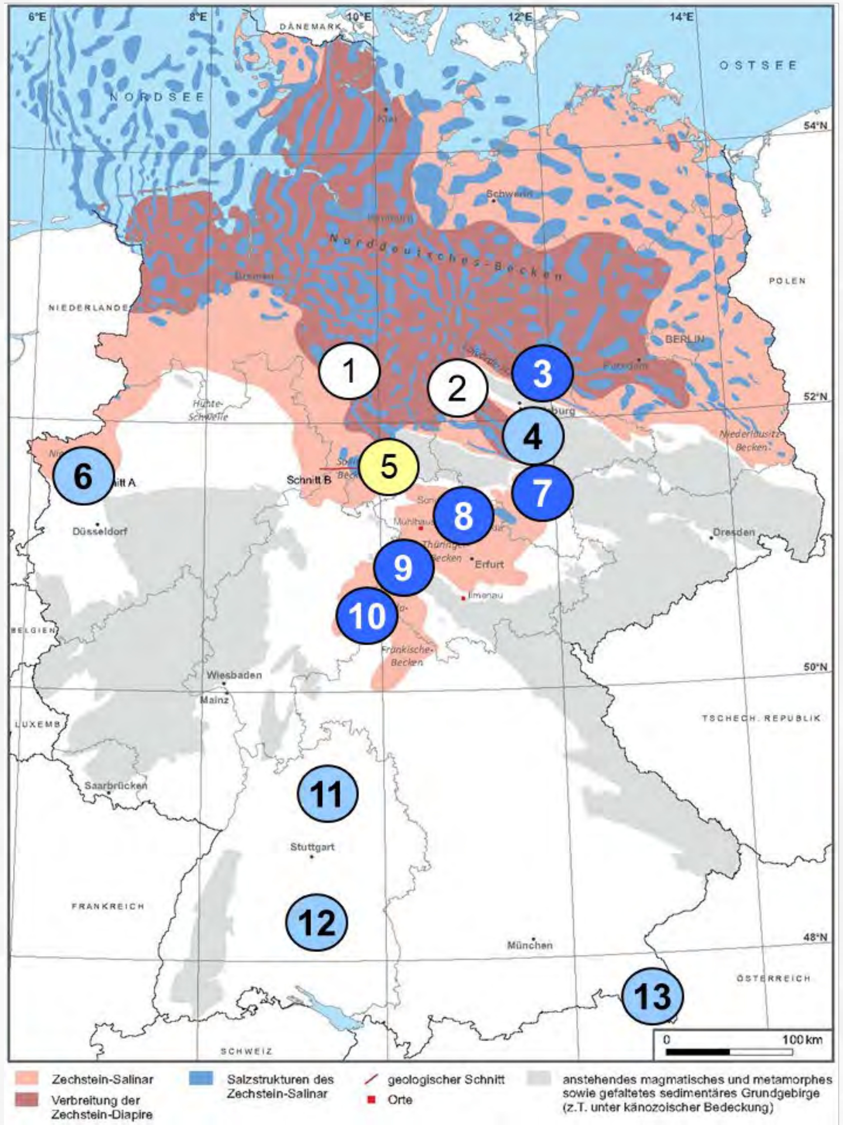
- 4 **Bernburg**
- 6 **Borth**
- 11 **Heilbronn / Bad Friedrichshall**
- 12 **Stetten**
- 13 **Bad Reichenhall / Berchtesgaden**
- 5 Luisenhall (saline)

Potash mines

- 3 **Zielitz**
- 7 **Teutschenthal (UTV)**
- 8 **Sondershausen (UTD, UTV)**
- 9 **Werra** (Hattorf, Unterbreizbach, Wintershall)
- 10 **Neuhof-Ellers**

- 1 Sigmundshall (diapir, inactive)
- 2 Braunschweig-Lüneburg (diapir)

Bedded salt deposits in Germany



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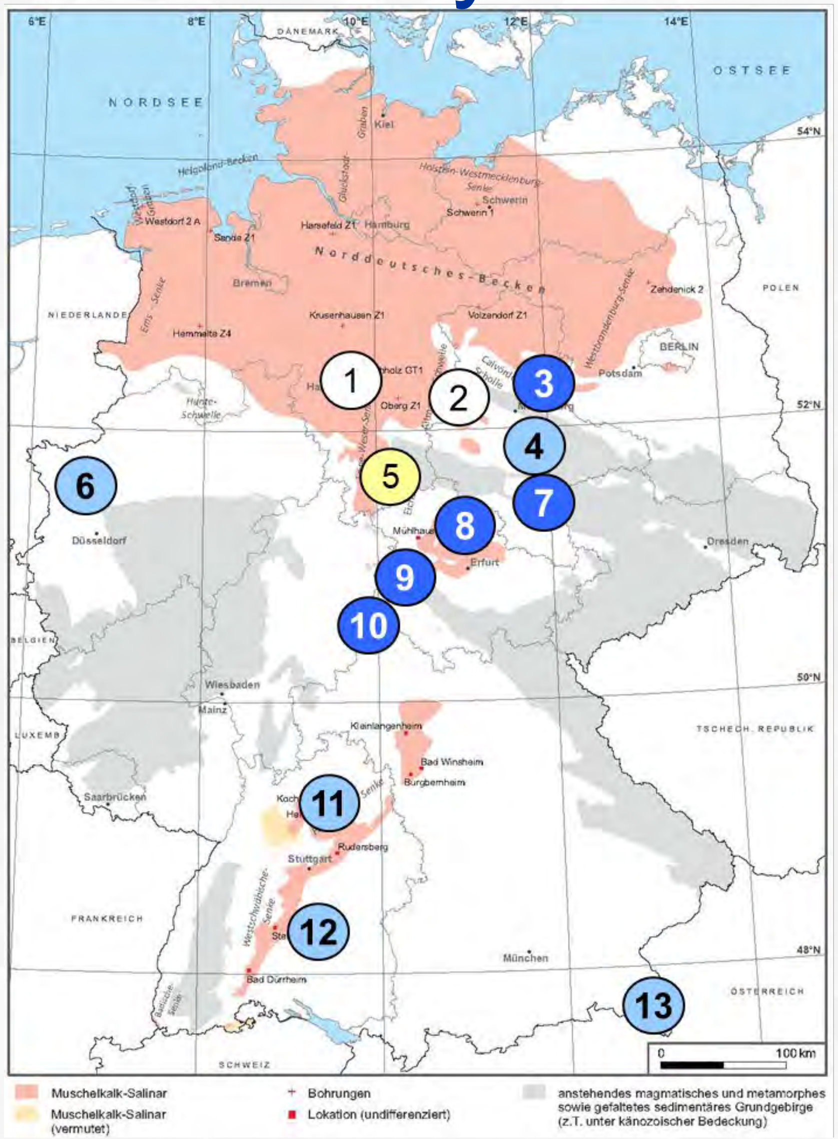
Bedded salt deposits in Germany



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Challenges

- Purpose of mines is the excavation of natural resources.
- Monitoring is conducted only at a few locations (safety).
  → very little monitoring data available (e. g. convergence)
- Excavation works should not be disturbed by the in-situ experiments
- Demands concerning company secrets have to be respected
- The results have to be representative for the salt deposits

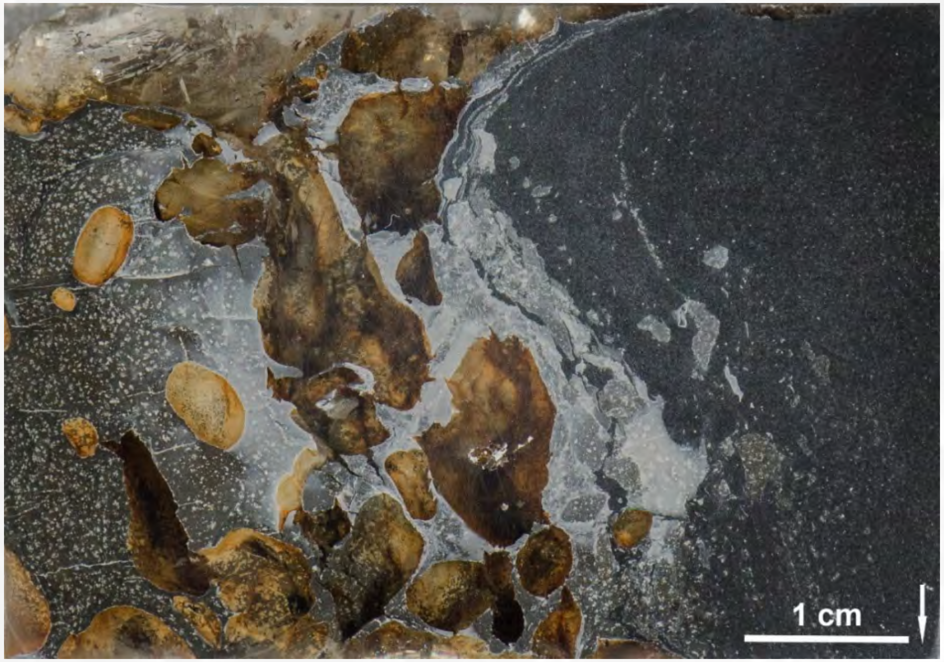
➔ Cooperation's with salt mine companies

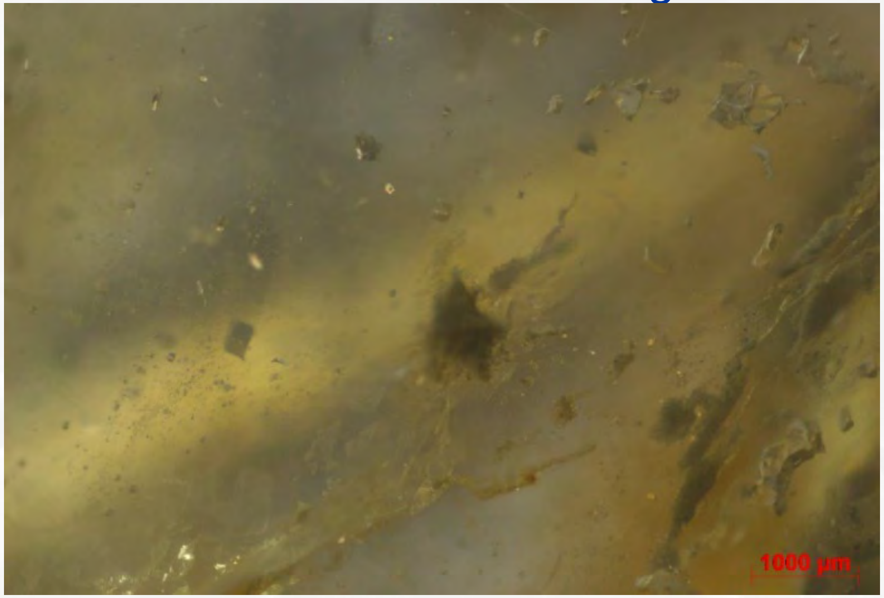
Series of In-situ experiments have been conducted *at two locations* (bedded rock salt deposits in Germany).

Mineralogical Analysis Thin Sections

Polished surface of a sample
Lenticular illusive brownish halite crystals within anhydrite. The shades of grey in the anhydrite matrix differ according to their secondary mineral composition:

Light grey: quartz, muscovite
Medium grey: dolomite
Dark grey: anhydrite, clay, pyrite, organic matter



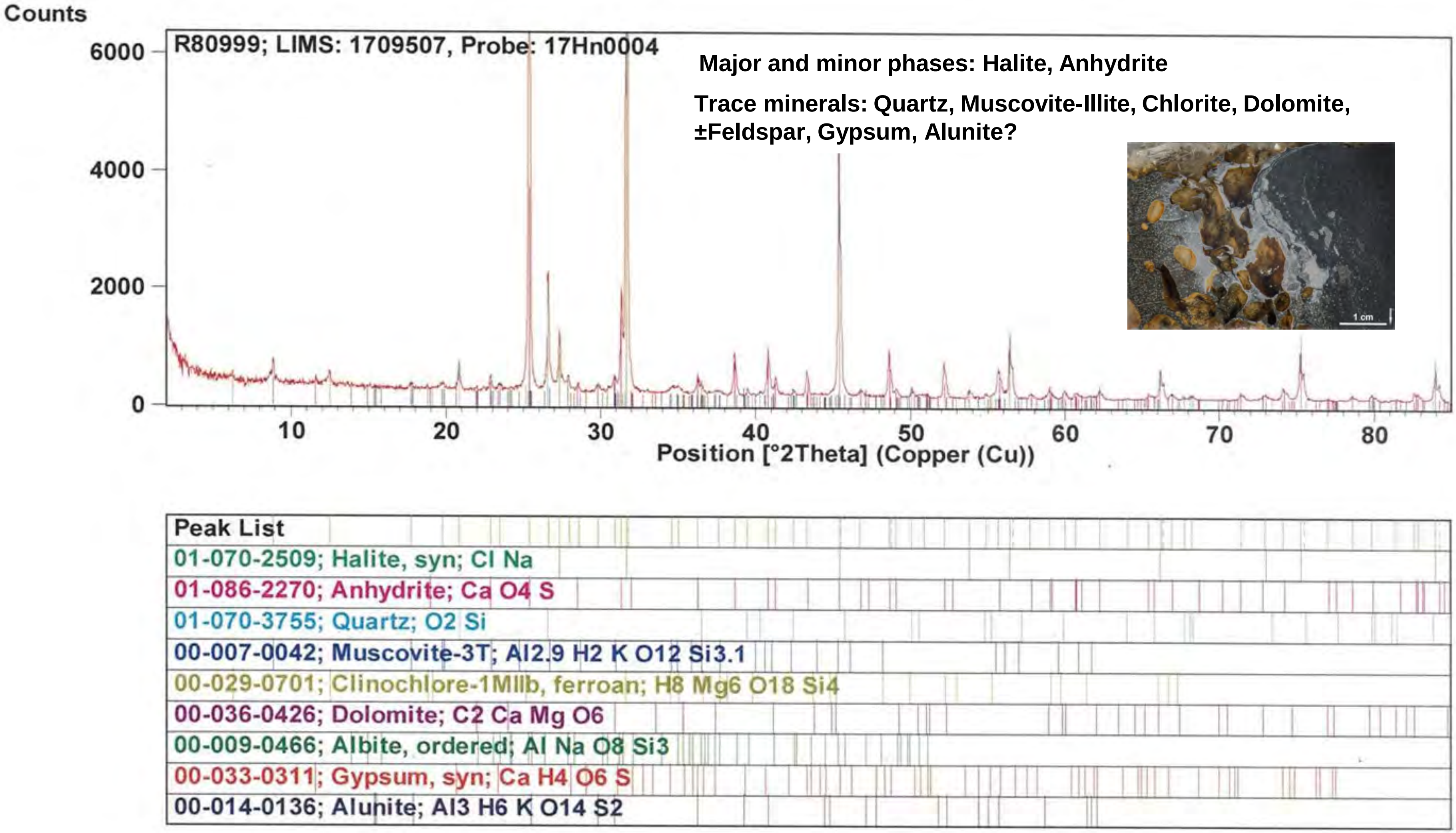


Cubic fluid inclusions within the lenticular halite crystals. The halite is colored illusive brown due to ferric phases at the boundary between anhydrite and halite.

Mineralogical Analysis - XRD

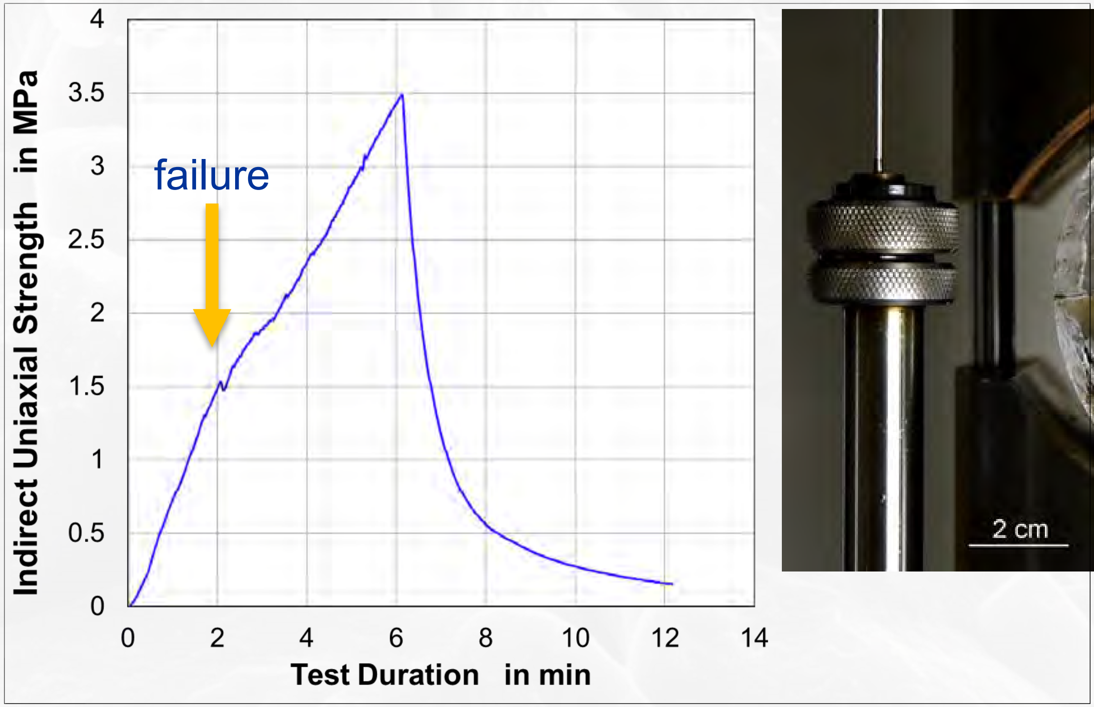
Major and minor phases: Halite, Anhydrite

Trace minerals: Quartz, Muscovite-Illite, Chlorite, Dolomite, ±Feldspar, Gypsum, Alunite?



Tensile Strength

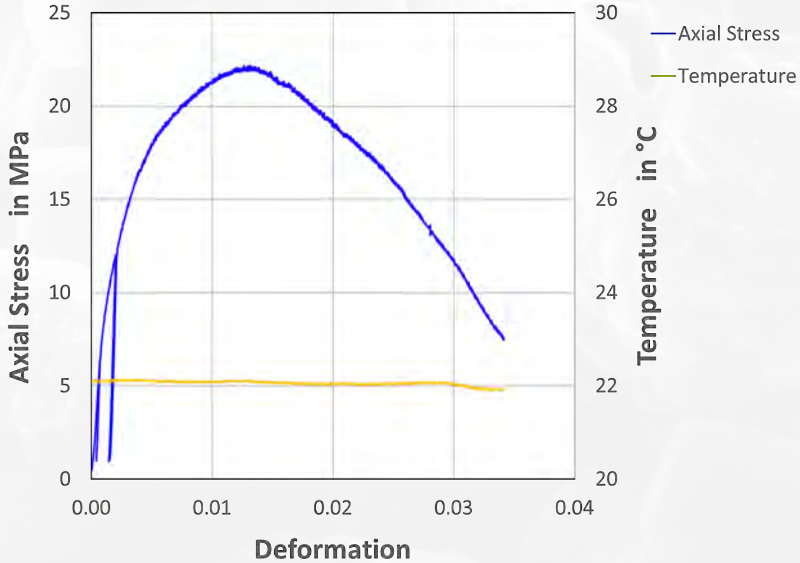
Brazilian Tests



- Camera assisted monitoring correlated neg. peak with crack forming
- Tensile splitting strength is not very different to indirect tensile strength of other locations

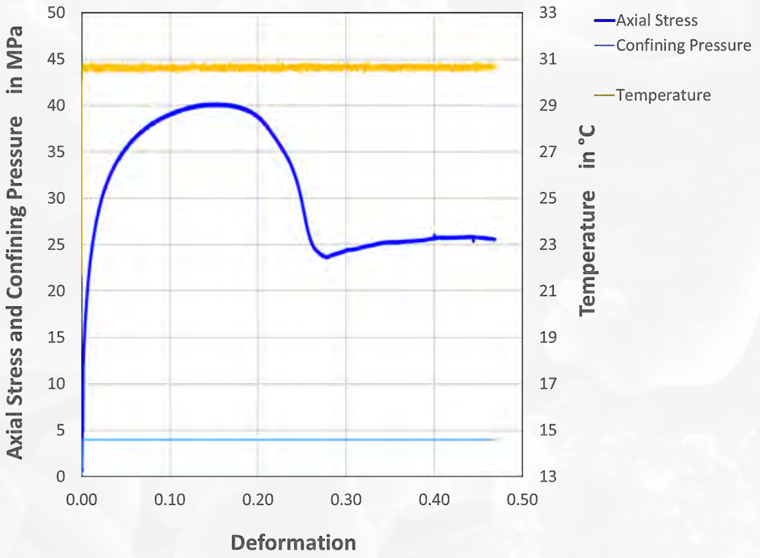
Compressive Strength

Uniaxial Compression Tests



- Room temperature
- Deformation controlled load with a rate of $2 \cdot 10^{-6}$
- Relaxation and Reloading for determination of Young's modulus

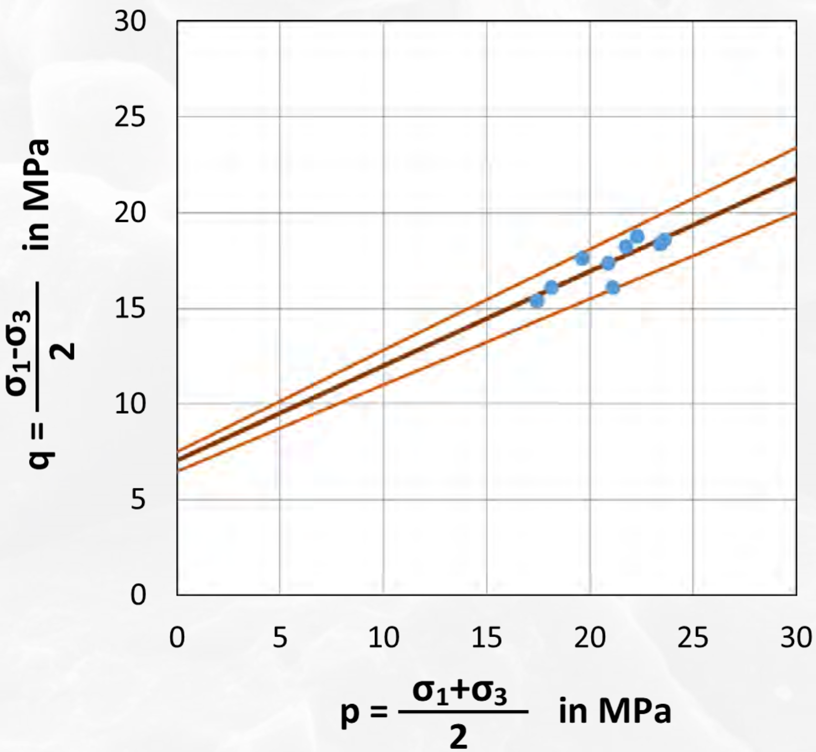
Triaxial Compression Tests

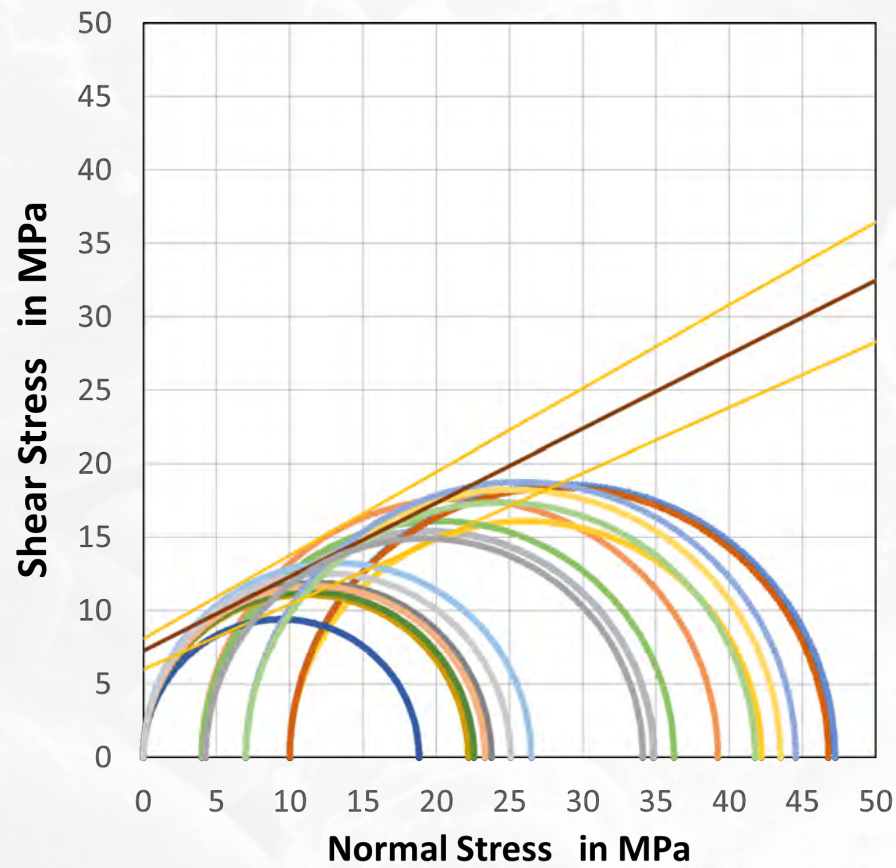


- Test temperature 30° C
- Deformation controlled load with a rate of $2 \cdot 10^{-6}$
- Relaxation and Reloading for determination of Young's modulus
- Variation of σ_3 depends on depth of the in situ location

Shear Parameters

Results of Triaxial Compression Tests

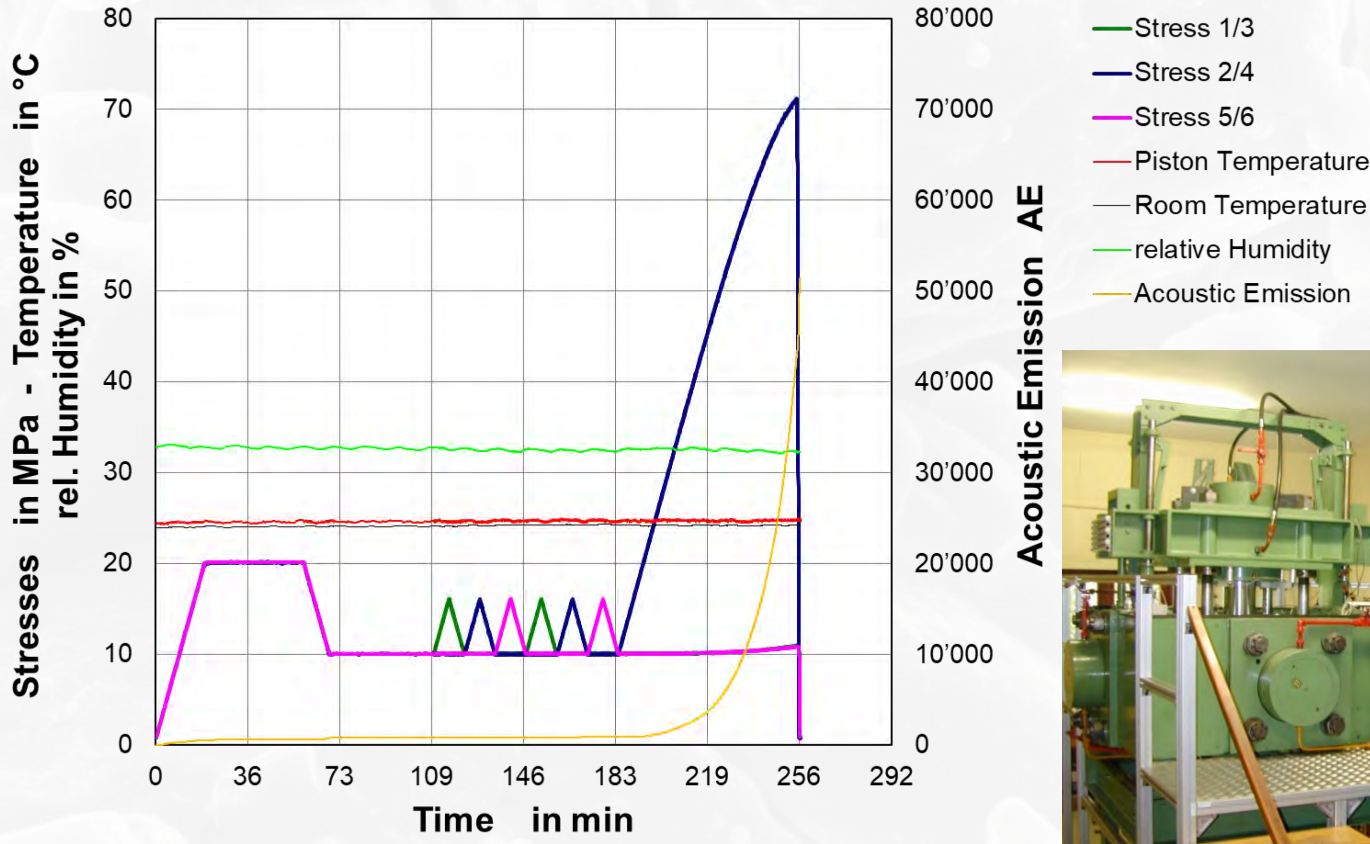




- Cohesion: 6 MPa - 8 MPa
- Angle of Inner Friction: 24 - 30 degrees

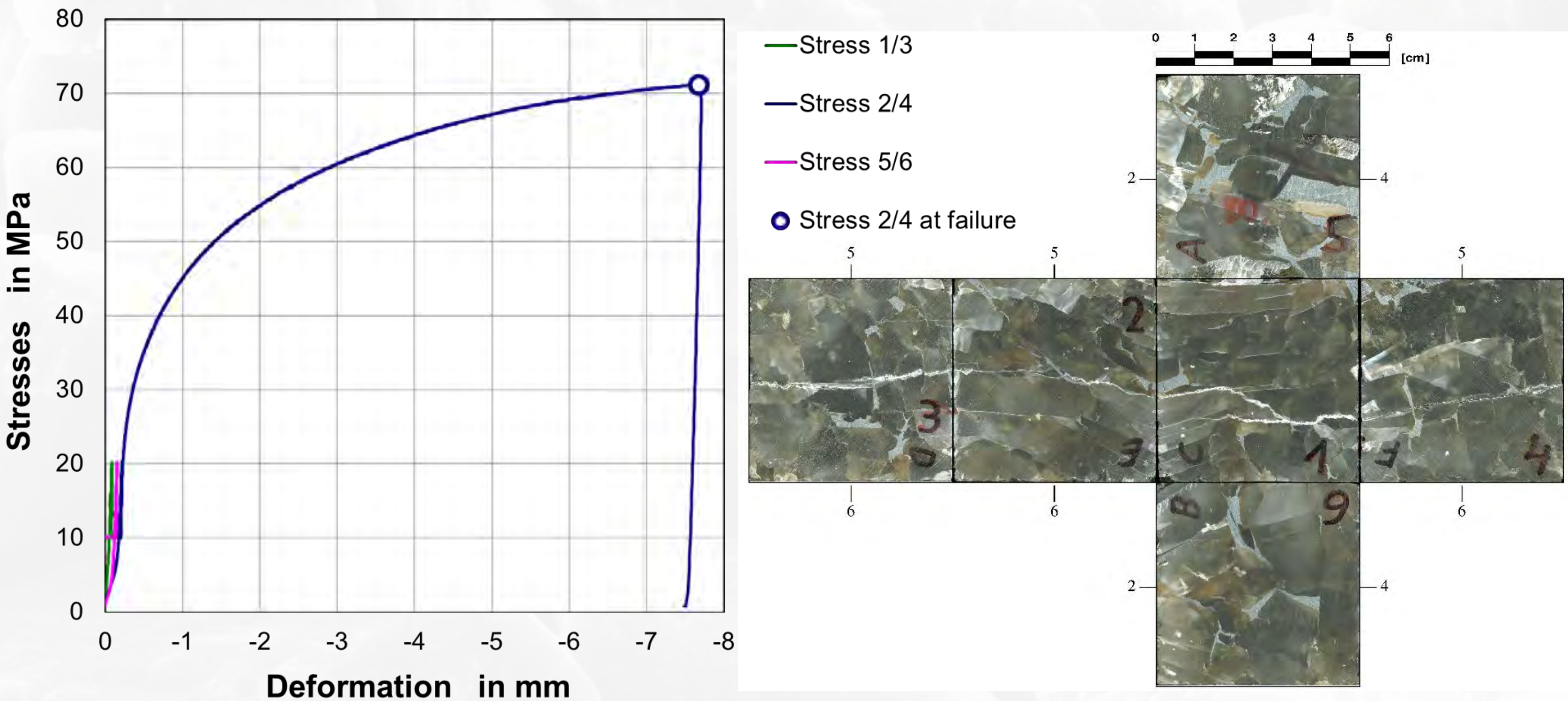
Compressive Strength

Real Three Axial Compression Tests



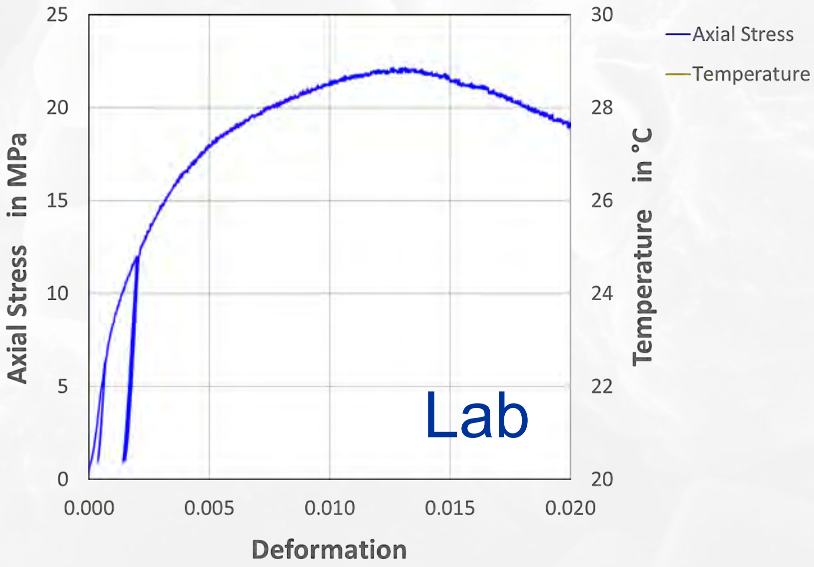
Compressive Strength

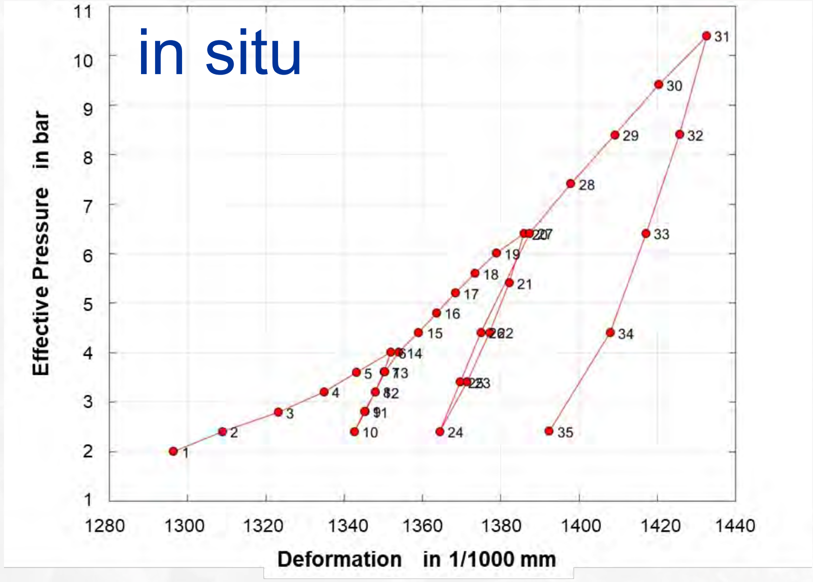
Real Three Axial Compression Tests



Deformation does not depend on load direction --> no anisotropy

Elastic Deformation Young's Modulus





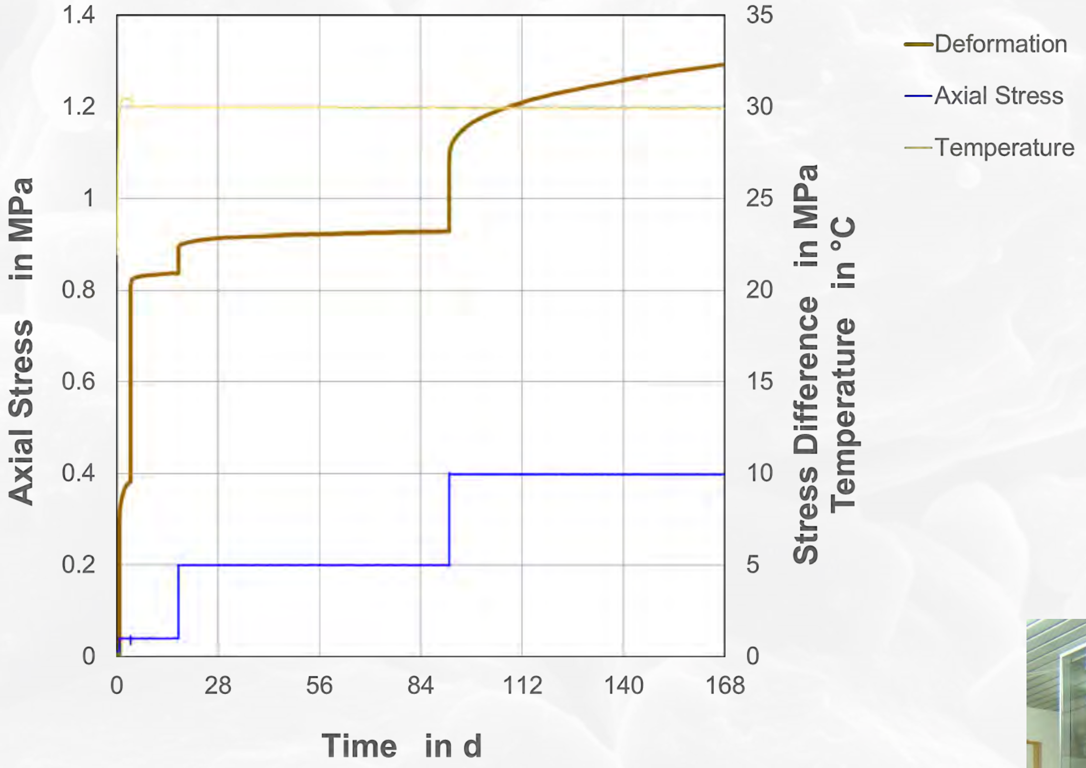
Young's Modulus determined in lab and in situ tests have the same dimension.

In situ reveal a much bigger bandwidth of deformation values as measured with dilatometer.

Anisotropy is not identified.

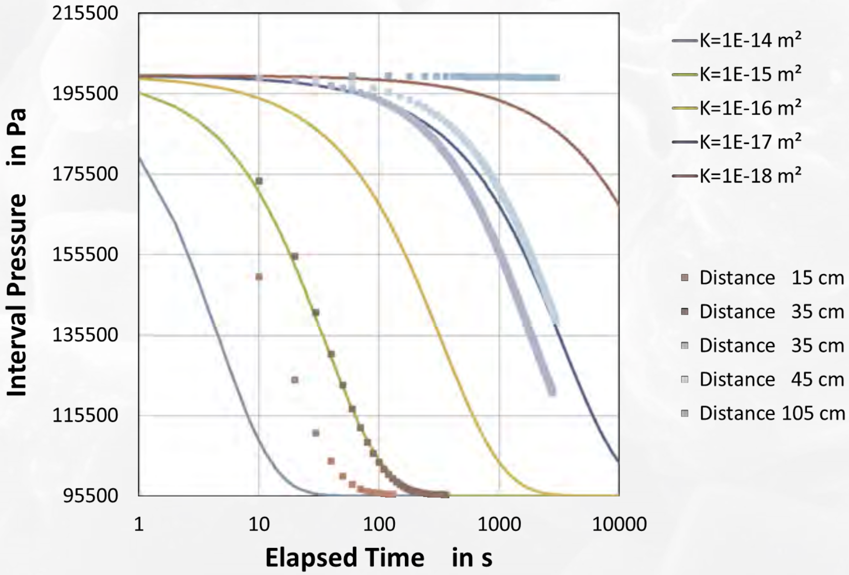
Flexible dilatometer with four deformation gauges

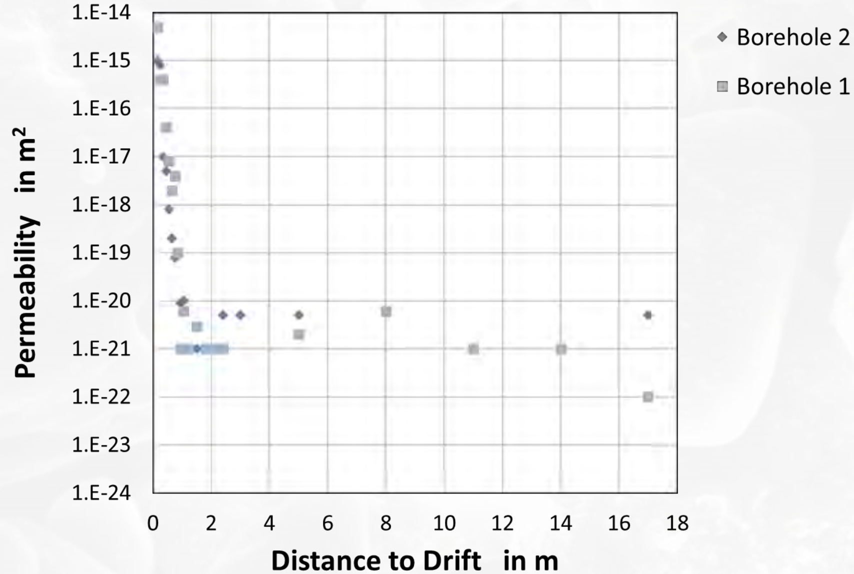
Creep Behaviour

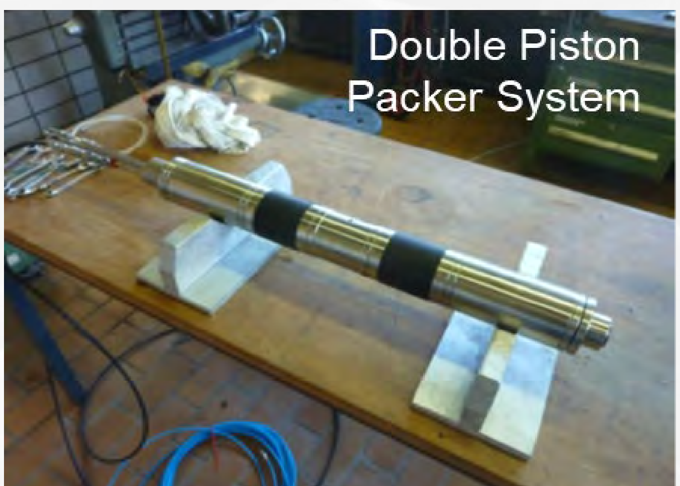


Determination of Creep Parameters is still in progress

Permeability



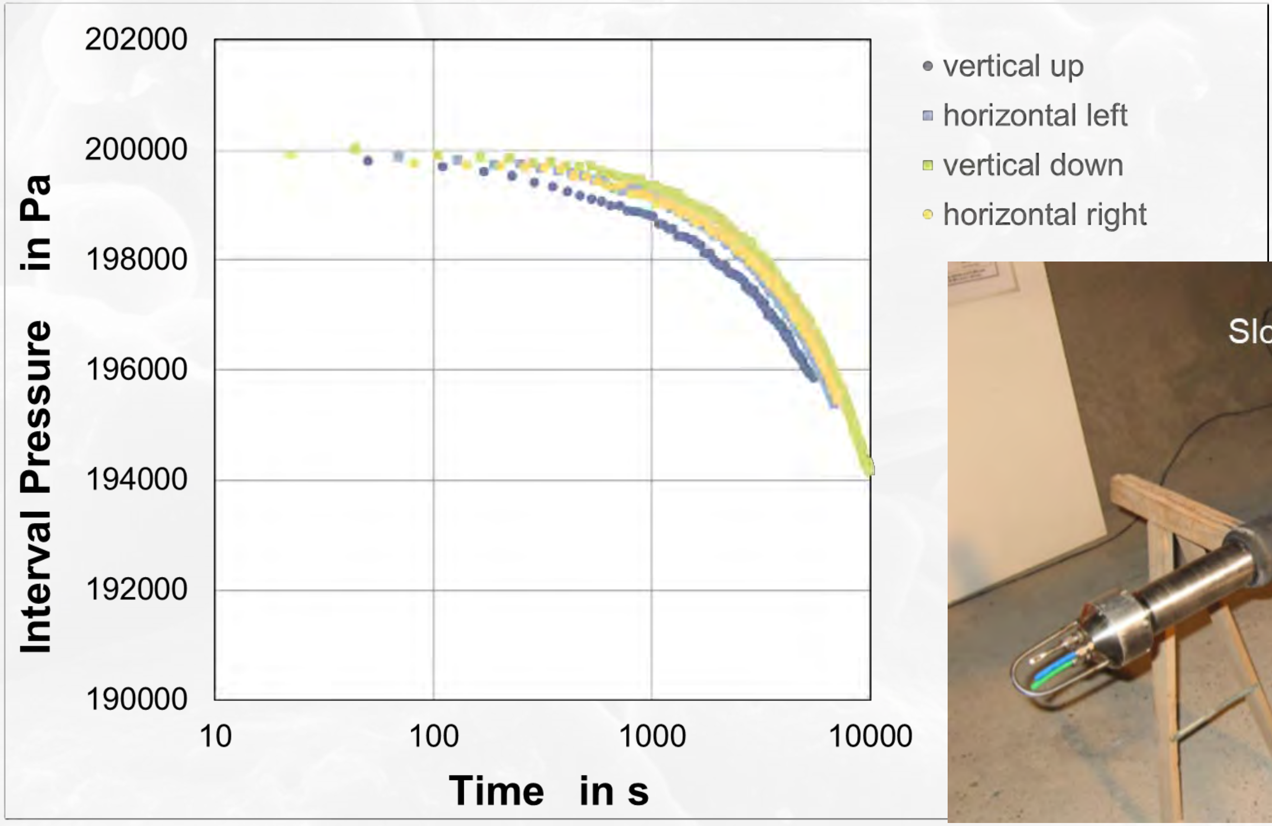




High permeability in the nearfield of drifts
→ EDZ / dilatancy

Low permeability in the deeper areas

Permeability



No hydraulic anisotropy has been identified

Conclusion and Outlook

- Aim is the characterization of bedded salt deposits in Germany
- In-situ experiments in two locations (rock salt) have been conducted so far
- Evaluation of in-situ data and laboratory test results have started
- So far, no anisotropy has been identified neither in-situ nor in laboratory
- Rock stress could not be determined so far, but is still in focus
- More in-situ measurements in other salt mines are planned / in preparation for both, rock salt mines and potash mines

Thanks for the **many team** members

of the subdepartment

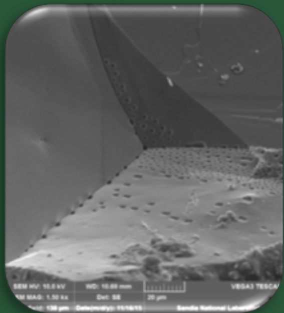
“Rock characterization of for storage and final disposal” at BGR

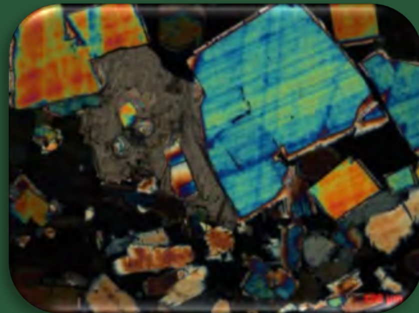
with the areas of responsibility of

Jürgen Hesser (In situ team) and

Werner Graesle (Geomechanical lab team)

and for your attention!





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Federal Ministry for Economic Affairs and Energy

M. Altmaier, D. Fellhauer, V. Metz
KIT-INE, Germany

Rapid City, SD, United States
May 28-30, 2019

- Context (Emergency preparedness Asse)
- CO_2-Production rates in saline systems

- **Context (Emergency preparednessAsse)**
- **CO_2-Production rates in saline systems**

Key data

Source: BGE

Asse II Mine

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

Facts of an old salt mine

Inflow of saline solution and stability problems

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

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

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

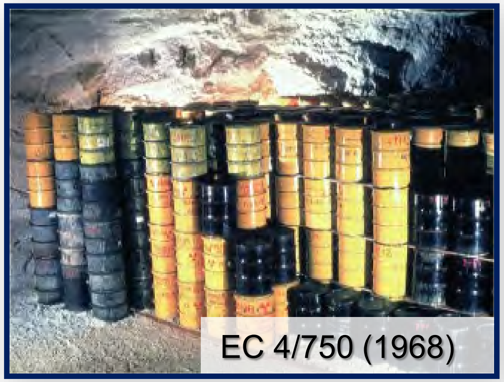
- measures to reduce the probability of occurrence and
- measures to minimize the consequences of an uncontrollable inflow of saline solution

Analysis of consequences

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

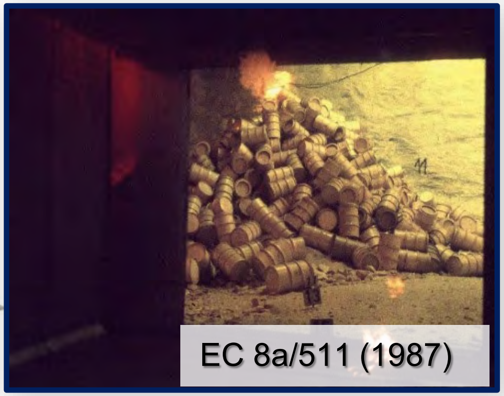
- Calculations and development of forecasts to be able to better evaluate the emergency measures.
- On the basis of calculations it can be estimated what radiological and chemo-toxic consequences would have to be expected in case of an uncontrollable inflow.
- The analysis also helps to evaluate what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

Emplacement of radioactive waste



Volume

125787 waste packages / ca. 47.000 cubic meters



Source: BGE

- Context (Emergency preparedness Asse)
- **CO_2-Production rates in saline systems**
  - Geochemical processes
  - Microbial processes in saline systems
  - Microbial CO_2-production rates
  - Conclusions

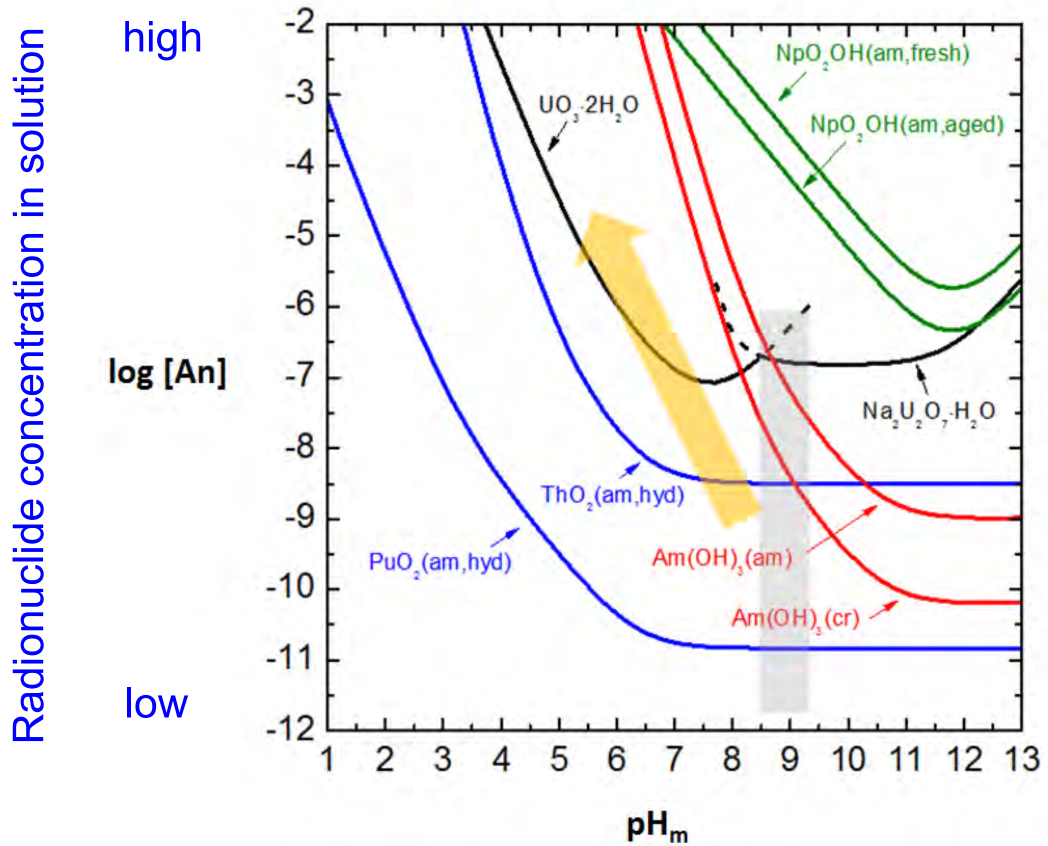
1) Geochemical processes

- The **chemical behavior of radionuclides** in aquatic systems is strongly depending on **geochemical parameters** like the **pH** and the concentration of dissolved **(CO_2) / carbonat**.

- Radionuclide solubility in carbonate containing solutions can be significantly enhanced due to **actinide-carbonate complexation**.

- The evolution of geochemical conditions (**brine composition, pH**) in the aquatic system can depend on **CO_2-production**.

1) Geochemical processes

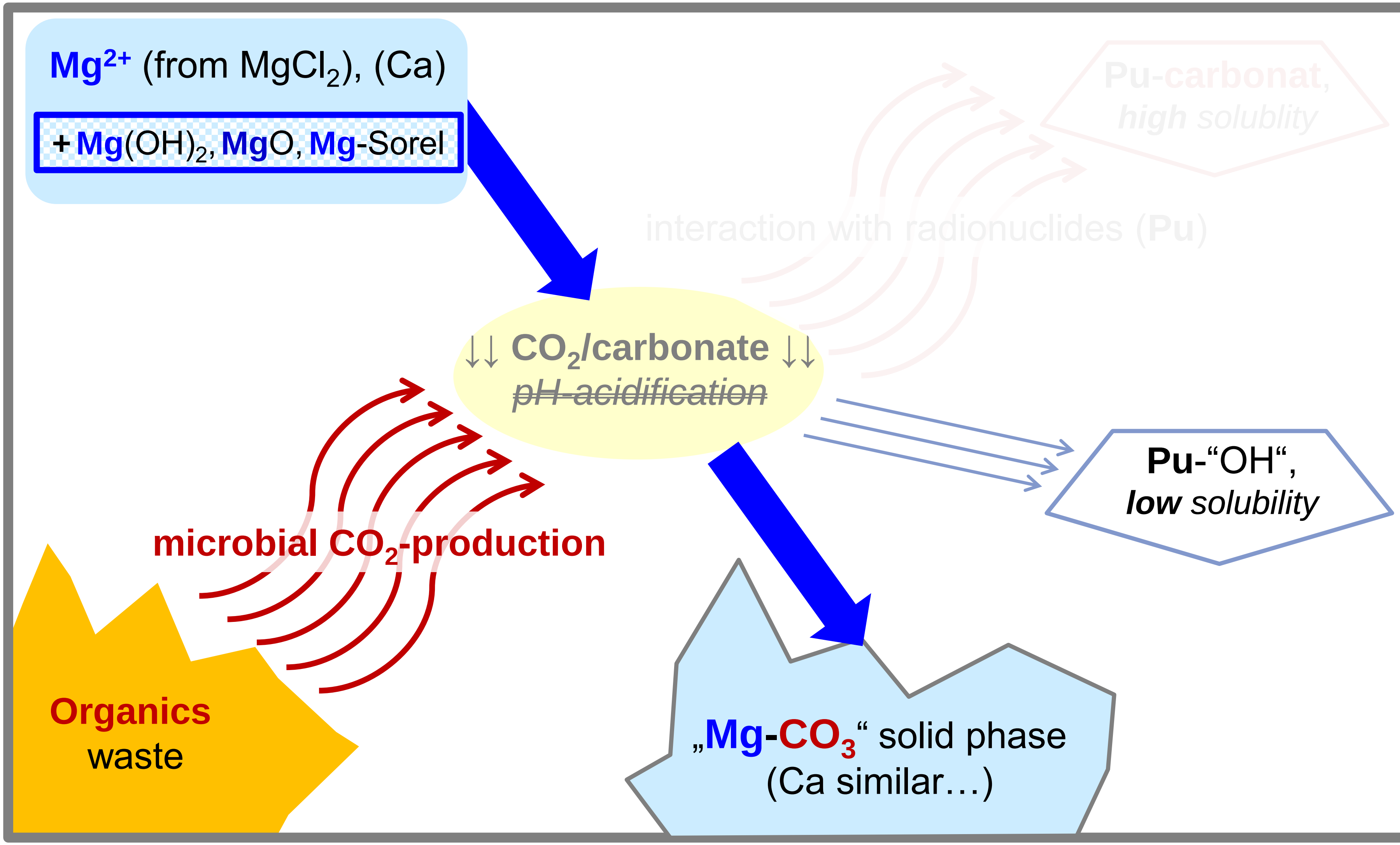


- *Orientative scheme of radionuclide solubility behavior*

1) Geochemical processes

- Emplacement chambers may contain **large inventories of organic materials** which can degrade over time.
- The (thermodynamic) **end-product of organics degradation is CO_2** or dissolved carbonate.
- The CO_2-production in the emplacement chambers is significantly determined by **microbial processes**.
- **Carbonate** can be **scavenged** from solution **by Mg^{2+} or Mg-rich materials** like Sorel, MgO or $Mg(OH)_2$ via the precipitation of Mg-carbonate solid phases with low solubility.
- Same applies for **calcium-rich** substances like cement-based materials.

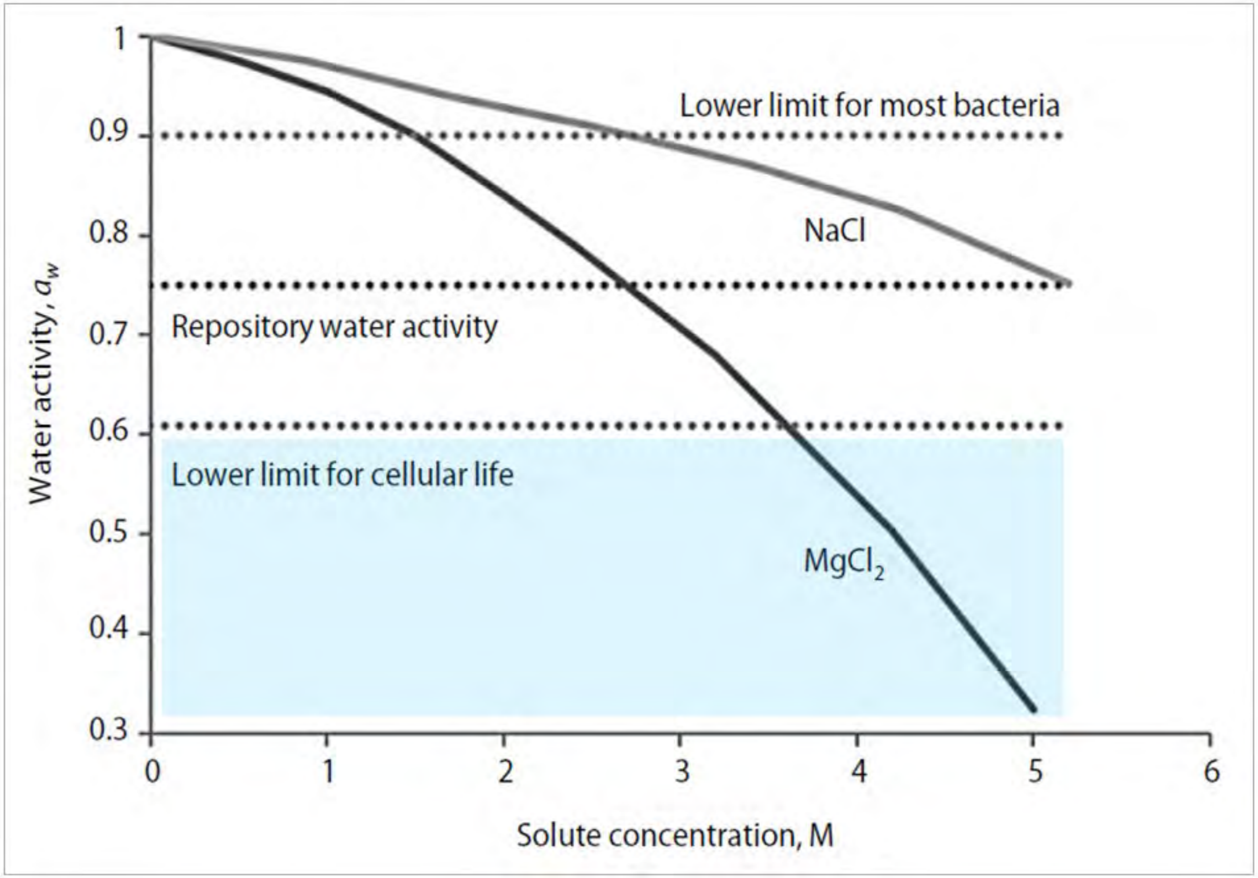
1) Geochemical processes



2) Microbial processes in saline systems

- Generally, **concentrated salt solutions feature unfavorable (!) conditions for microbial activities**.
- Specific properties of **saline solutions** lead to the expectation that only **limited microbial activity** should be relevant in the emplacement chambers:
  - **Very high ionic strength in $MgCl_2$-rich solutions**, connected to a low thermodynamic water activity,
  - **Chaotropic properties** of saline solutions, or
  - **Strongly alkaline pH-conditions** (pH ~ 12) in systems dominated by cement-based materials.

2) Microbial processes in saline systems

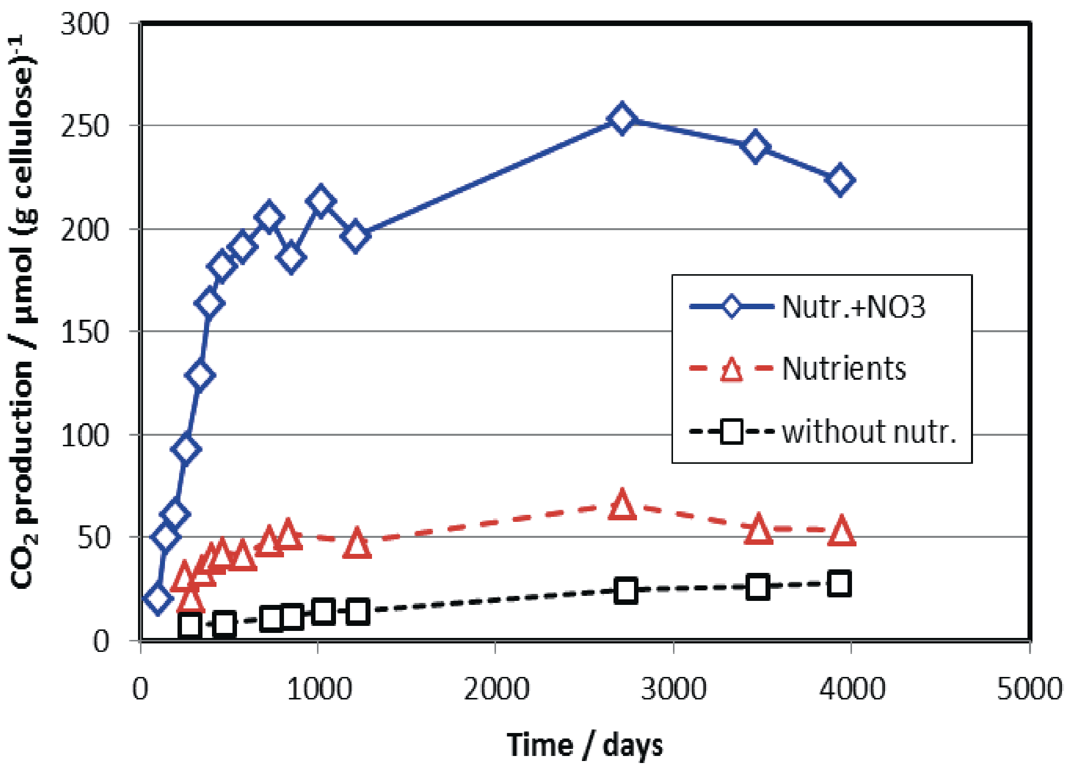


- *Boundary limits for cellular live, adapted from* [2018_SWA/CHE] *as function of thermodynamic water activity.*

3) Microbial CO_2-production rates

- Microbial processes in **saline solutions** must not be estimated or extrapolated from data for **dilute solutions**.
- **Microbial degradation processes in saline solutions** were studied in the US (WIPP project).
- Data still used to **assess CO_2-production in saline systems.**
- Work aimed at establishing **upper-limits** for the **maximum possible CO_2-production** in solution.

3) Microbial CO_2-production rates



- *Example for measured CO_2-production rates in saline solutions as function of nutrient supply (from* [2017_KIE/SWA]*).*
- *=> questions remain on how realistic the adopted conditions are for near-field conditions in deep underground facilities in rock salt.*

3) Microbial CO_2-production rates

- Critical discussion of production rates in saline solutions was recently made available within NEA SC related publication [2018_SWA/CHE]:

  Quote:

- ***It is unknown whether microbial gas generation under realistic, near-field repository conditions can ever be shown. Numerous attempts to do so have failed, but input for performance assessments is necessary. In order to generate input, experiments must be manipulated beyond realistic repository conditions, thus resulting in optimistic and conservative estimates of gas generation. WIPP currently uses gas generation data obtained from experiments using a rich inoculum containing brine lake sediments*** *(Gillow and Francis, 2006)****".***

3) Microbial CO_2-production rates

- Similar conclusions were drawn in the German report [2017_WIS/POP_a] related to microbial activities and CO_2-production in the emplacement chambers of Schachtanlage Asse II*:*
  „Der maximale mikrobielle Umsatz von C_{org} zu DIC bzw. TIC dient der Abgrenzung von Extremwerten. Aufgrund der hohen zu erwartenden Ionenstärken, damit verbundenen niedrigen Wasseraktivitäten und hohen Mg-Konzentrationen ist es jedoch wahrscheinlich, dass die Aktivität von Mikroorganismen in den ELK der Schachtanlage Asse deutlich eingeschränkt sein wird“.

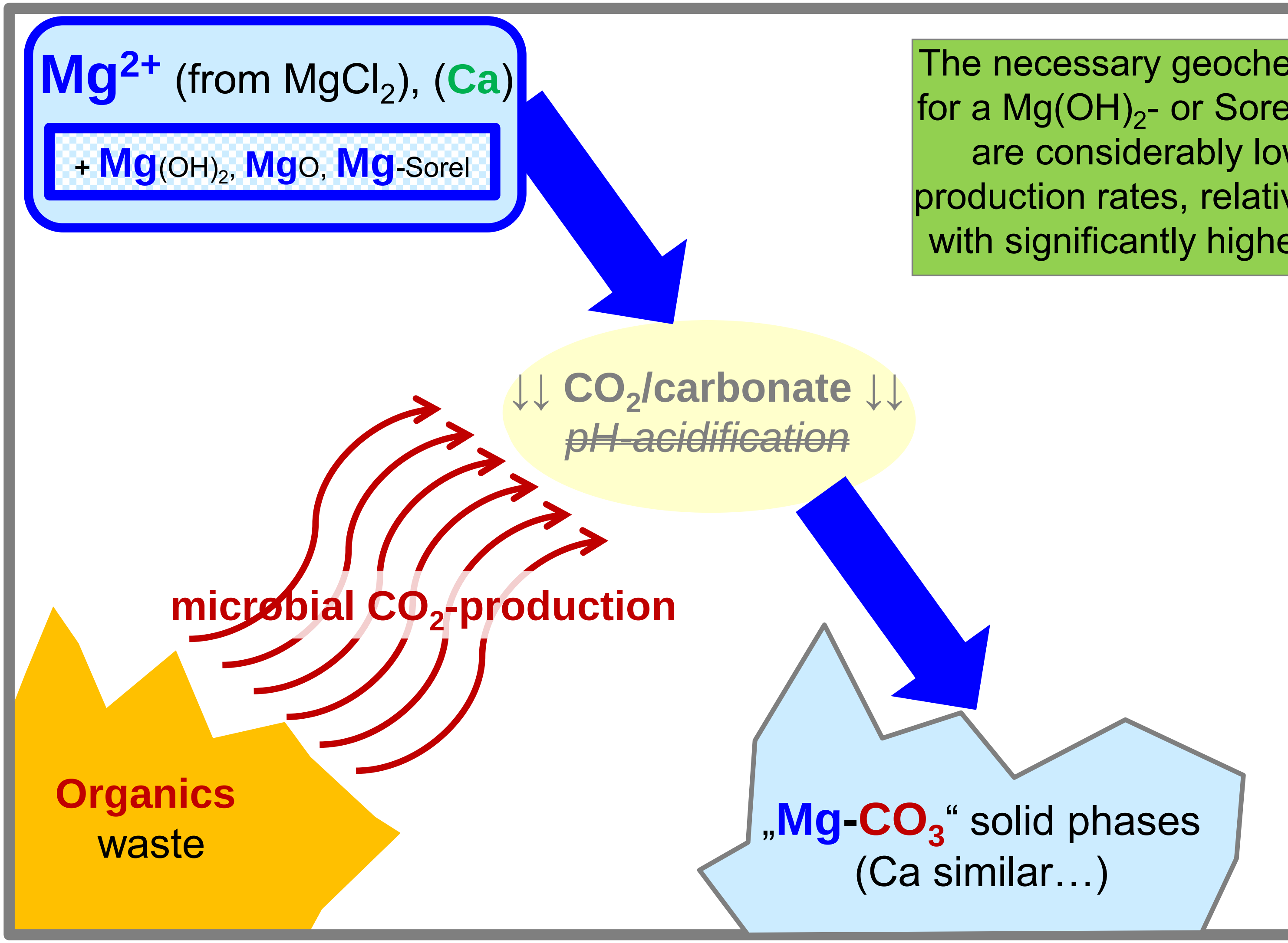
Translation (M.A.):

- **The maximum microbial turnover of C_{org} to dissolved inorganic carbon or total inorganic carbon is defining extremes. Because of the expected high ionic strength, the related low water activities and high Mg-concentrations it is likely, however, that the activity of microorganism in the emplacement chambers of Schachtanlage Asse will be distinctly limited.**

4) Conclusions

- On the basis of the **"conservative" CO_2-production rates** derived, it is **not possible to derive a realistic assessment of microbial CO_2-production** for the emplacement chamber of Asse, but only calculate maximum CO_2 amounts.
- It should be expected, that the **actual CO_2-production will be decisively lower**.
- The **requirements regarding nature, amount and reactivity** of potential **Sorel or $Mg(OH)_2$-based material** to be emplaced depend on:
  - **(i)** expected **total amount of produced CO_2 in connection with the production rates**, and
  - **(ii)** the **availability of other components in a chamber** which can **scavenge CO_2/carbonate from solution** by precipitation processes.

4) Conclusions



The necessary geochemical requirements for a $Mg(OH)_2$- or Sorel-based component are considerably lower for low CO_2-production rates, relative to considerations with significantly higher production rates.

4) Conclusions

Karlsruhe Institute of Technology

Mg^{2+} (from $MgCl_2$), (**Ca**)

+ $Mg(OH)_2$, MgO, Mg-Sorel

The necessary geochemical requirements for a $Mg(OH)_2$- or Sorel-based component are considerably lower for low CO_2-production rates, relative to considerations with significantly higher production rates.

↓↓ CO_2/carbonate ↓↓

~~*pH-acidification*~~

microbial CO_2-production

Organics
waste

„**Mg-CO_3**“ solid phases
(Ca similar…)

Literature

- [2018_SWA/CHE] J.S. Swanson, A. Cherkouk, T. Arnold, A. Meleshyn, D. T. Reed, *Microbial Influence on the Performance of Subsurface, Salt-Based Radioactive Waste Repositories - An Evaluation Based on Microbial Ecology, Bioenergetics and Projected Repository Conditions.* NEA No. 7387, OECD-NEA, 2018. (http://www.oecd-nea.org/rwm/pubs/2018/7387-salt-club.pdf).
- [2017_KIE/SWA] B. Kienzler and J.S. Swanson, *Microbial Effects in the Context of Past German Safety Cases.* KIT SCIENTIFIC REPORTS 7744, Karlsruhe, Germany, 2017. (http://dx.doi.org/10.5445/KSP/1000073559)
- [2017_WIS/POP_a] L. Wissmeiner, J. Poppei, M. Niemeyer, D. Fellhauer, C. Borkel, V. Metz, M. Altmaier, *Kenntnisstand zu Reaktionen organischer Abfallbestandteile in den Einlagerungskammern der Schachtanlage Asse II mit Relevanz für das geochemische Milieu und die Gasbildung*. Gemeinsamer Bericht, AF-Consult Switzerland AG, Baden; Karlsruher Institut für Technologie – Institut für Nukleare Entsorgung, Eggenstein-Leopoldshafen, Deutschland, BfS-KZL 9A/24250000/EGB/RZ/001/00; AF 1764/93; KIT-INE 001/17, 2017.

Acknowledgement:

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

The 10th US/German Workshop on “Salt Repository Research, Design, and Operation”

CO_2 production rates from organic waste in saline solutions: Modelling approach and quantification

29th May 2019, Rapid City, USA

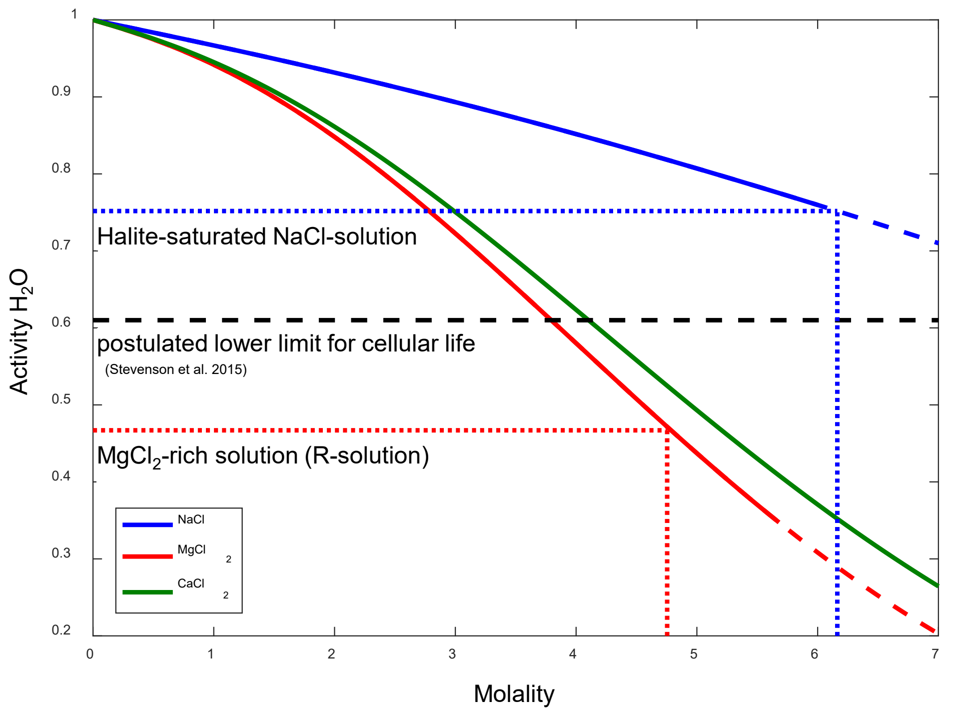
Laurin Wissmeier (CSD), Jörg Mönig (GRS)

CSD ENGINEERS
INGENIOUS BY NATURE

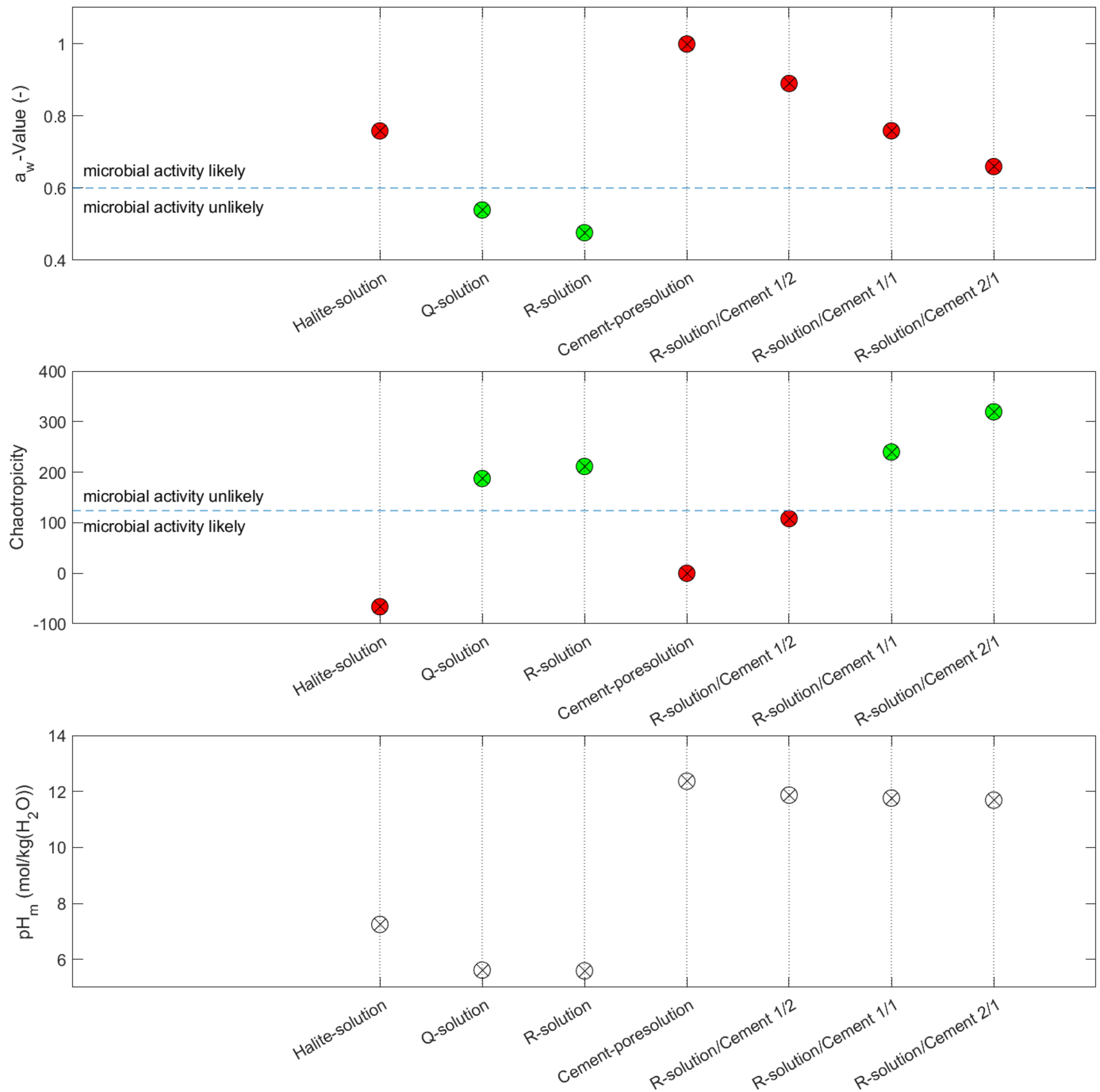
GRS

Indicators for Microbial Activity

- a_w-value
  - Thermodynamic activity of H_2O in solutions
    Limit for microbial activity ~0,6
- Chaotropicity
  - Measure for the disturbance of hydrogen bonds
  - Limit for microbial activity in a pure $MgCl_2$ solution ~2,3 M
  - Estimation for complex solutions based on Cray et al. “A Universal Measure of Chaotropicity and Kosmotropicity.” 2013.
- pH_m-value
  - Inhibition of microbial activity (e.g. in cement)



Indicators of Microbial Activity in Relevant Systems



CSDENGINEERS
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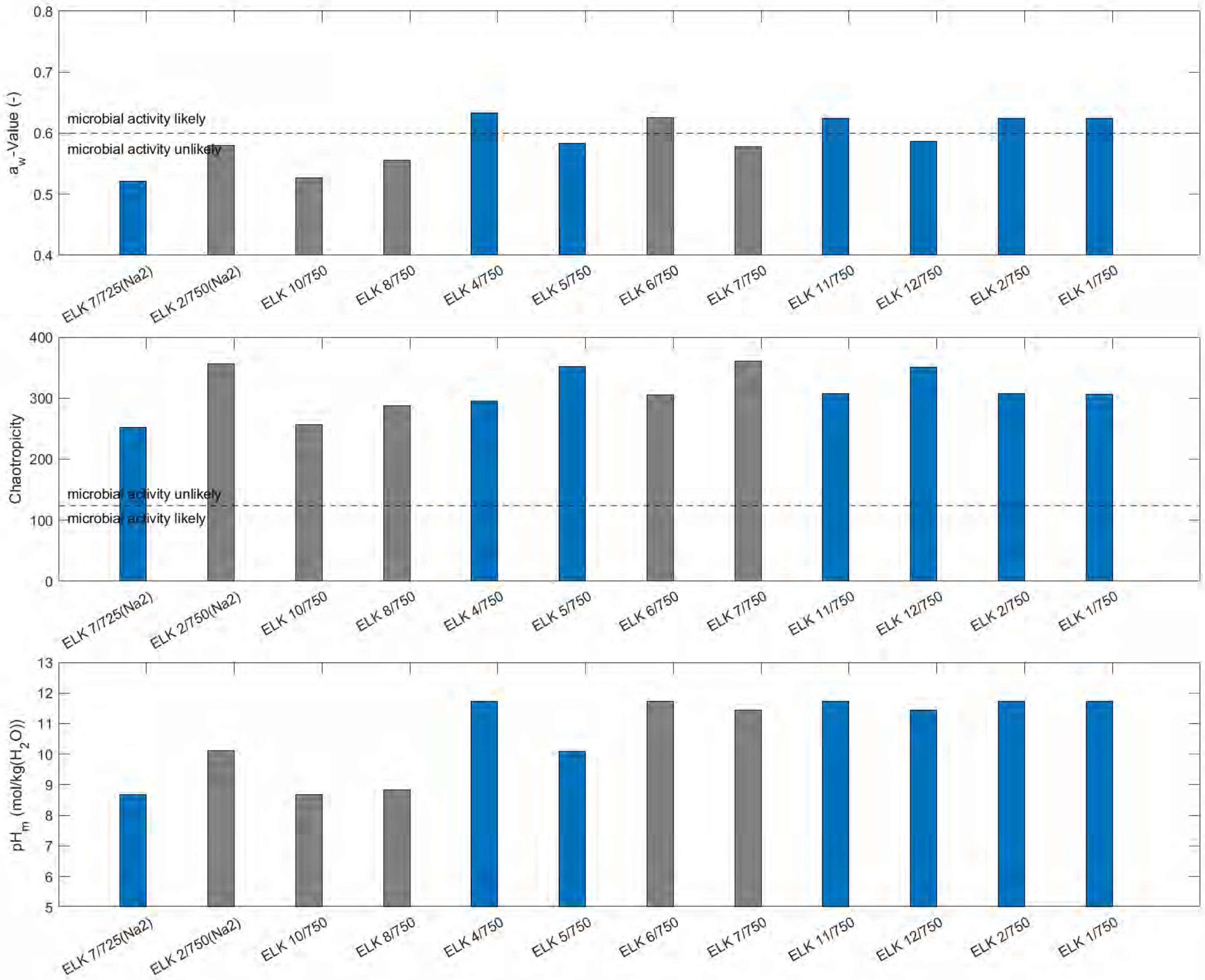
GRS

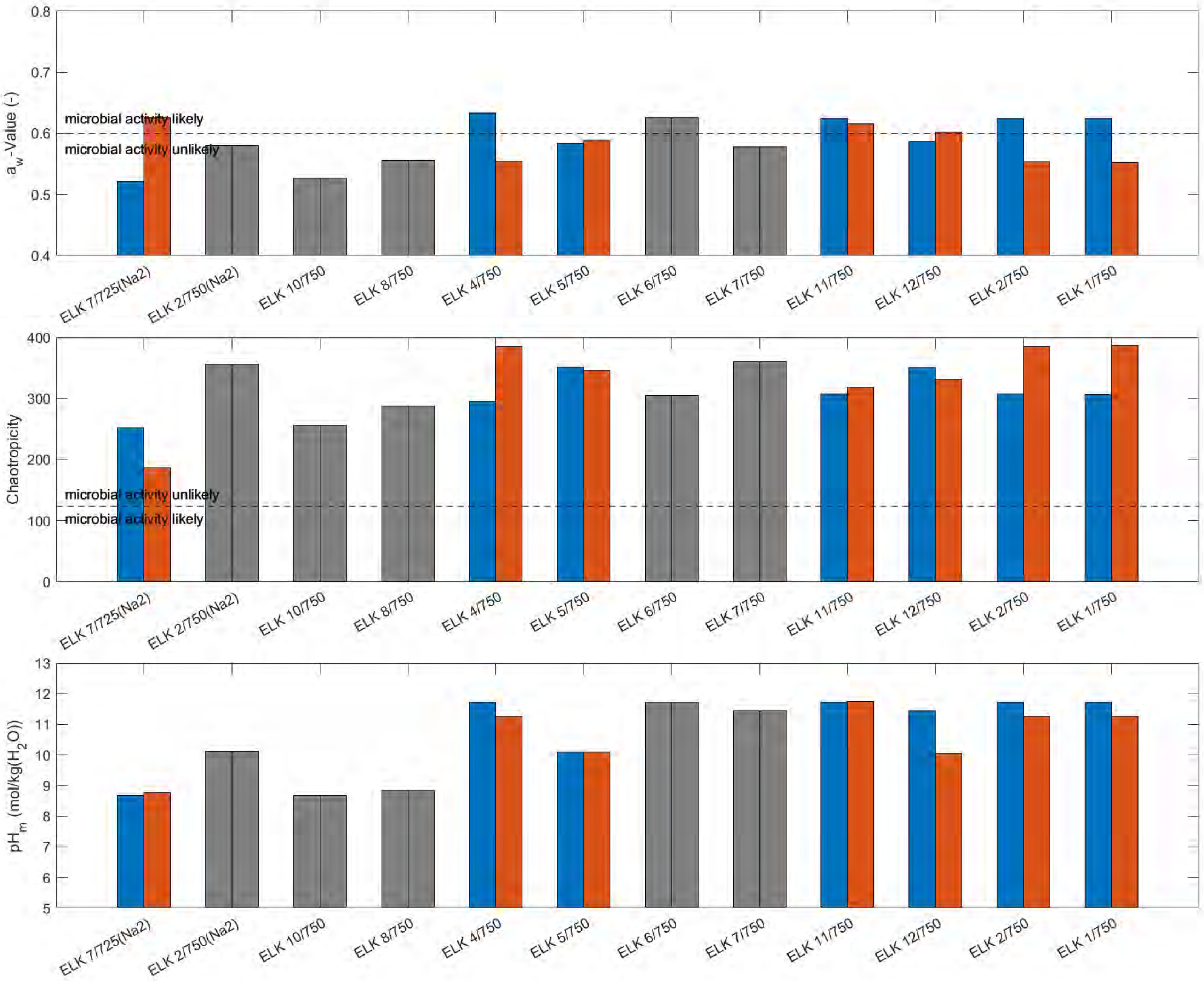
Key Messages

1. Low a_w values and high chaotropicity indicate that in the long term (at full efficacy of the milieu-defining substances in the chamber) the microbial activity and thus CO_2 formation in the disposal chambers is unlikely with and without the Mg-depot.

Indicators of Microbial Activity at Equilibrium of the Milieu-defining Substances in the Chambers without Mg-depot



Indicators of Microbial Activity at Equilibrium of the Milieu-defining Substances in the Chambers <u>with</u> (orange) and <u>without</u> Mg-Depot (blue)



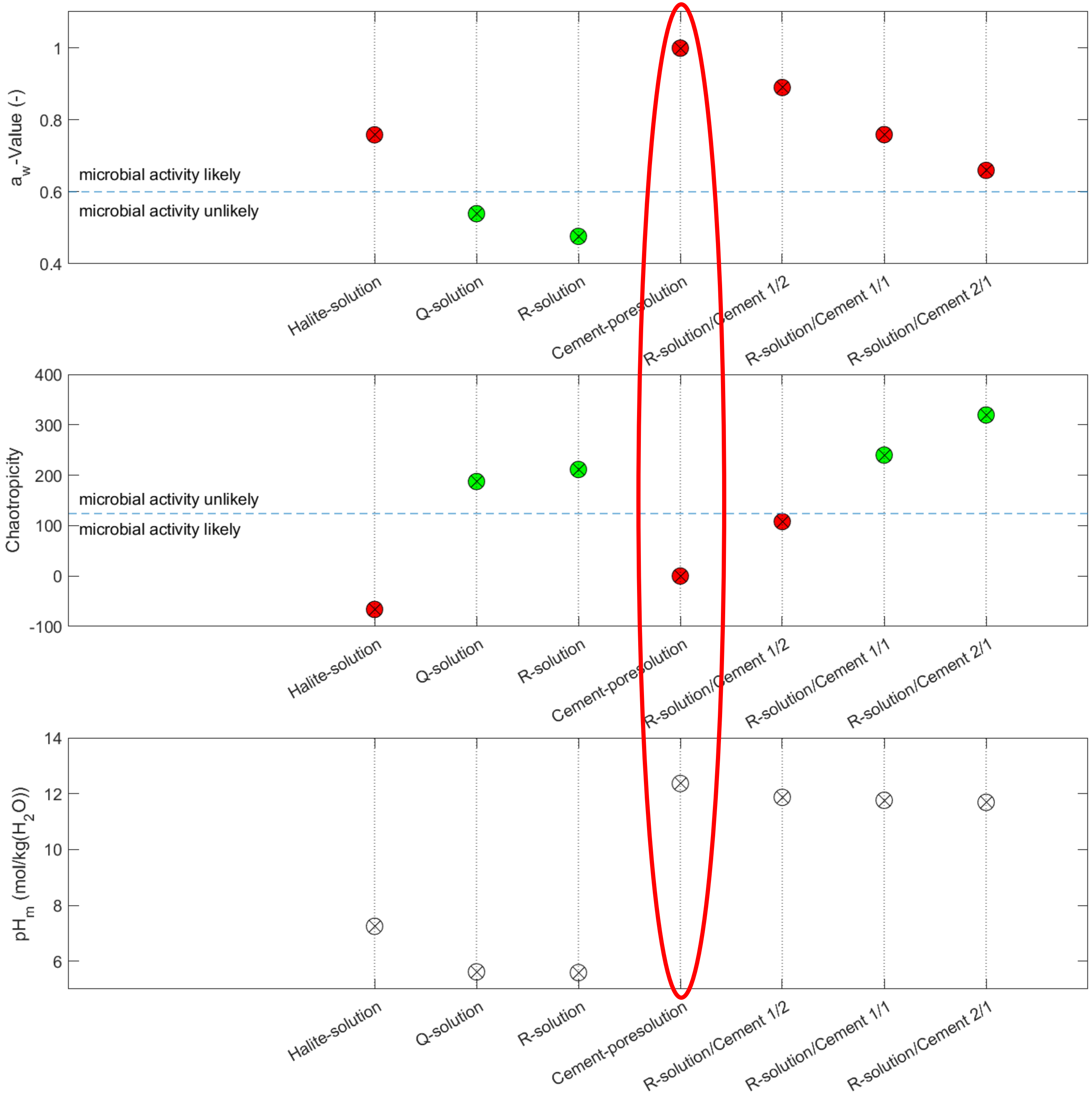
CSDENGINEERS INGENIOUS BY NATURE
GRS

Key Messages

1. Low a_w values and high chaotropicity indicate that in the long term (at full efficacy of the milieu determining substances in the chamber) the microbial activity and thus CO_2 formation in the disposal chambers is unlikely with and without the Mg-depot.

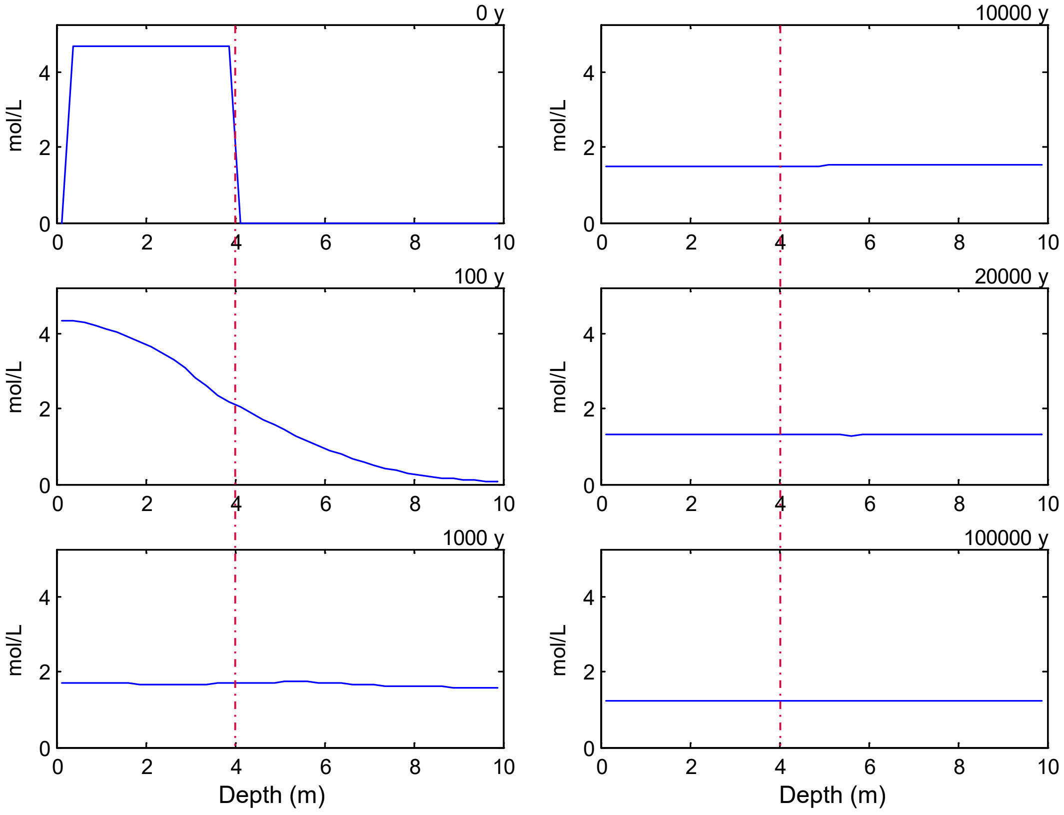
2. Due to the high chemical buffering capacity of cement, it must be assumed that the cement-conditioned chemical properties of the waste will stabilize over significant periods of time. Initially, CO_2 formation in the cement-conditioned solutions cannot be ruled out.

Indicators of microbial activity in relevant systems

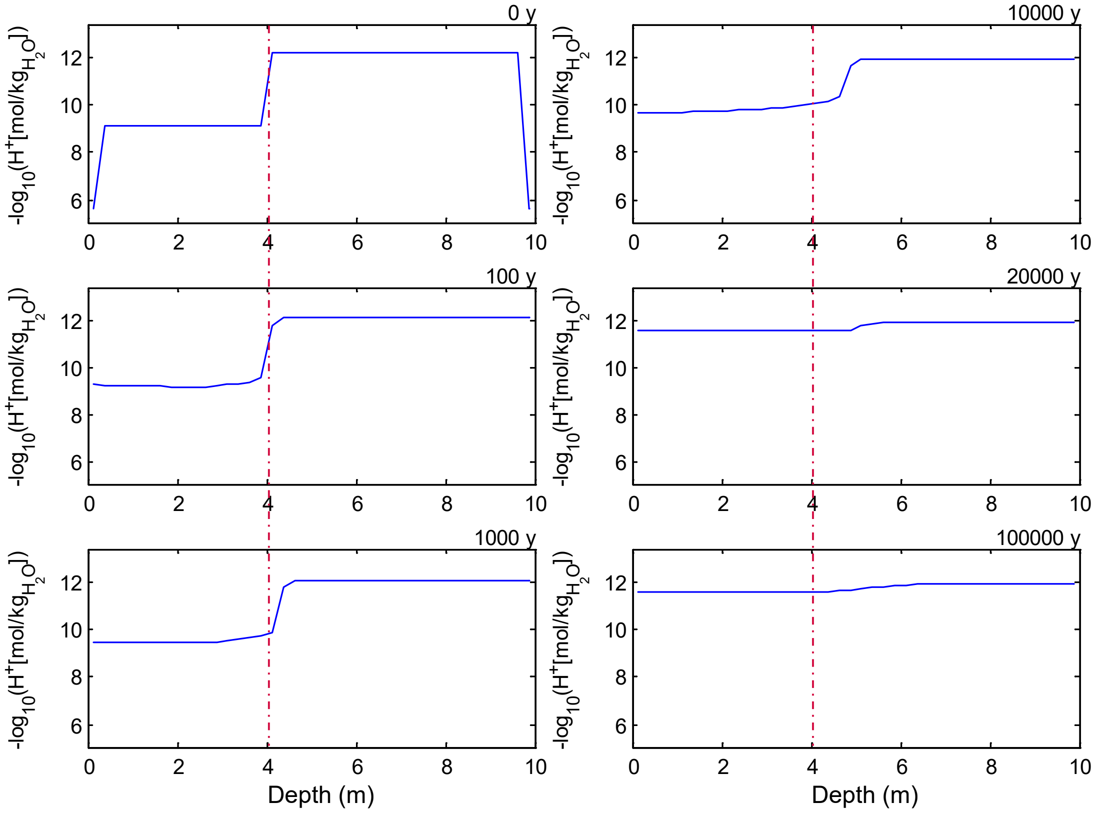


Tracer Diffusion versus Reactive Transport between Cement and Mg-Depot

Tracer diffusion



pH_m – reactive transport



Key Messages

CSDENGINEERS INGENIOUS BY NATURE

GRS

1. Low a_w values and high chaotropicity indicate that in the long term (at full efficacy of the milieu determining substances in the chamber) the microbial activity and thus CO_2 formation in the disposal chambers is unlikely with and without the Mg-depot.

2. Due to the high chemical buffering capacity of cement, it must be assumed that the cement-conditioned chemical properties of the waste will stabilize over significant periods of time. Initially, CO_2 formation in the cement-conditioned solutions cannot be ruled out.

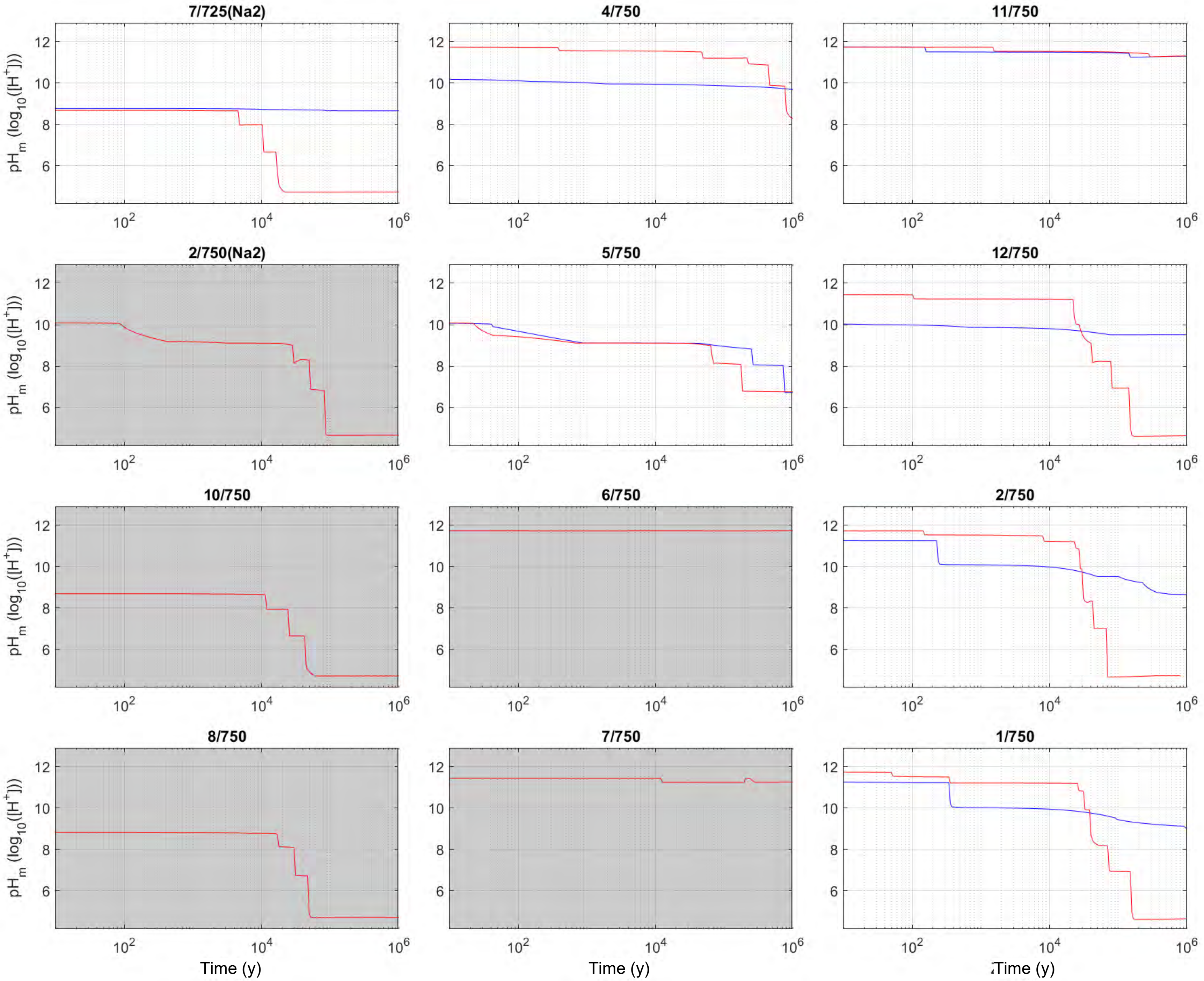
3. Initially, the cement inventory buffers the generated CO_2 through carbonation.

4. Acidification of the environment through high CO_2 concentration and formation of carbonic acid in a disposal chamber is unlikely if the cement inventory can buffer the generated CO_2 until the introduced concentrated $MgCl_2$ solution becomes effective.

5. Due to the decelerated CO_2 formation at high pH_m, it is unlikely that the buffer capacity of the cement inventories is exceeded before the introduced $MgCl_2$ solution becomes effective.

Differences in the chemical evolution* with (blue) and without Mg-depot (red)

*with preliminary (slower) conversion rates for microbial CO_2 formation; using the "closed mixing cell approach"; without inhibition of microbial activity by a_w value or chaotropicity



Key Messages

CSDENGINEERS INGENIOUS BY NATURE

GRS

1. Low a_w values and high chaotropicity indicate that in the long term (at full efficacy of the milieu determining substances in the chamber) the microbial activity and thus CO_2 formation in the disposal chambers is unlikely <u>with</u> and <u>without</u> the Mg-depot.

2. Due to the high chemical buffering capacity of cement, it must be assumed that the cement-conditioned chemical properties of the waste will stabilize over longer periods of time. Initially, CO_2 formation in the cement-conditioned solutions must be expected.

3. Initially, the cement inventory buffers the generated CO_2 through carbonation.

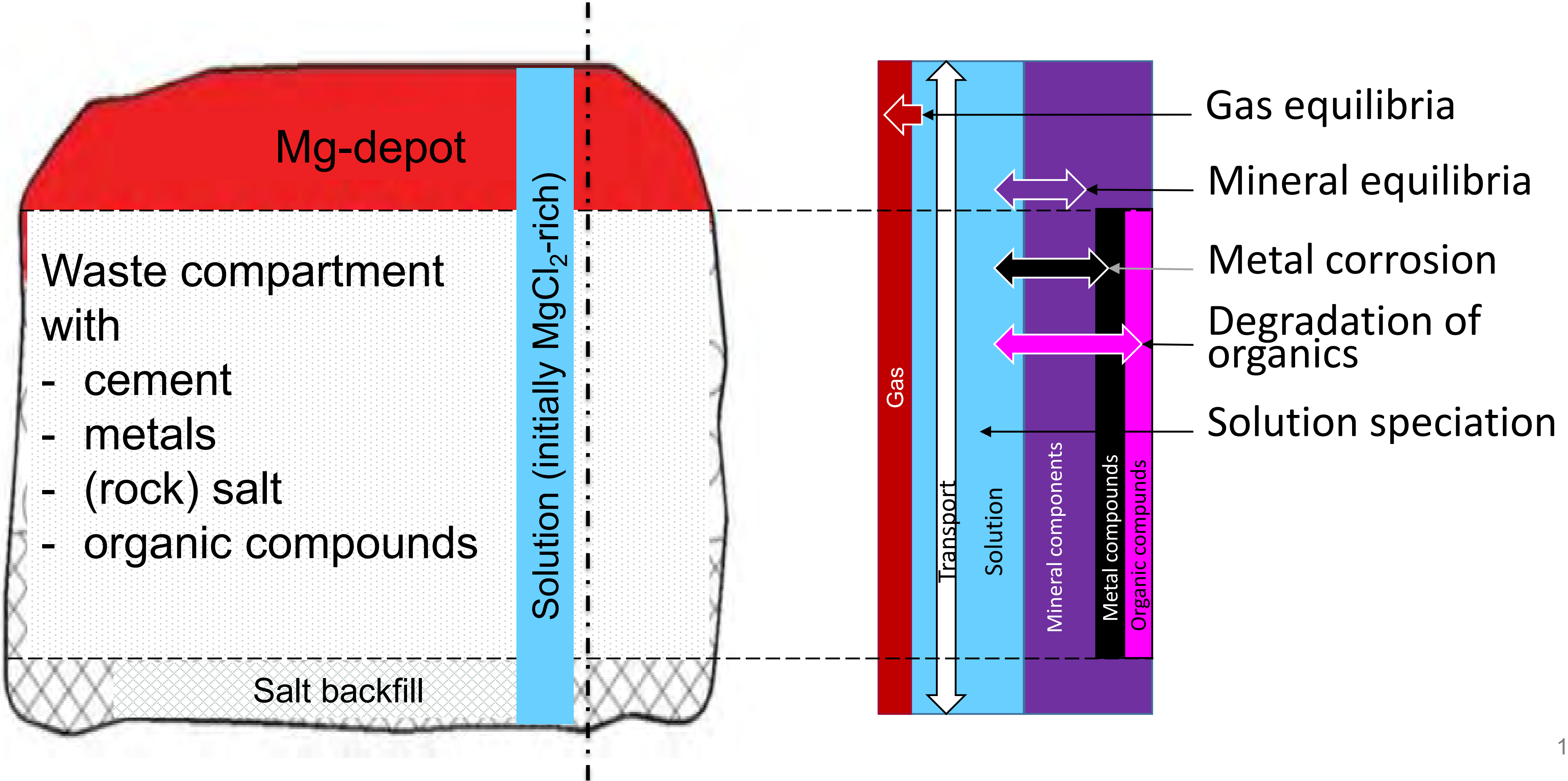
4. Acidification of the environment through high CO_2 concentration and formation of carbonic acid in a disposal chamber is unlikely if the cement inventory can buffer the generated CO_2 until the introduced concentrated $MgCl_2$ solution becomes effective.

5. Due to the decelerated CO_2 formation at high pH_m, it is unlikely that the buffer capacity of the cement inventories is exceeded before the introduced $MgCl_2$ solution becomes effective.

6. The time until the concentrated $MgCl_2$ solution becomes effective in the waste has not been sufficiently investigated so far.

Modelling Concept for a Disposal Chamber

Wissmeier et al. “Modellkonzepte zur Ermittlung von Geochemischem Milieu, Gasbildung und Radionuklid-Quelltermen.” 2018.



Acknowledgments

Project partners

Many thanks to BGE and KIT-INE for the constructive cooperation!

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- Altmaier, M. “Mikrobielle CO2-Gasbildungsraten in Salinaren Systemen.” Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, 2018.

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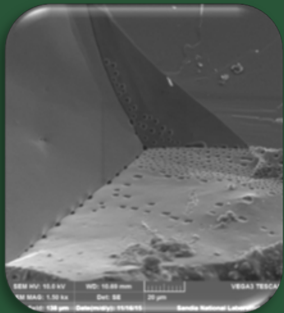
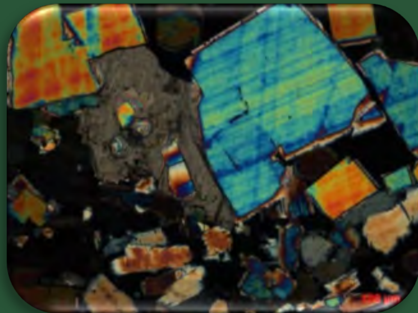

10^{th} US/German Workshop on Salt Repository Research, Design, and Operation

Sandia National Laboratories
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PTKA Project Management Agency Karlsruhe Karlsruhe Institute of Technology
RESPEC
SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY
U.S. DEPARTMENT OF ENERGY
Federal Ministry for Economic Affairs and Energy

Philip Stauffer

Los Alamos National Laboratory

Rapid City, SD, United States

May 28-30, 2019

Simulations of a Heated Borehole Experiment at WIPP

Early Results

LA-UR-24532

WIPP Salt Field Test Team

Sandia National Laboratories (SNL)

Kris Kuhlman, Melissa Mills, Courtney Herrick, Martin Nemer, Ed Matteo, Yongliang Xiong, Jason Heath

Los Alamos National Laboratory (LANL)

Phil Stauffer, Hakim Boukhalfa, Eric Guiltinan, Doug Ware, Thom Rahn

Waste Isolation Pilot Plant (WIPP) Test Coordination Office (LANL)

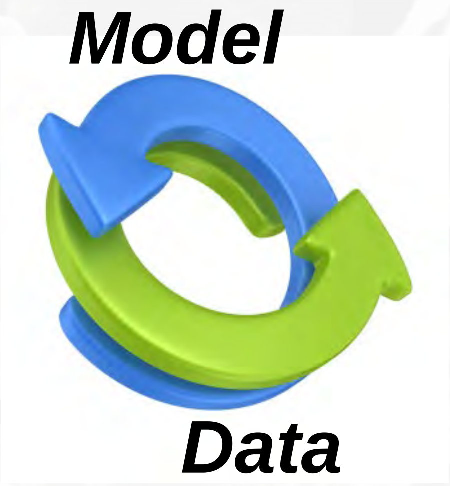
Doug Weaver, Brian Dozier, Shawn Otto

Lawrence Berkeley National Laboratory (LBNL)

Yuxin Wu, Jonny Rutqvist, Jonathan Ajo-Franklin, Mengsu Hu

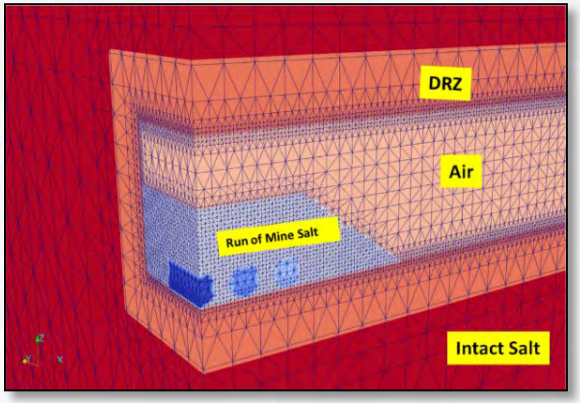
Process-level Modeling Goals

- **Simulation tools demonstrate understanding of repository processes**
- **Gain confidence in long-term predictions**
- **Explore uncertain processes and inputs prior to designing new experiments to reduce uncertainty**
- **Integrate process-level physics into the GDSA performance assessment (PA) tool**



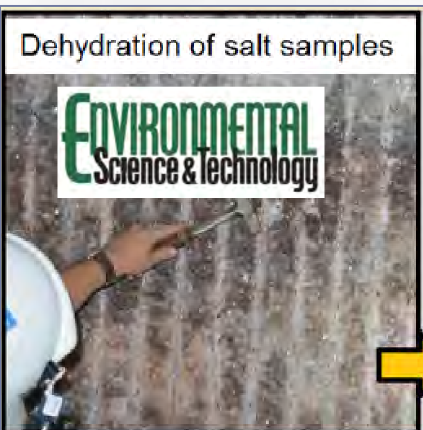
THMC Process-Level Modeling

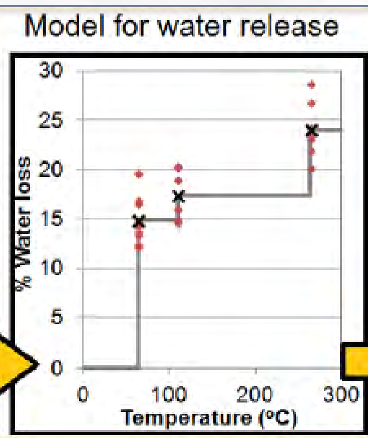
- **Thermal-Hydrological-Mechanical-Chemical (THMC)**
- **TOUGH-FLAC simulates large-deformation THMC**
- **FEHM numerical model simulates small-deformation THMC**
- **Isolating specific processes allows more rapid validation**
- **Some processes are validated using TH, TM, THC, or THM**

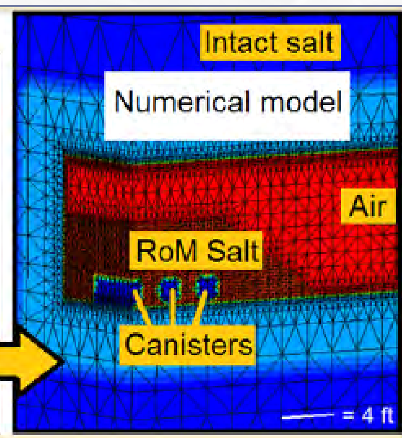


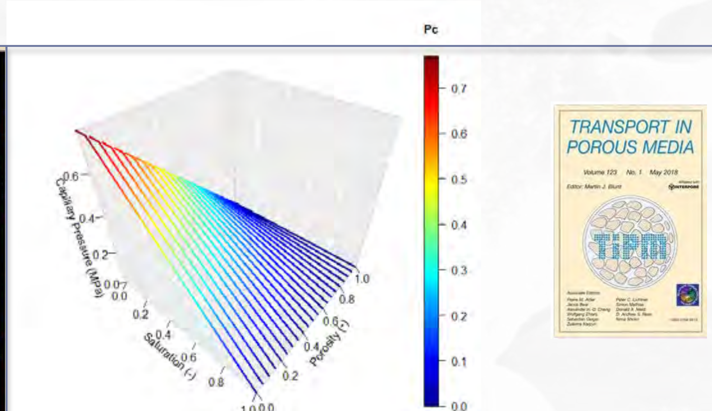
Salt THMC Couplings

Deformation (strain)	***F(stress, time, saturation, temperature)***
Vapor pressure lowering	***F(capillary pressure, salinity)***
Porosity	***F(dissolution, precipitation, stress, strain)***
Thermal conductivity	***F(porosity, saturation, temperature)***
Permeability	***F(dissolution, precipitation, porosity, saturation)***
Capillary pressure	***F(porosity, saturation, temperature)***
Water vapor diffusion	***F(porosity, saturation, temperature)***
Clay dehydration	***F(temperature)***
Salinity	***F(temperature)***









Capillary pressure / porosity function

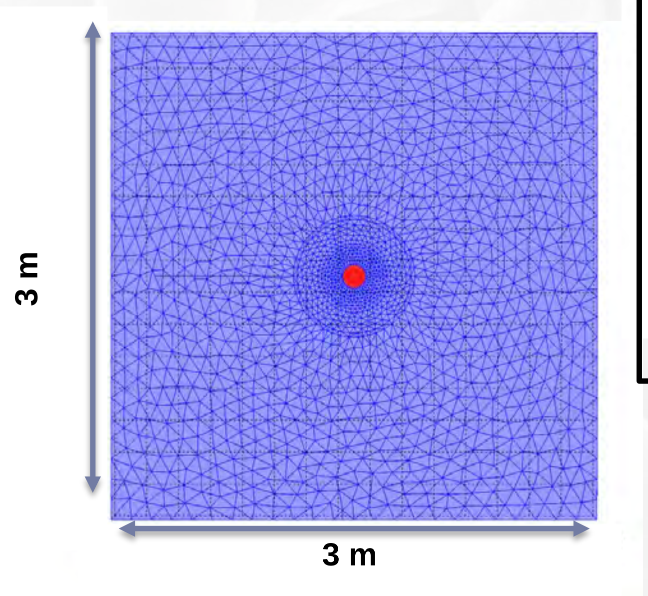
BATS Shakedown Test in existing boreholes

Brine
Availability
Test in
Salt

BATS Shakedown Test

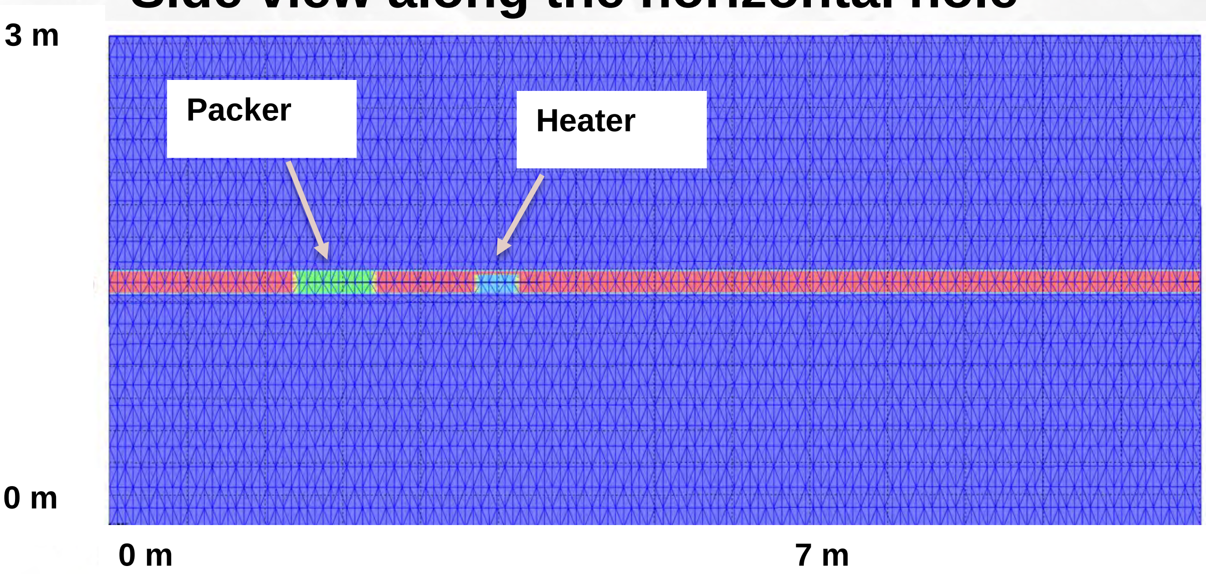
THC Model of Shakedown Test

Shakedown Test
3-D Borehole heater simulation domain

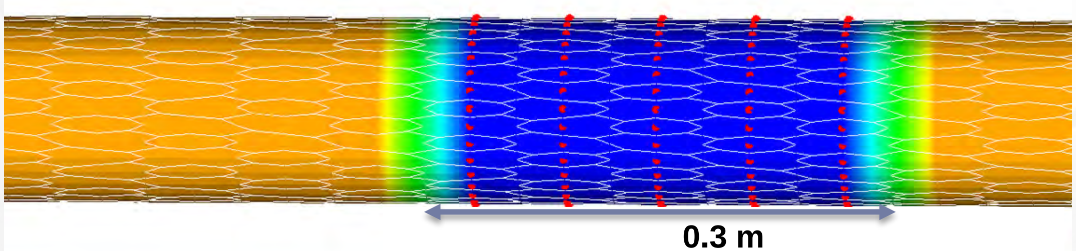


Drift view looking into horizontal hole

Side view along the horizontal hole



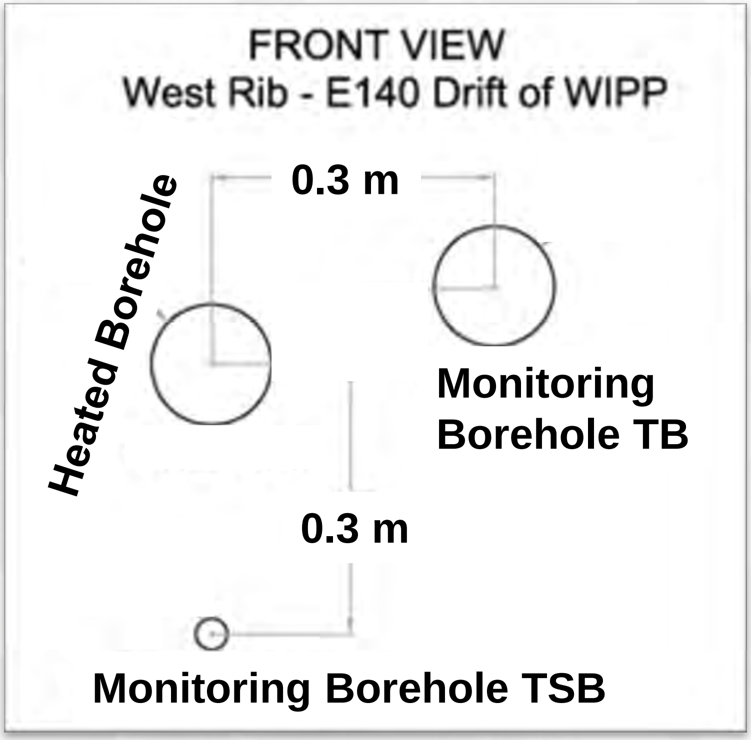
Meters from the drift face



Zoom into the heater mesh

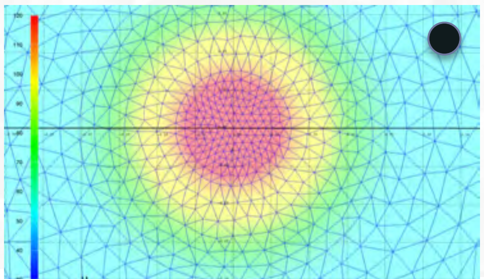
BATS Shakedown Test

Original Block Heater

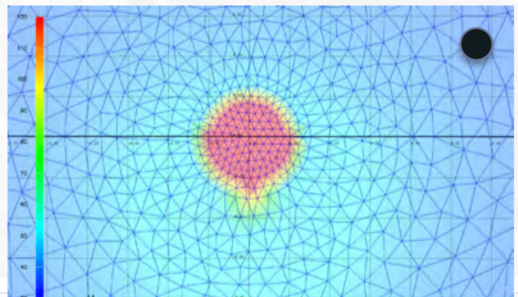


Simulations Assist Design

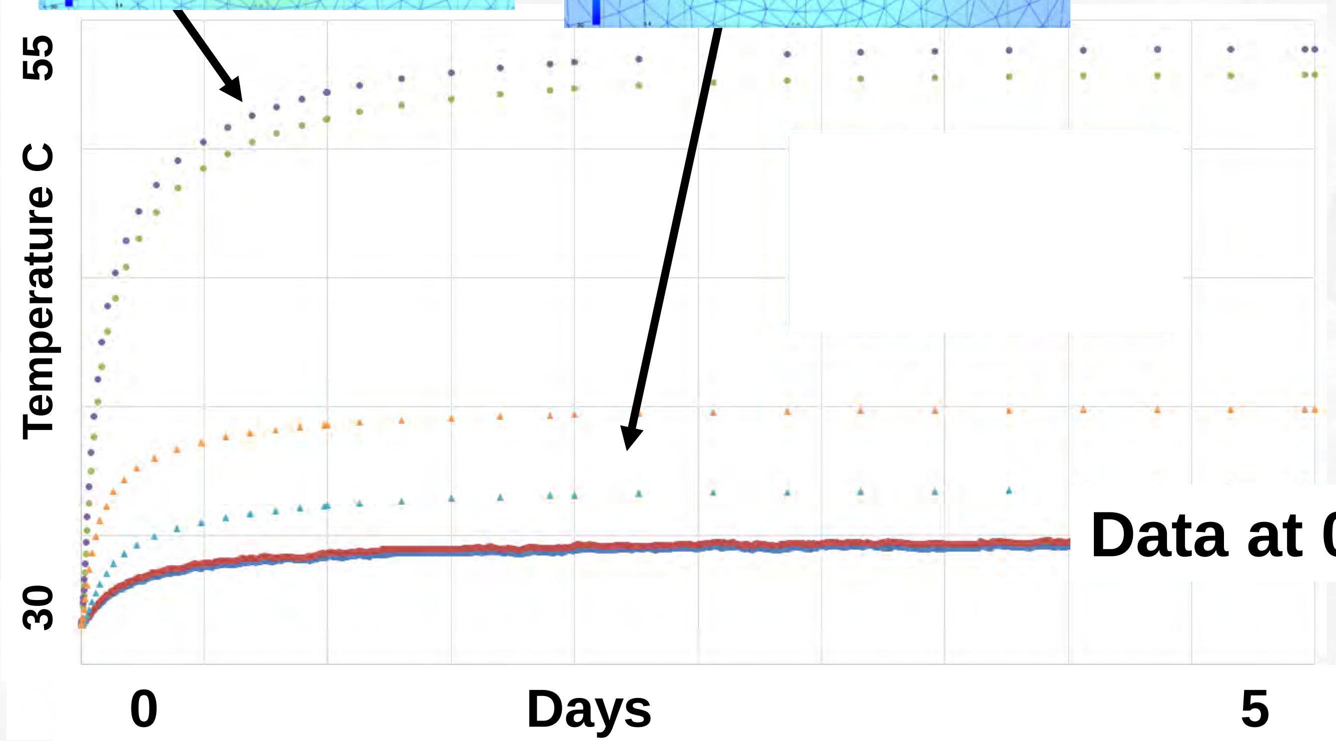
Full contact (radiation) sim



Small contact (conduction) sim



View into heated borehole

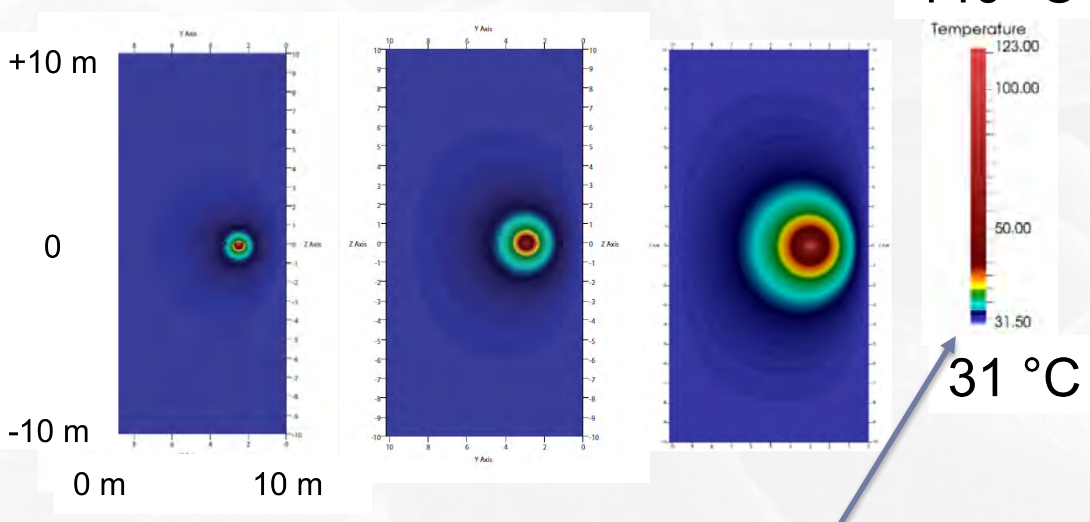


Simulations compared to shakedown data show that infrared heating would better transfer heat to the rock salt.

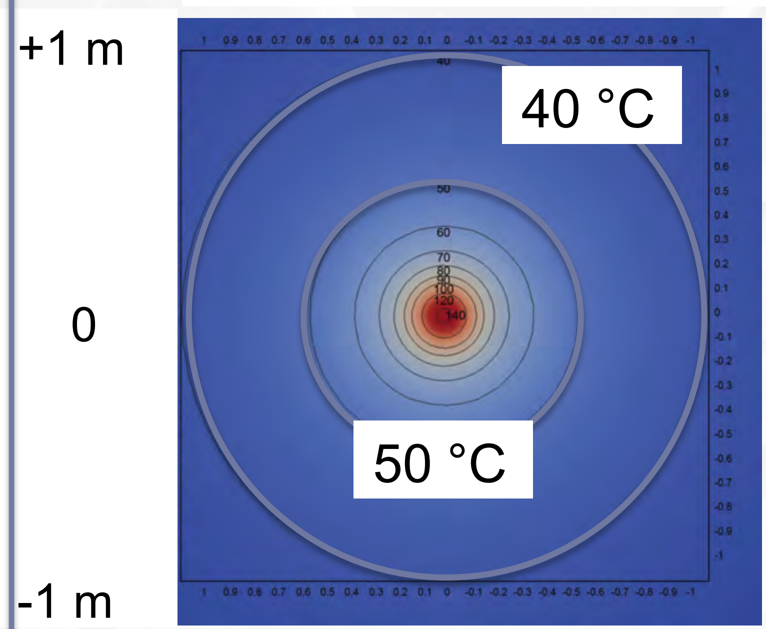
BATS Shakedown Test

Modeling Improved Heater Design

Initial metal block heater	Small infrared (IR) heater	Design IR heater power
120 C	260 W	750 W



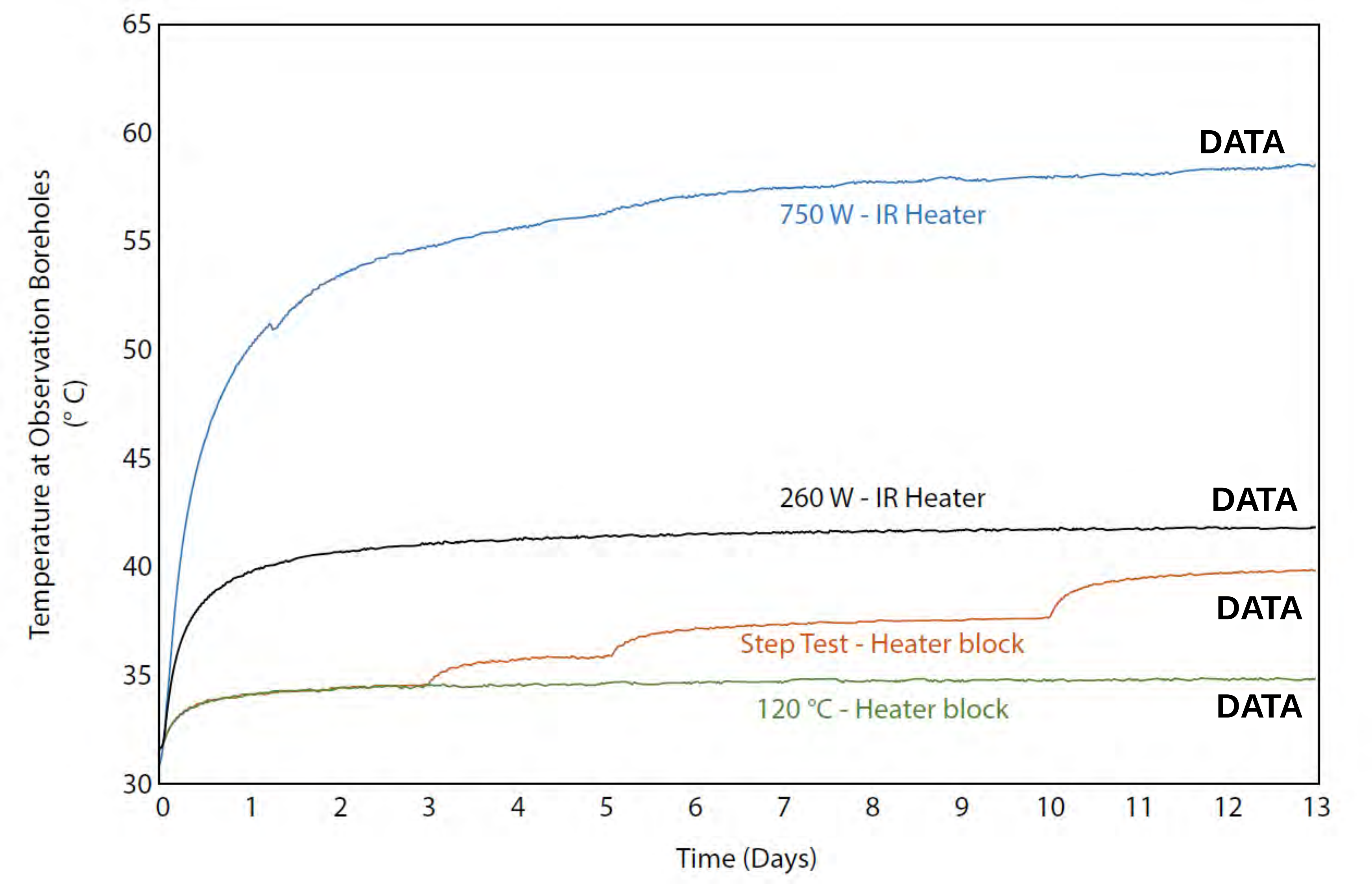
Final IR heater 750W



Temperature contours °C (@ heater midplane)

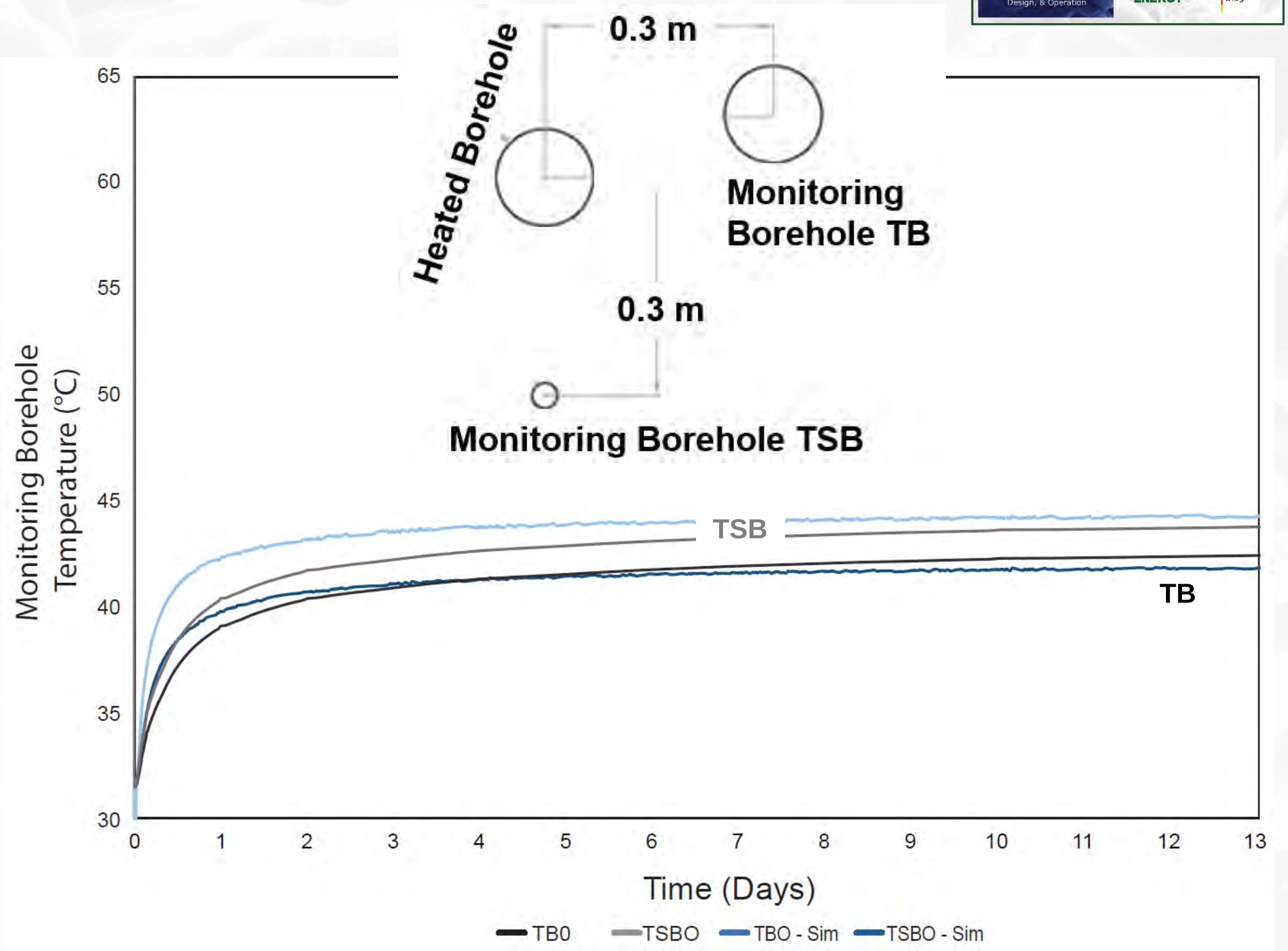
Color bar axis skewed to increase contrast in temperature difference

Heater Field Performance



Thermal data vs Simulation 260W

260 W Infrared Heater

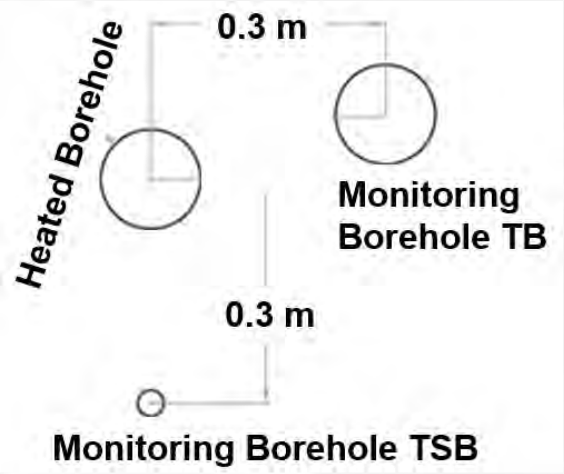


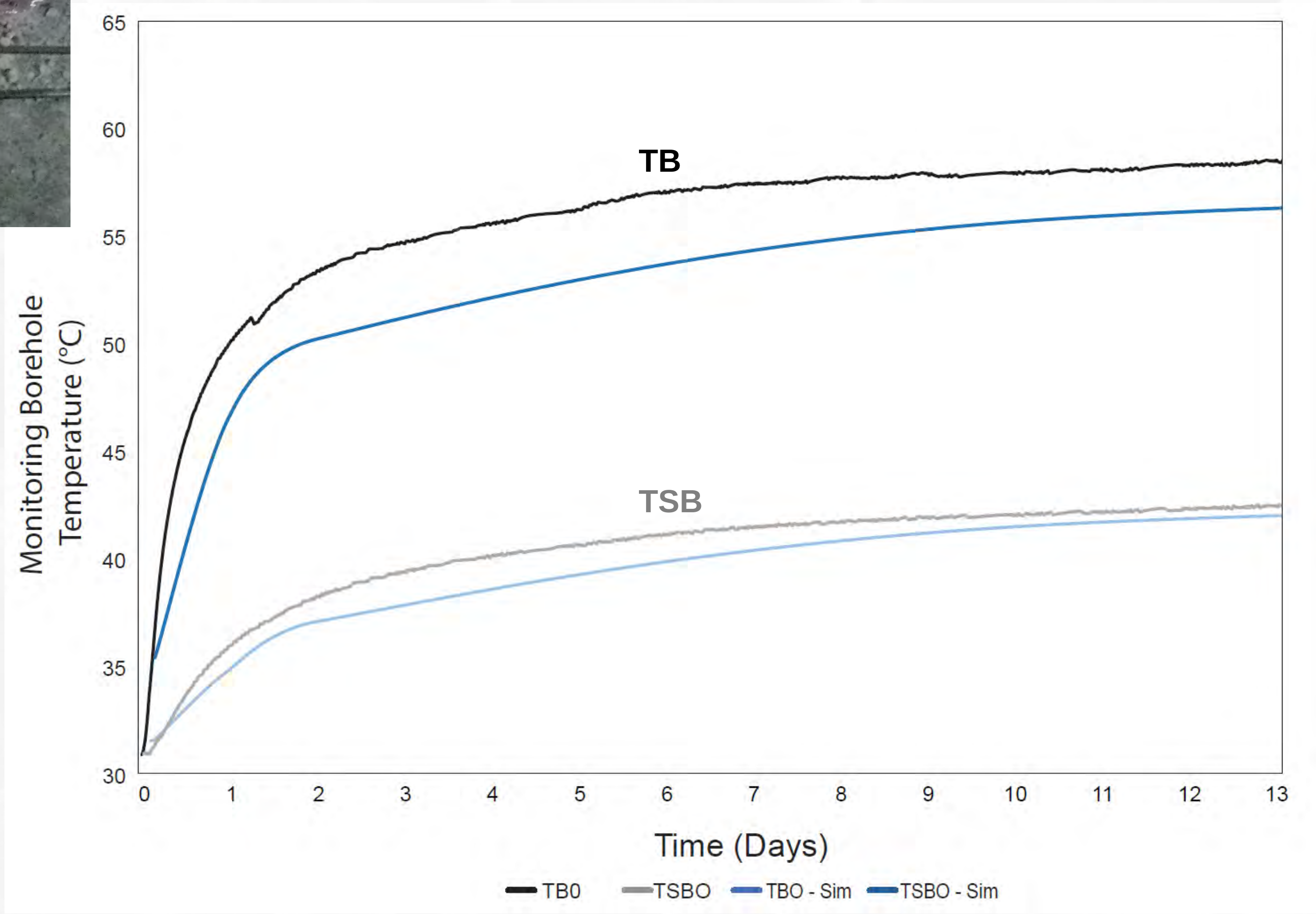
DATA SIMULATIOIN

Thermal data vs Simulation 750W

Heater shifted deeper into the borehole

TSB is farther from the heater than TB



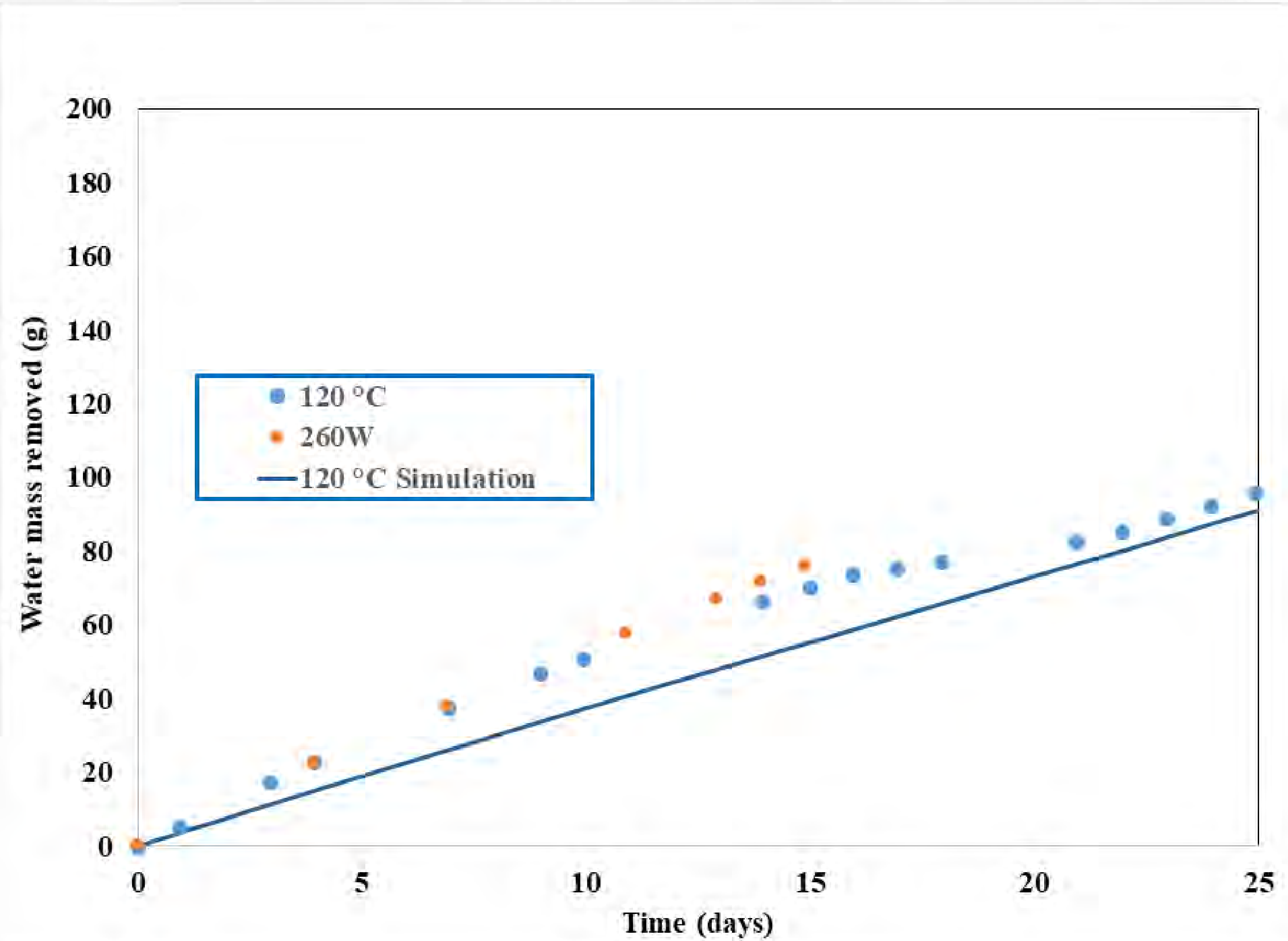


Experimental water removal

- Dry nitrogen flow behind the packer across the heater
- Evaporative water removal
- Water mass measured by
  - Drierite mass change
  - Humidity x flow rate
  - Both gave nearly identical results

Water removal data vs simulation

FEHM 3-D Shakedown 10x10x10m mesh



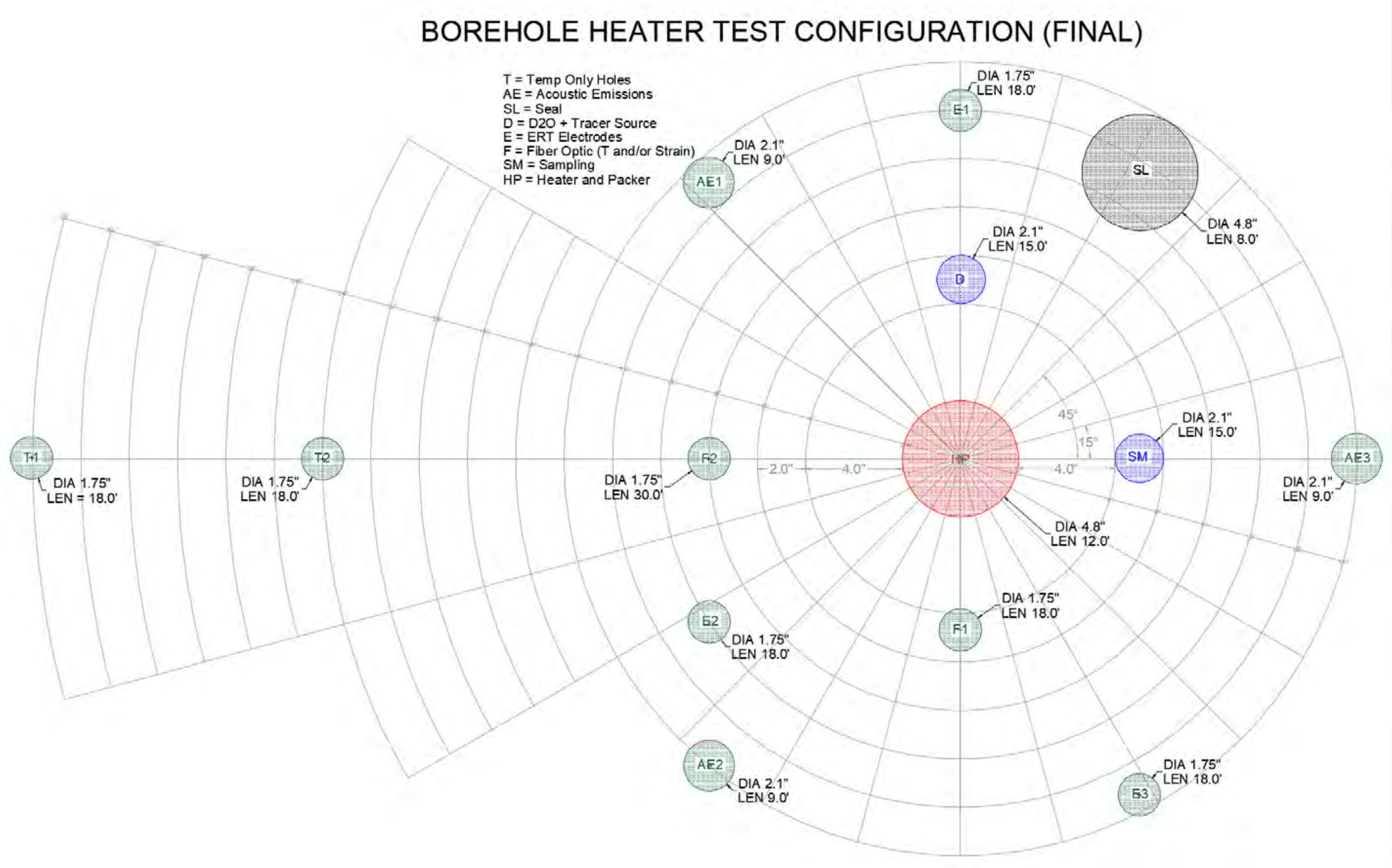
FEHM relative humidity boundary condition on incoming gas

Gas exiting the simulation carries water in the vapor phase

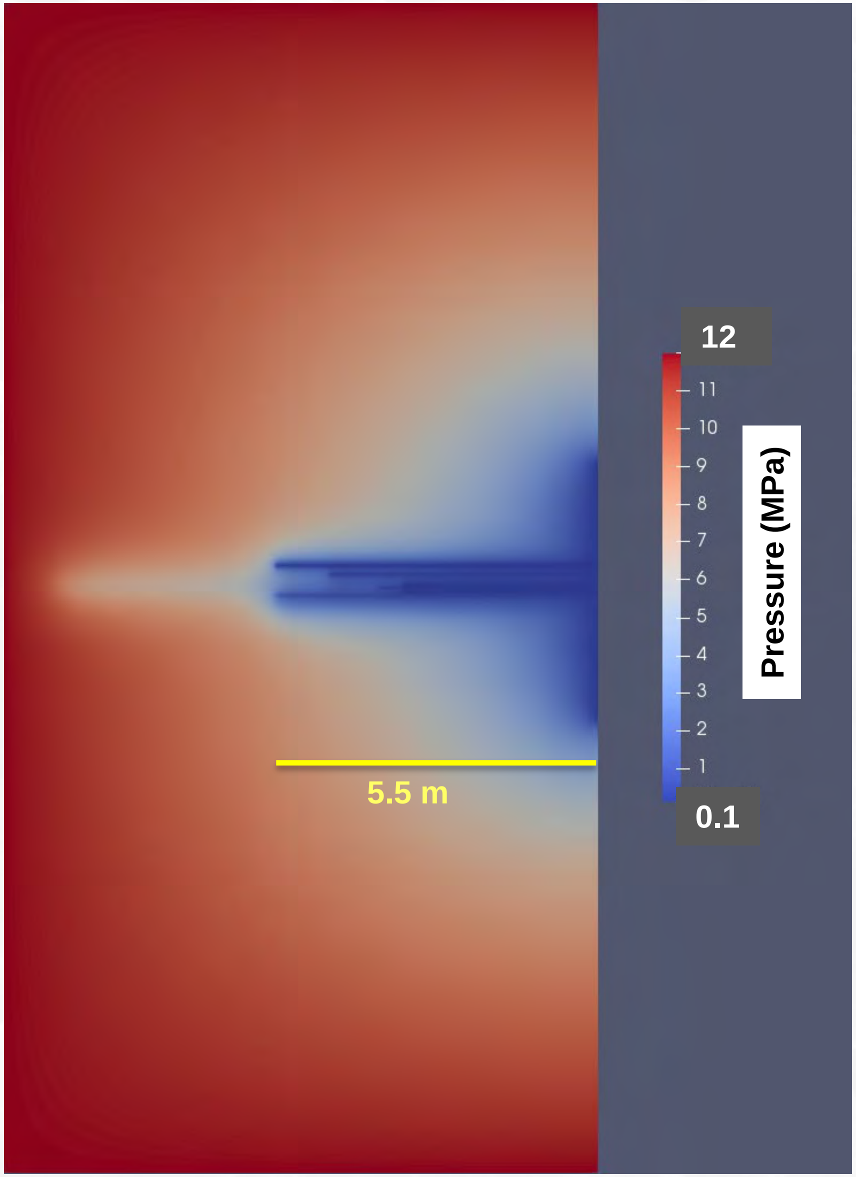
Background permeability 1e-21 m^2

<u>pressure equilibration</u>
30 years drift
5 years borehole

BATS borehole pattern



BATS pressure prediction

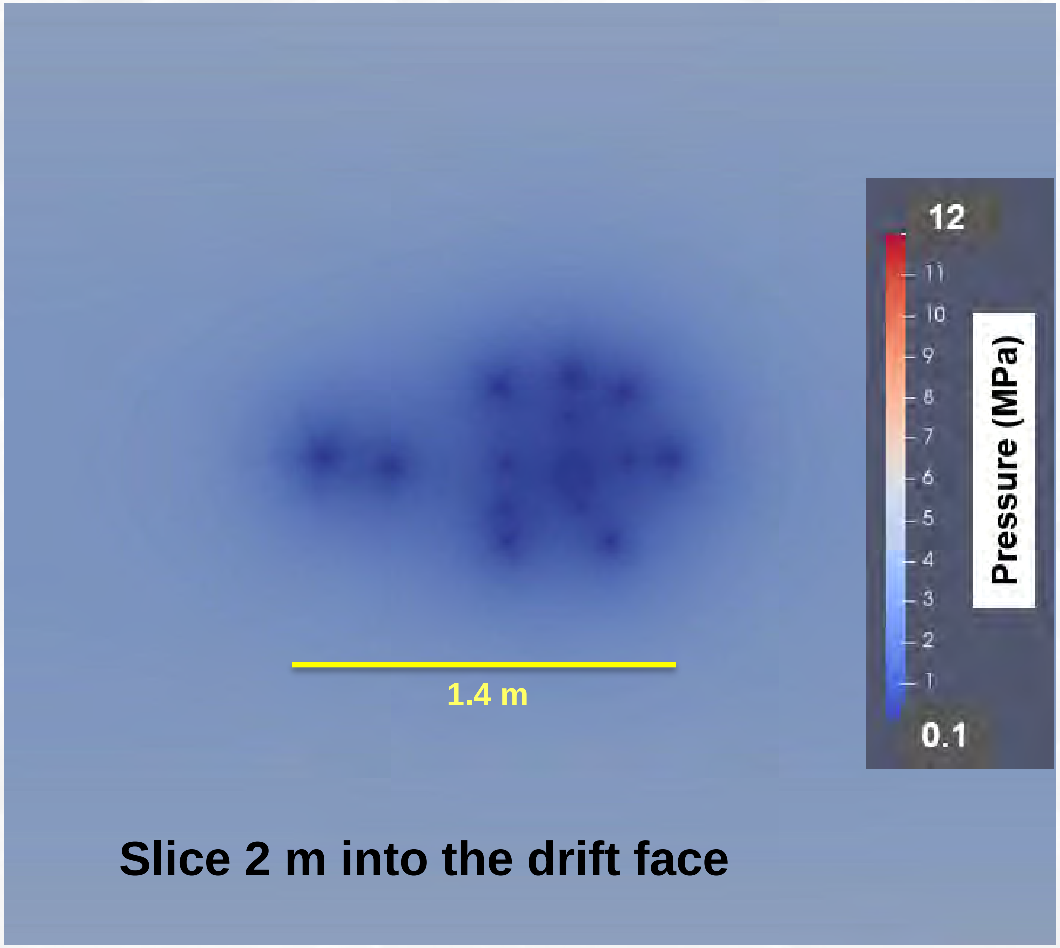


FEHM
3-D
Boreholes approximate

7 years of open drift

5 days of open boreholes

BATS pressure prediction

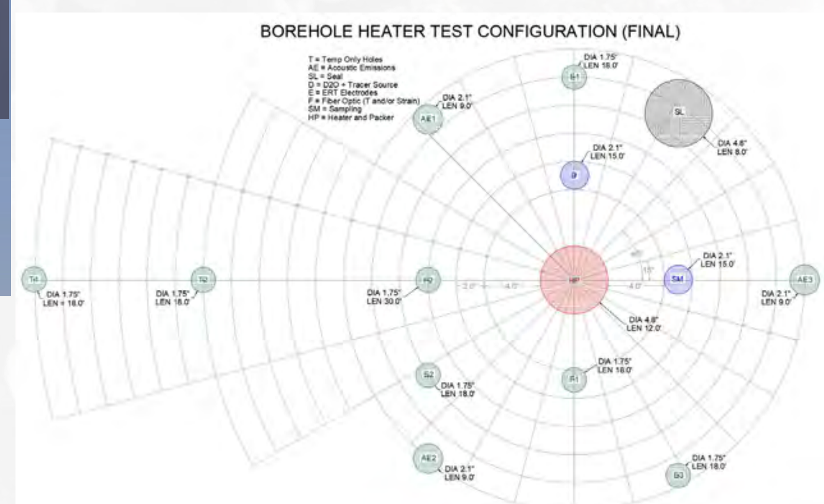


Slice 2 m into the drift face

FEHM
3-D
Boreholes approximate

7 years of open drift

5 days of open boreholes

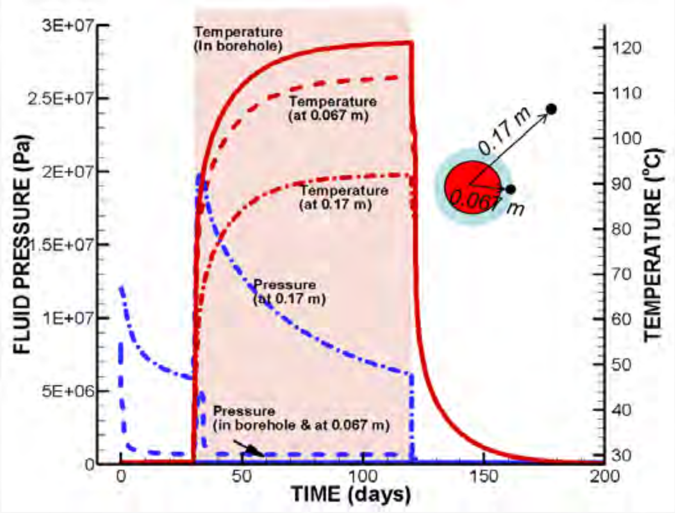


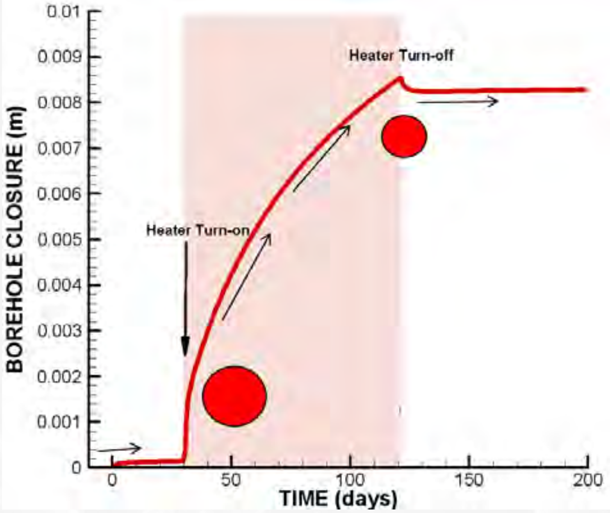
BATS: THM Model

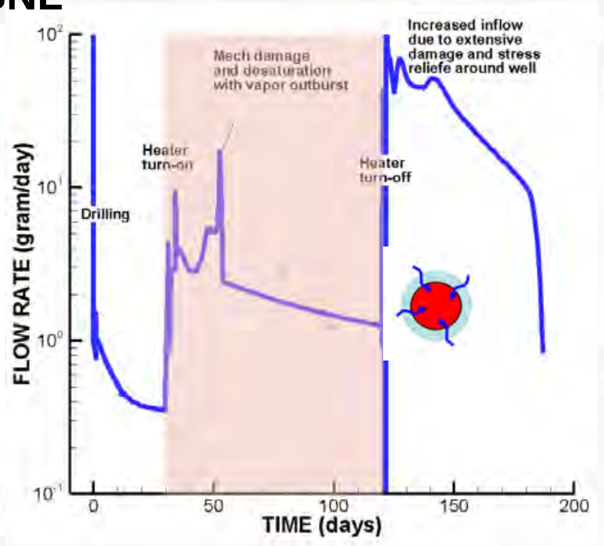
TOUGH-FLAC Prediction of THM behavior

- The constitutive THM model (Lux-Wolters) was developed from a large number of laboratory experiments in domal salt (Germany)
- Parameters for bedded salt more uncertain
- WIPP heater test will provide in situ data for improving confidence in heat-driven salt convergence and brine release

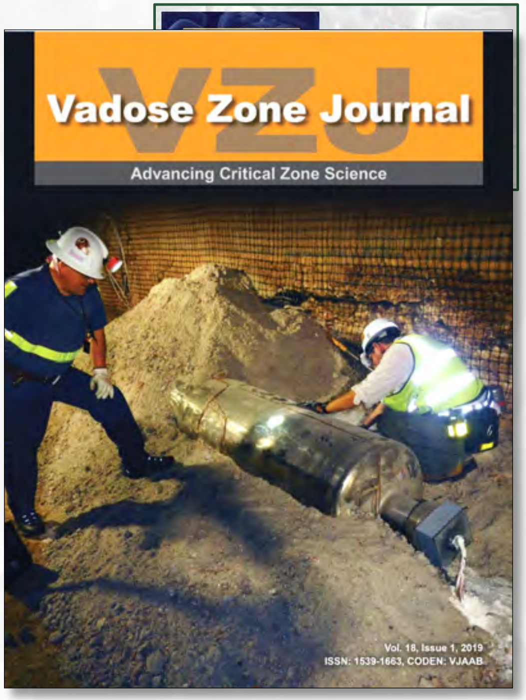
Simulations by Jonny Rutqvist, LBNL





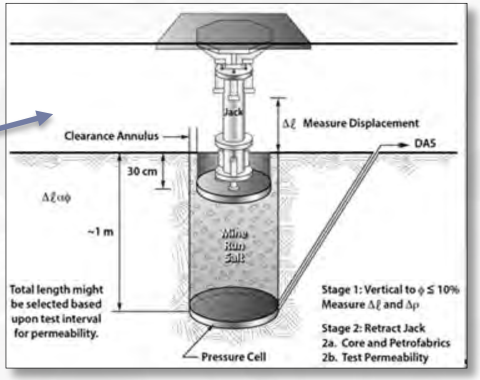


Salt Disposal R&D "Five-Year Plan"

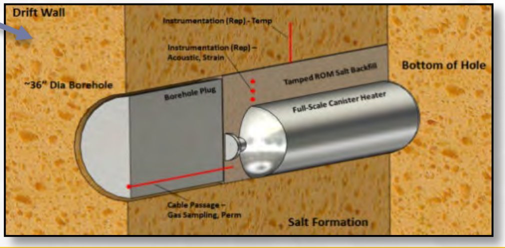


- **WIPP Borehole Heater Test**
  - FY19 execution (~120 ℃ & unheated)
  - Possible follow-on tests at higher temp

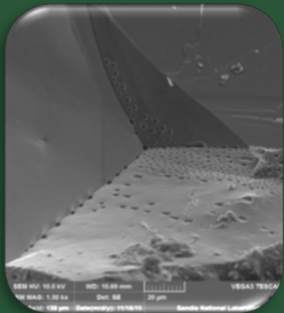
- **Possible Follow-on Tests**
  - Further borehole test configurations
  - Moving towards larger-scale tests
  - Intermediate-scale testing
    1. Large-scale granular salt reconsolidation
    2. Single-canister thermal test

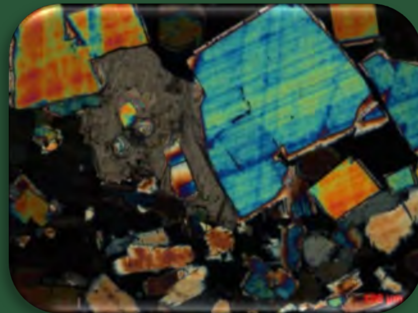


- **Laboratory / Modeling Investigations**
  - Investigations supporting field test design or data interpretation



Questions





How to correctly derive requirements for waste packages designed for SF and HLW - The R&D project KoBrA -

Sandia National Laboratories
BGE TEC
PTKA Project Management Agency Karlsruhe
RESPEC
SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY
U.S. DEPARTMENT OF ENERGY
Federal Ministry for Economic Affairs and Energy

Wilhelm Bollingerfehr, Sabine Prignitz , Ansgar Wunderlich
BGE TECHNOLOGY GmbH

Holger Völzke, Christian Herold, Teresa Orellana,
BAM

Rapid City, SD, United States

May 28-30, 2019

Contents

- Context/Motivation
- Waste Data
- The R&D-Project KoBrA
    - Objectives
    - Program of Work
    - Selected Approach
    - First Results
- Summary Outlook

Context

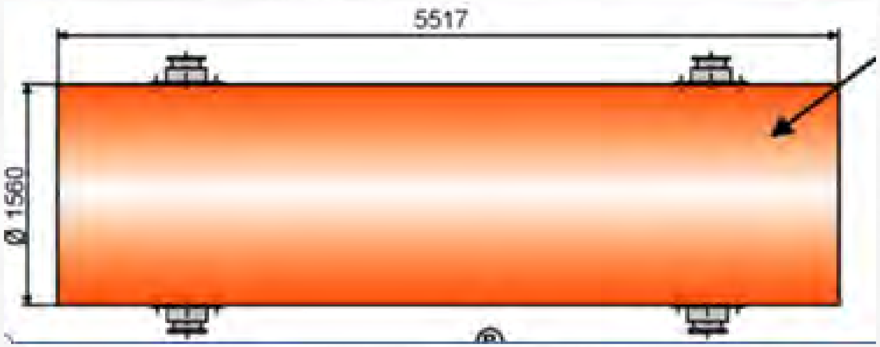
According to the new German Site Selection Act:

- repository systems for three host rock formations (rocksalt, claystone and crystalline rock) to be considered
- waste package considered as a pivotal barrier of the entire repository system (in particular with regard to retrievability/recovery)

Waste Packages:

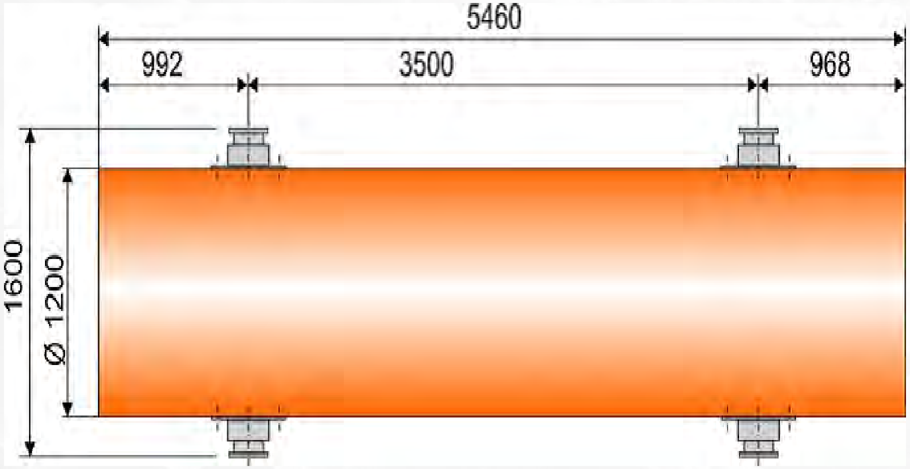
- provide the boundary conditions for the design of the transport- and emplacement technique in a repository
- provide a basis for the proof of the operational safety and/or the long-term safety

Motivation

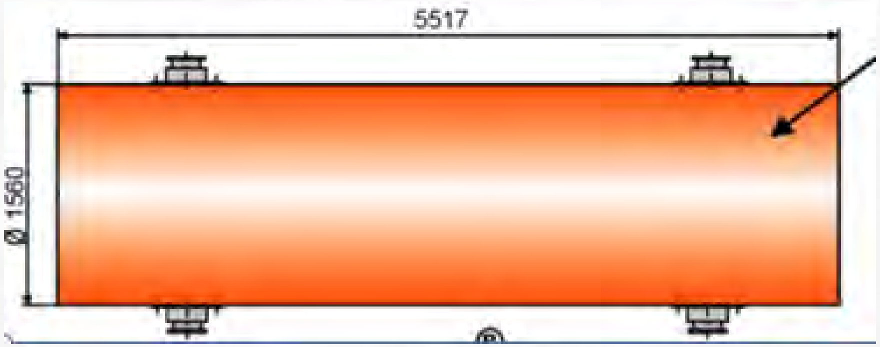


POLLUX®-10
filled with fuel rods of
10 disassembled
DWR fuel elements

POLLUX®-3
filled with fuel rods of
3 disassembled
DWR fuel elements



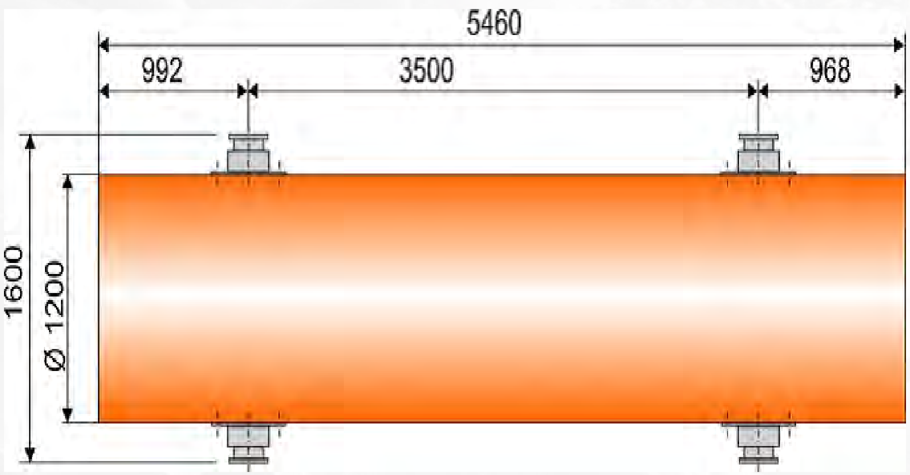
Motivation



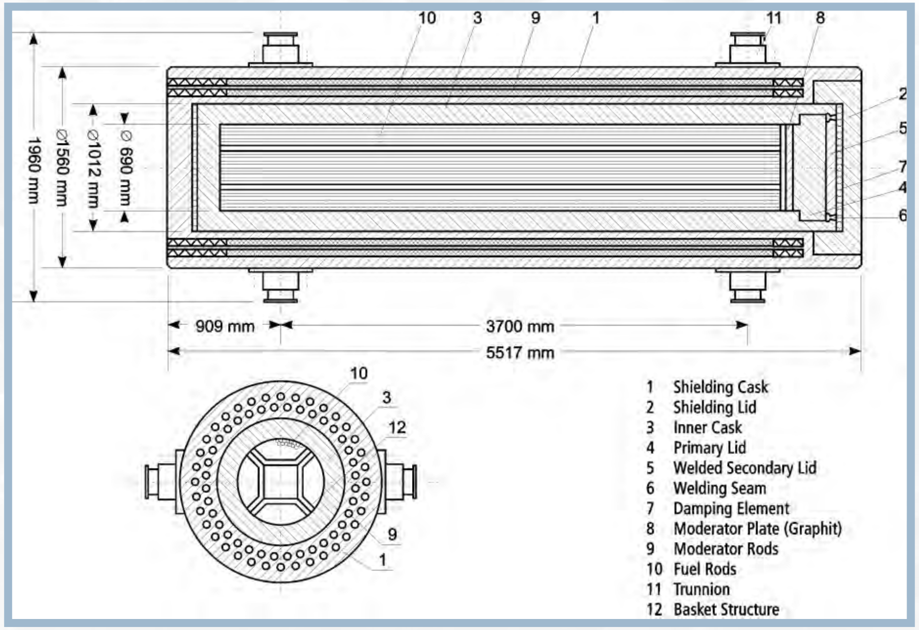
POLLUX®-10
filled with fuel rods of
10 disassembled
DWR fuel elements

What is the main difference between these two container sketches?

POLLUX®-3
filled with fuel rods of
3 disassembled
DWR fuel elements



Motivation



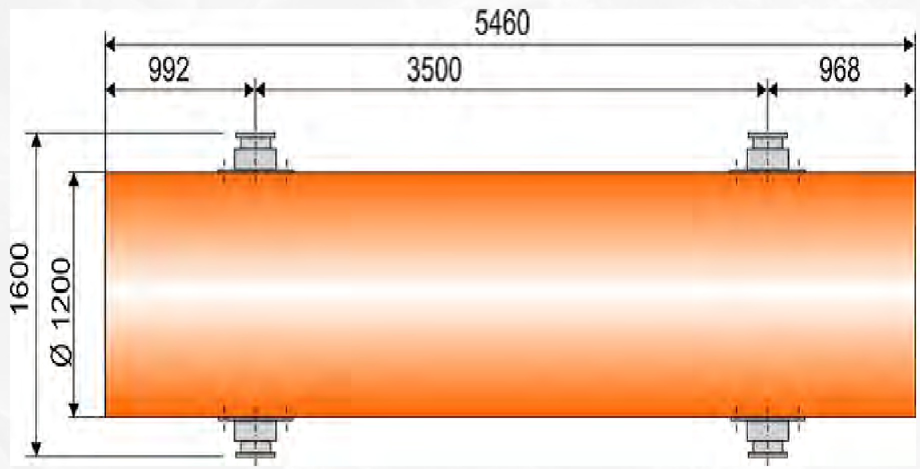
POLLUX® 10

- real existing waste package (prototype),
- manufactured on the basis of detailed calculations and planning

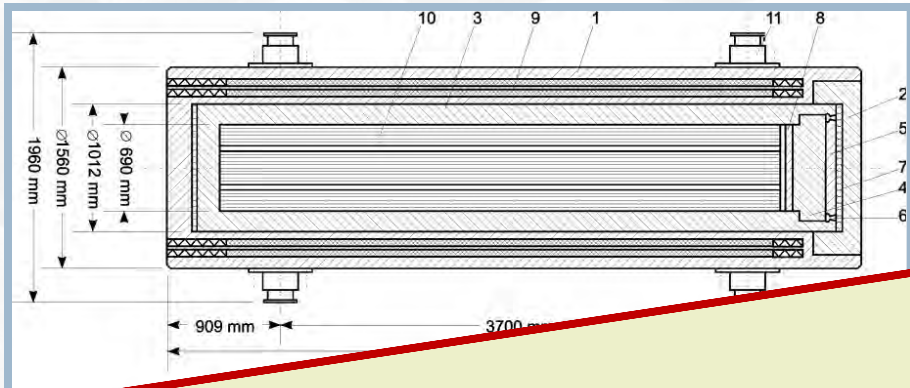
source: GNS

POLLUX® 3

- idea of a waste package without any detailled planning
- adjusted for a repository concept in claystone



Motivation



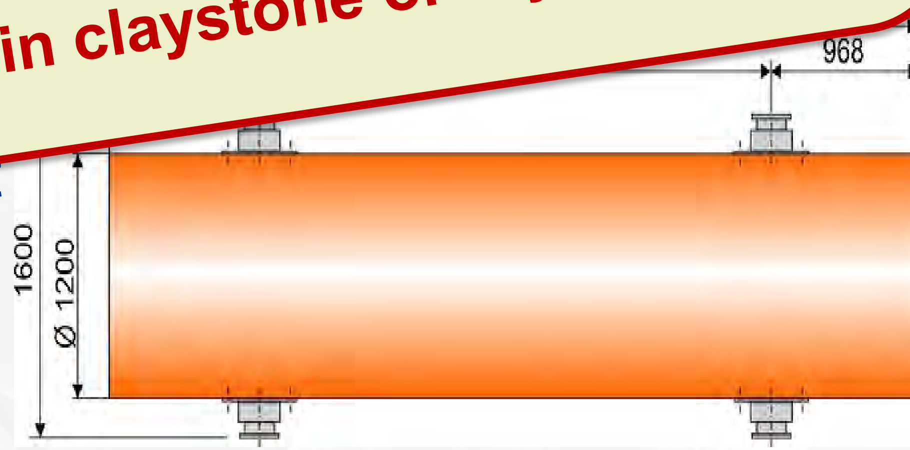
POLLUX® 10

- real existing container (pr...

we know details about one type of waste package (POLLUX®) for a repository in salt

but we know little about the waste packages necessary for a repository in claystone or crystalline rock

- ... without any detailled planning
- adjusted for a repository concept in claystone



Type and Amount of Waste

Time (a)	01.01.20 31.12.22	01.01.15 31.12.19	01.01.10 31.12.14	01.01.05 31.12.09	01.01.00 31.12.94	01.01.95 31.12.99	01.01.90 31.12.94	01.01.85 31.12.89
Type of Waste								
CSD-V					500	360	1.310	1.565
CSD-B					19	14	50	58
CSD-C					550	395	1.445	1.714
DWR UO2	1.220	1.580	2.150	3.200	2.550	1.600	150	
DWR MOX	60	110	160	700	450	50		
SWR UO2	780	1.730	2.190	5.450	3.550	450	200	
SWR MOX	110		340	350	450			
WWER							5.050	

(source: VSG, NaPro)

summary of waste streams from 1985 until 2022*:

- reprocessing waste:
  number of coquilles (CSD-V, CSD-B und CSD-C)
- number of spent fuel elements

* year of shut down of the last three electricity producing nuclear reactors in Germany (Isar 2, Emsland und Neckarwestheim 2)

Assumptions

- waste package disposal: 2050 (Repository Commission)
- operating time: 20-30 years (Repository Commission)
- operating conditions (planning assumptions e.g.):
  - definition of waste package stream per waste category and disposal concept
  - transport and emplacement of waste packages in a continuous manner and constant duration
  - no parallel emplacement operations
- calculated interim storage time :
  - 57 years for PWR/BWR-SF-elements
  - 60 to 70 years for WWER-SF-elements
  - 50 to 60 years for reprocessing waste

R&D-Project KoBrA:

„Requirements and concepts for waste packages for the disposal of heat generating radioactive waste and spent nuclear fuel in rock salt, claystone and crystalline rock“

(„Anforderungen und ***Ko****nzepte für* ***B****ehälter zur Endlagerung von Wärme entwickelnden* ***r****adioaktiven* ***A****bfällen und ausgedienten Brennelementen in Steinsalz, Tonstein und Kristallingestein“)*

project partners:

- BAM (a senior scientific and technical federal institute with responsibility to the Federal Ministry for Economic Affairs and Energy),Berlin and
- BGE TECHNOLOGY GmbH, Peine (coordinator)

start in summer 2017, duration 30 months

Main Objectives

- derivation of requirements for waste packages
- development of respective options/ideas for implementation of generic waste packages
- assessment of consequences of respective design decisions on repository layout

Work Programme

- survey of national and international existing requirements and concepts for waste packages and compilation of safety relevant waste package features
- identification of waste package relevant boundary conditions and load values from the host rock
- derivation and compilation of requirements for waste packages resulting from:
  - regulations
  - site specific geology
  - repository design and repository operation
  - long-term safety aspects
- development of ideas and concepts for waste package designs

Work Programme

- survey of national and international existing requirements and concepts for waste packages and compilation of safety relevant waste package features
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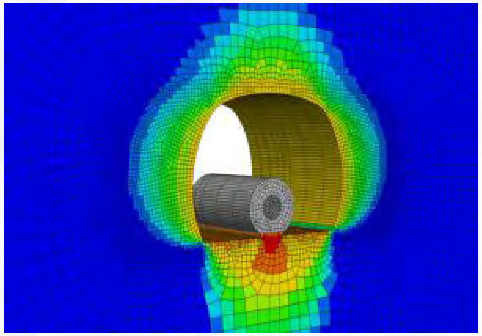
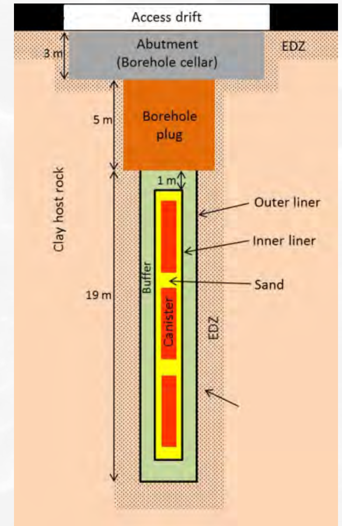
- **derivation and compilation of requirements for waste packages resulting from:**
  - **regulations**
  - **site specific geology**
  - **repository design and repository operation**
  - **long-term safety aspects**
- development of ideas and concepts for waste package designs

Boundary Conditions

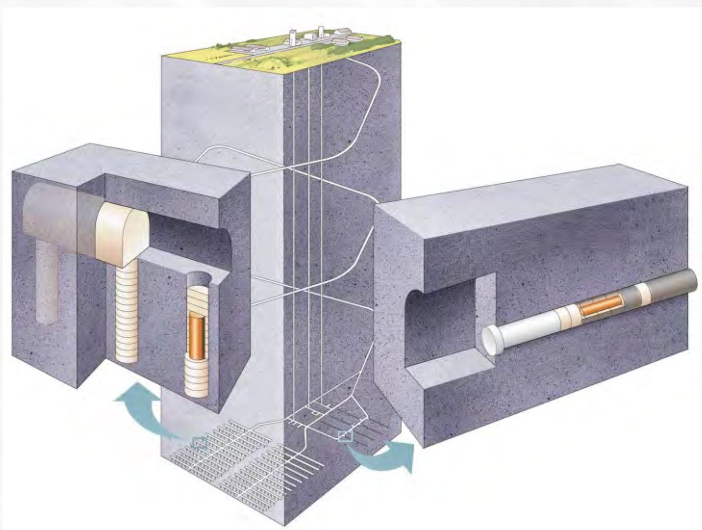


disposal concept for a repository in salt



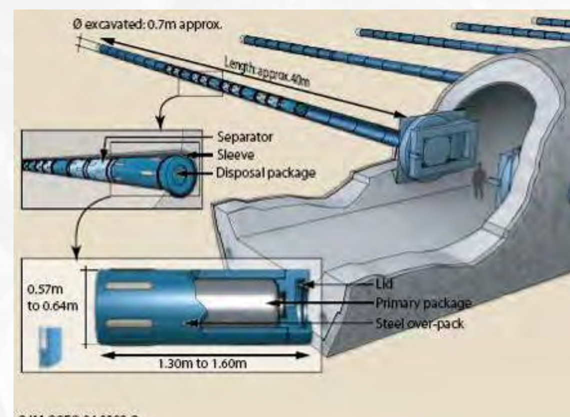
German Concept
AnSicht

disposal concepts for a repository in claystone



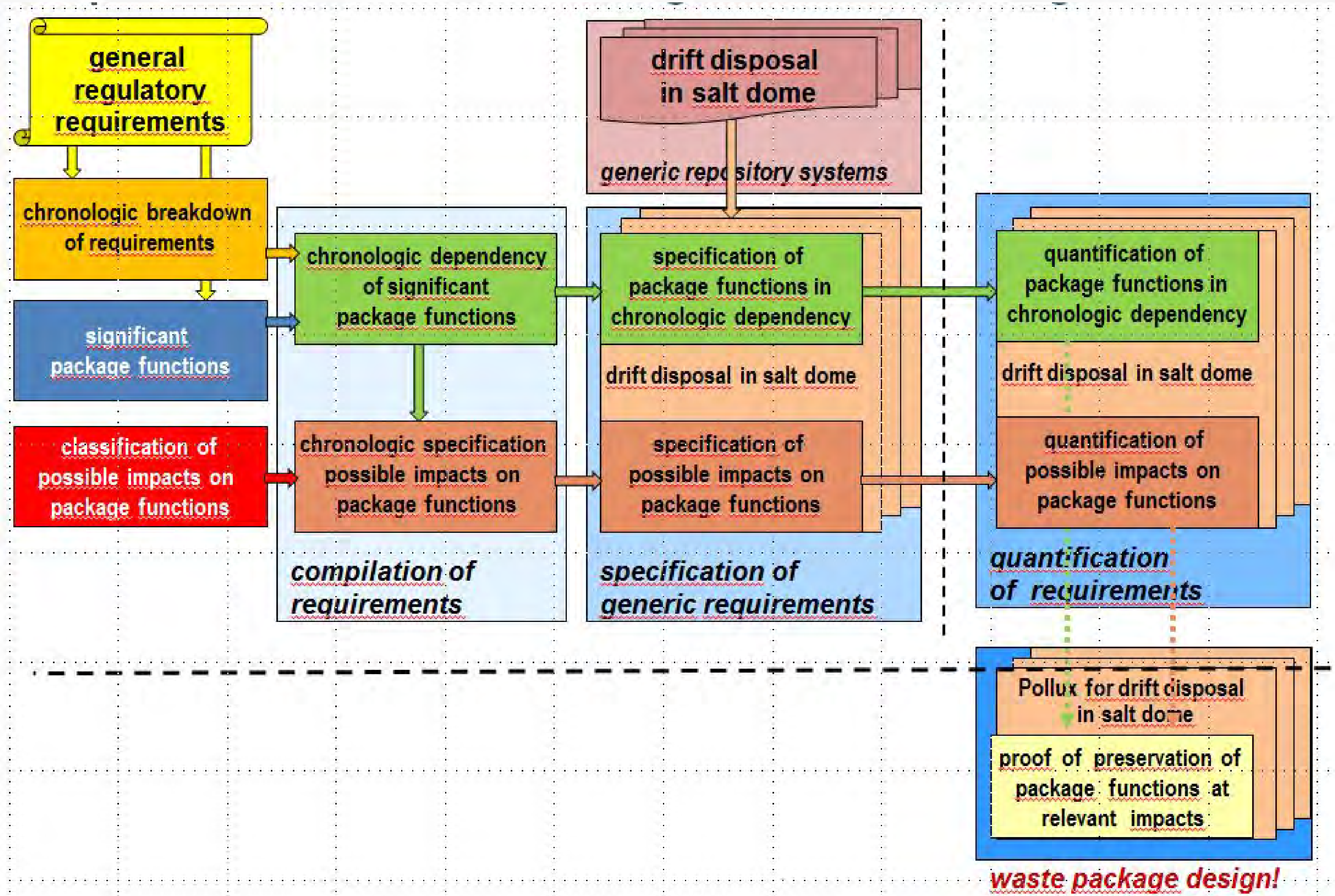
Source: SKB

disposal concept for a repository in crystalline rock



Source: Andra

Selected Top-Down Approach



Qualitative Waste Package Functions example: drift disposal (repository in salt)

function	repository lifetime periods			
	emplacement	retrievability	recovery	late post operational period
containment of radioactive waste	to be ensured unrestricted		to be ensured for the probable evolution	
shielding (ionizing radiation)	to be ensured for repository operation		to be ensured for the probable evolution	
		avoidance of radiologically or radiolytically fostered damage of barriers		
exclusion of criticality	for dry conditions	even in case of fluid intrusion		
limitation of temperature	to be ensured for repository operation		to be ensured for the probable evolution	
		ensure avoidance of thermal damage of the barriers and the host rock		
limitation of gas production			to ensure in case of fluid intrusion avoidance of undue high gas pressures	
operability	to be ensured unrestricted		to be ensured for the probable evolution	

Quantitative Waste Package Functions example: drift disposal (repository in salt)

<table>
<tr><th rowspan="2">function</th><th colspan="4">repository lifetime periods</th></tr>
<tr><th>emplacement</th><th>retrievability</th><th>recovery</th><th>late post operational period</th></tr>
<tr><td>containment of radioactive waste</td><td colspan="2">gastight containment, leakagerate of 10-7 Pa*m3/s ???
or limitation of releases (inhalation rate pers.< 0,5 mSv/a?</td><td>dito</td><td></td></tr>
<tr><td rowspan="2">shielding (ionizing radiation)</td><td colspan="2">limitation of local dose rate package surface to <2 mSv/h,
in 1m distance to 0,1 mSv/h</td><td>dito</td><td></td></tr>
<tr><td></td><td colspan="3">limit of rock salt damage by radiolysis:
dose rate 104 Gy/h, corresponds to 104 Sv/h</td></tr>
<tr><td>exclusion of criticality</td><td>for dry conditions: keff< 0,95</td><td colspan="3">in case of fluid intrusion: : keff< 0,95</td></tr>
<tr><td rowspan="2">limitation of temperature</td><td colspan="2">50°C at all exposed surfaces,
390/410°C for spent fuel elements of PWR/BWR in waste package at storage conditions at surface;
surface temperature for handling processes ≤85°C</td><td>dito</td><td></td></tr>
<tr><td></td><td colspan="3">100°C for host rock (StandAG; (>100°C to be confirmed by R&D)</td></tr>
<tr><td>limitation of gas production</td><td></td><td></td><td colspan="2">system: inner gas pressure on barriers less than hydrostatic brine pressure on shaft seal</td></tr>
<tr><td>operability</td><td colspan="2">according to impacts during handling processes</td><td>dito</td><td></td></tr>
</table>

Quantitative Waste Package Functions example: drift disposal (repository in salt)

function	repository lifetime periods			
	emplacement	retrievability	recovery	late post operational period
containment of radioactive waste	gastight containment, leakagerate of 10-7 Pa*m3/s ??? or limitation of releases (inhalation rate pers.< 0,5 mSv/a)?		**to be decided**	
shielding (ionizing radiation)	limitation of local dose rate package surface to <2 mSv/h, in 1m distance to 0,1 mSv/h		dito	
		limit of rock salt damage by radiolysis: dose rate 104 Gy/h, correspond		
exclusion of criticality	for dry conditions: keff< 0,95			
		°C for host rock (StandAG; (>100°C to be confirmed by R&D)		
production			system: inner gas pressure on barriers less than hydrostatic brine pressure on shaft seal	
operability	according to impacts during handling processes		dito	

done for all repository concepts considered

Impacts on Waste Package Functions example: drift disposal (repository in salt)

function	containment				shielding				exclusion of criticality				tmperture limitation				limitation gas production				operability			
period / impact	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p
static, mechanical loads	a	a	A	-	a	a	a	-	a	a	a	a	-	-	-	-	-	-	-	-	a	a	A	-
dynamic, mechanical loads	a	a	A	-	a	a	a	-	a	a	a	a	-	-	-	-	-	-	-	-	a	a	A	-
thermal impacts	a	a	a	-	-	-	-	-	-	-	-	-	A	A	A	A	a	a	a	a	a	a	a	-
brittleness by radiation	a	a	A	-	a	a	a	a	-	-	-	-	-	-	-	-	-	-	-	-	a	a	A	-
brittleness by hydrogen	-	-	A	-	-	-	a	a	-	-	-	-	-	-	-	-	-	-	-	-	-	-	A	-
corrosion	-	-	A	-	-	-	A	A	-	-	a	a	-	-	A	A	-	-	A	A	-	-	A	-
degradation oforganica	-	-	-	-	-	a	A	A	-	-	-	-	-	-	-	-	-	a	A	A	-	a	a	-
microbial impacts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
unscheduled impacts	A	A	A	-	A	A	A	-	a	a	a	a	-	-	-	-	-	-	-	-	A	A	A	-

A – relevant for designing **a – relevant for designing , but covered by other functions or periods** **- covered by loading**

Impacts on Waste Package Functions example: drift disposal (repository in salt)

function	containment				shielding				exclusion of criticality				tmperture limitation				limitation gas production				operability			
period / impact	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p	emplacement	retrievability	recovery	late post oper.p
static, mechanical loads	a	a	A	-	a	a	a	-	a	a	a	a	-	-	-	-	-	-	-	-	a	a	A	-
dynamic, mechanical loads	a	a	A	-	a	a	a	-	a	a	a	a	-	-	-	-	-	-	-	-	a	a	A	-
thermal impacts	a	a	a	-	-	-	-	-	-	-	-	-	A	A	A	A	a	a	a	a	a	a	a	-
brittleness by radiation	a	a	A	-	a	a	a	a	-	-	-	-	-	-	-	-	-	-	-	-	a	a	A	-
brittleness by hydrogen	-	-	A	-	-	-	a	a	-	-	-	-	-	-	-	-	-	-	-	-	-	-	A	-
corrosion	-	-	A	-	-	-	A	A	-	-	a	a	-	-	A	A	-	-	A	A	-	-	A	-
degradation oforganica	-	-	-	-	-	a	A	A	-	-	-	-	-	-	-	-	-	a	A	A	-	a	a	-
microbial impacts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
unscheduled impacts	A	A	A	-	A	A	A	-	a	a	a	a	-	-	-	-	-	-	-	-	A	A	A	-

A – relevant for designing **a – relevant for designing , but covered by other functions or periods** **- covered by loading**

Summary and Outlook

- international status of waste package design requirements and examples of waste packages compiled
- boundary conditions like type and amount of waste as well as the conditions and potential impacts coming from the geological environment and the operation of the repository are summarized
- methodological approach developed to derive waste package requirements for a repository for three different host rocks
- drafting of ideas for waste packages complying with the derived requirements: ongoing
- deriving recommendations for the implementation of the methodological approach: ongoing

Acknowledgements

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

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BGE TECHNOLOGY and BAM are sincerely thankful for the support.

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PTKA
Projektträger Karlsruhe
Karlsruher Institut für Technologie

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

Thank you for your attention!

The National Academies of SCIENCES ENGINEERING MEDICINE

Nuclear and Radiation Studies Board

Disposal of Surplus Plutonium at the Waste Isolation Pilot Plant: *Interim Report*

(adapted from NAS Public Release Presentation of November 2018)

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International Atomic Energy Agency

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Statement of Task

Evaluate the general viability of the U.S. Department of Energy's (DOE's) conceptual plans for disposing of surplus plutonium in the Waste Isolation Pilot Plant (WIPP) to support U.S. commitments under the Plutonium Management and Disposition Agreement, identify gaps, and recommend actions that could be taken by DOE and others to address those gaps.

This evaluation will specifically address the following issues:

1. DOE's plans to ship, receive, and emplace surplus plutonium in WIPP.

2. DOE's understanding of the impacts of these plans on the following:

a) Transportation safety, security, and regulatory compliance.

b) Current and future WIPP operations, including the need to construct additional waste disposal panels and/or operate WIPP beyond its currently planned closure date.

c) Disposal of other potential waste streams in WIPP, for example other plutonium wastes, Greater-than-Class-C-like wastes, and tank wastes.

d) WIPP pre- and post-closure safety and performance.

e) Compliance with WIPP waste acceptance criteria; Environmental Protection Agency disposal regulations; and The Land Withdrawal Act, National Environmental Policy Act, and Resource Conservation and Recovery Act requirements.

The Academies may examine policy options but should not make policy recommendations that require nontechnical value judgments.

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The PMDA Challenge

- The Plutonium Management and Disposition Agreement (PMDA), which was signed by the United States and the Russian Federation in 2000 and amended in 2010, commits both countries to disposition 34 MT of surplus plutonium by incorporating into mixed oxide (MOX) fuel followed by irradiation.
- The DOE started building the MOX plant at the Savannah River Site in 2007 even though its own analyses concluded it would be faster and cheaper to mix the plutonium with high-level radioactive waste from past weapons production and store it permanently in an underground repository (Yucca).
- In 2014, the Obama administration proposed to stop construction of the MOX facility and instead use a “dilute and dispose process” to disposition the surplus plutonium.
- In 2018, the Trump administration announced plans to cancel the MOX plant in May 2018 and declared the dilute and dispose process as the program of record.

Dilute and Dispose

- Irradiated MOX spent fuel met the ‘spent fuel standard’.
  - a condition in which weapons plutonium has become roughly as difficult to acquire, process, and use in nuclear weapons as it would be to use plutonium in commercial spent fuel for this purpose. The rationale for the spent-fuel standard is, first, that the bulk, composition, and ionizing radiation field of spent fuel pose very appreciable barriers to the theft or diversion of this material and extraction of contained plutonium
- DOE-NNSA asserted that through chemical (dilution) and physical (repository emplacement) barriers the end state of the dilute and dispose process would meet the intent of the PMDA for preventing plutonium recovery and reuse.
  - The “**dilute**” portion of the dilute and dispose process entails the oxidization of surplus plutonium followed by dry blending with an adulterant to dilute the plutonium-239 content. Details of the adulterant composition and processing steps are classified.
  - The “**dispose**” portion of the plan involves packaging, characterizing, and transporting the blended material to WIPP for final emplacement.
- The dilute and dispose process is not currently a PMDA-approved method for dispositioning U.S. surplus plutonium.

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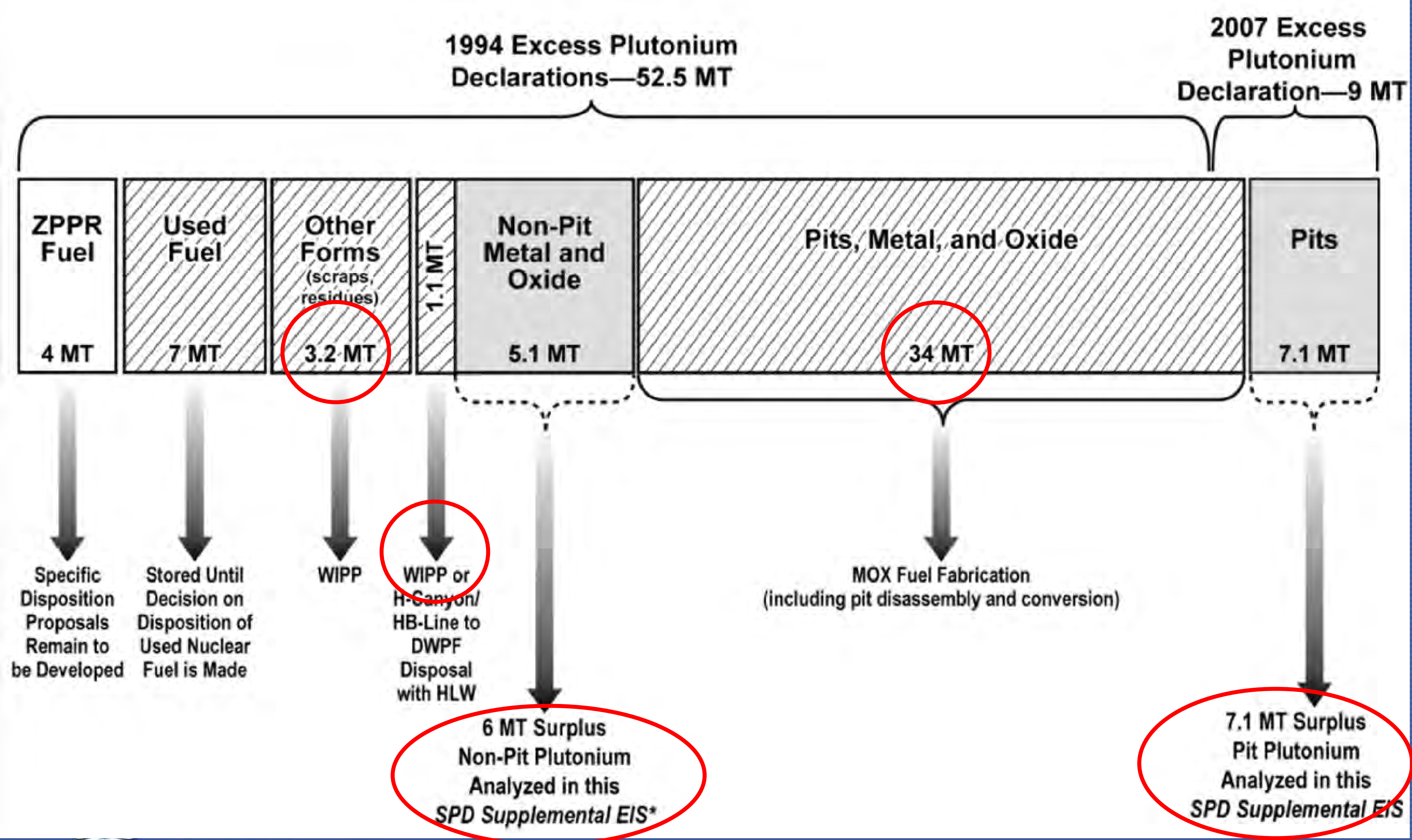
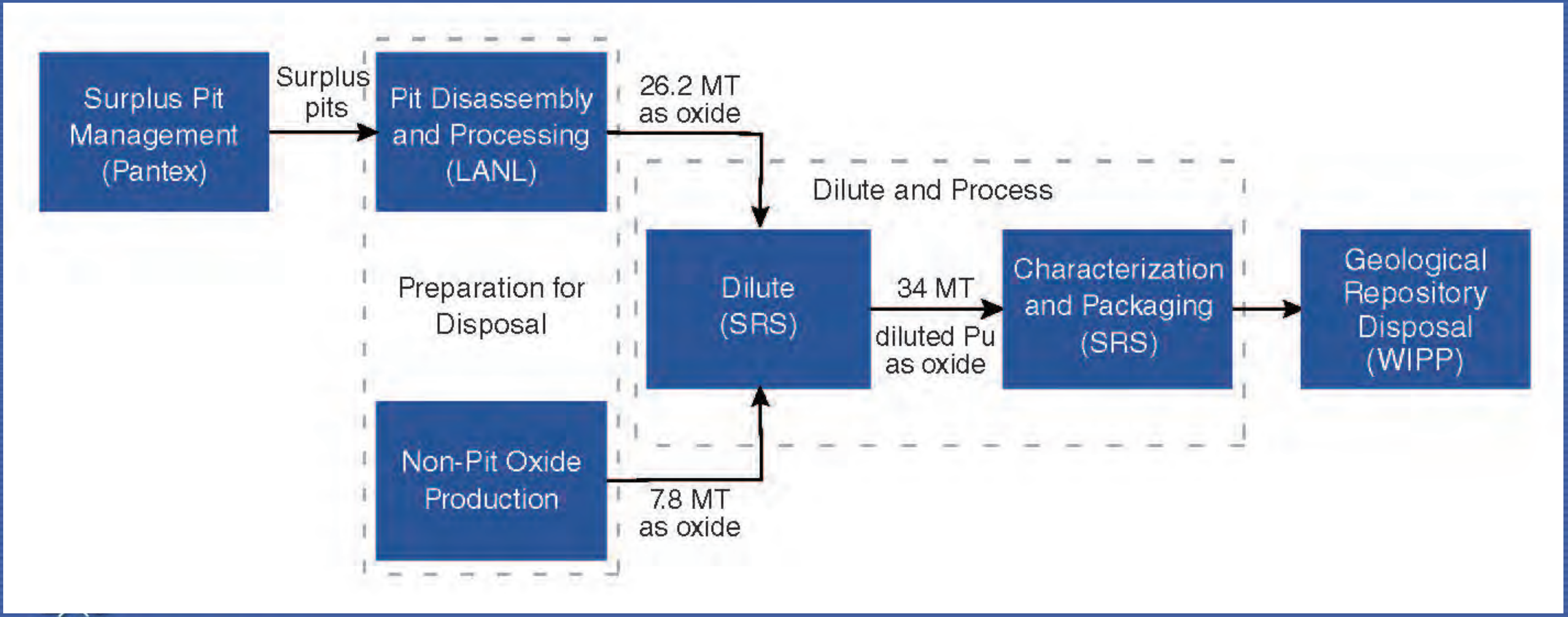
Surplus Pu Inventories



Dilute and Dispose

- The dilution process entails first the oxidization of surplus plutonium metal and
- Then the dry blending of the plutonium oxide with an adulterant to dilute the plutonium-239 content
- The blended material will be packaged to make it suitable for transport to and disposal in WIPP, a deep geologic repository located within a bedded salt formation near Carlsbad, New Mexico.



D&D Process Flow

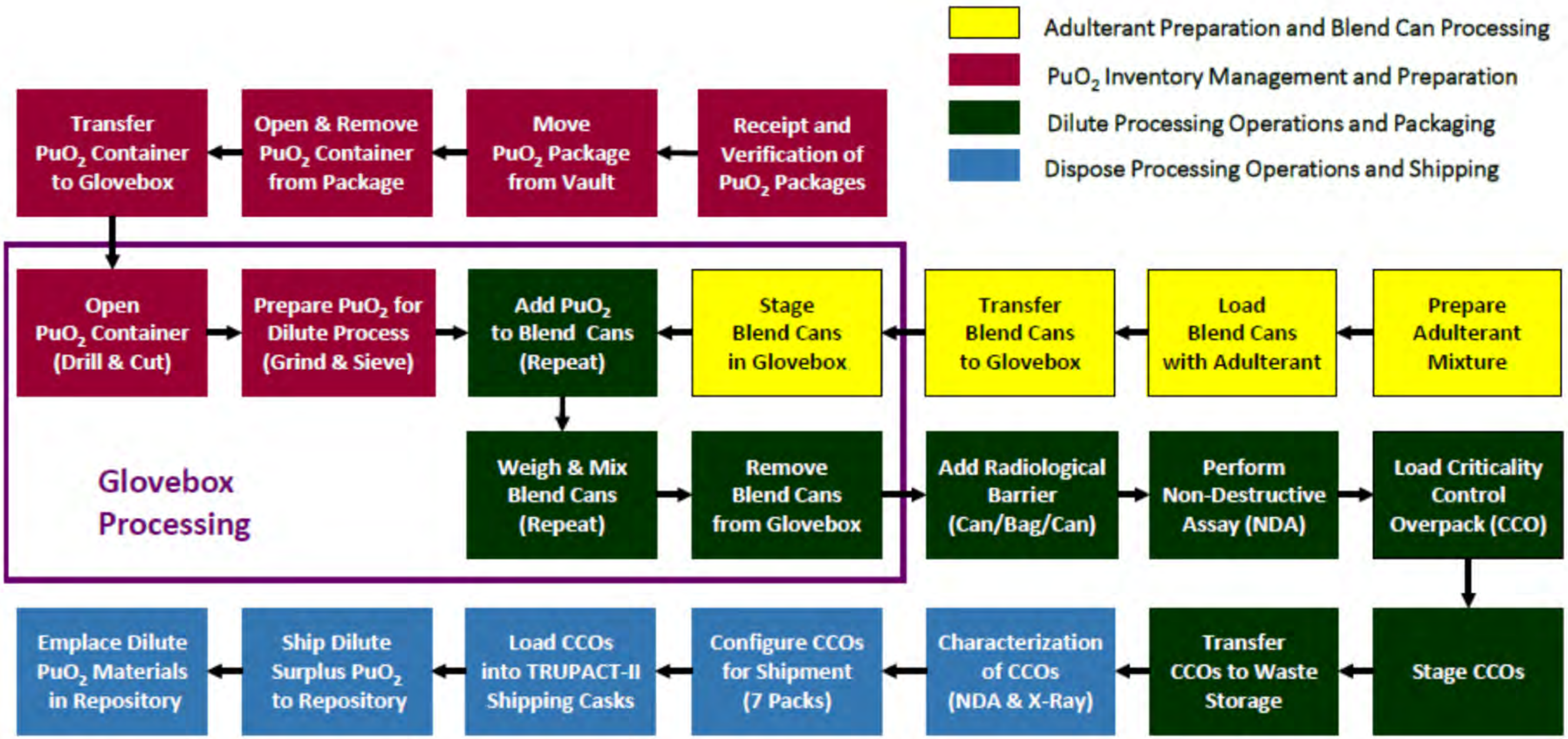
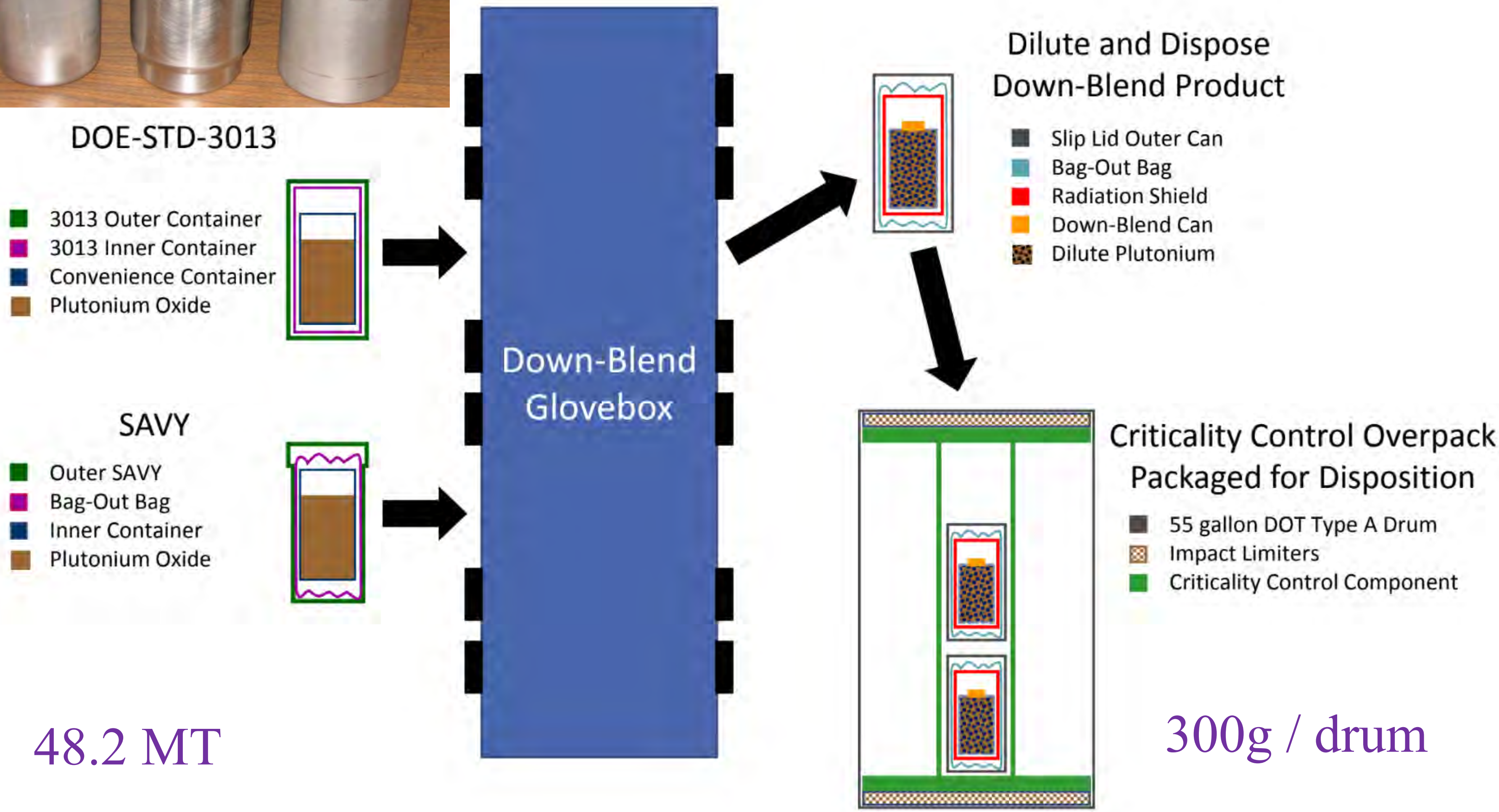


FIGURE 2-3a Block diagram of the "Dilute and Processing" and "Geological Repository Disposal" steps shown in Figure 2-2, beginning with receipt of the oxidized plutonium at the Savannah River Site (Receipt and Verification of the PuO_2 [plutonium oxide] Packages) and ending with emplacement in WIPP. As the final diluted product is prepared to be removed from the glovebox, no more than 150 fissile gram equivalents (FGE) of plutnoium-239 is placed inside an inner can, which is then placed inside a plastic bag, which is placed into another can ("Can/Bag/Can"). A cross section of the can/bag/can assembly is shown in Figure 2-3b. SOURCE: Image provided by the U.S. Department of Energy (McAlhany 2017).

Feedstock to Down-Blend Product



48.2 MT

300g / drum

Conceptual Plan Timeline

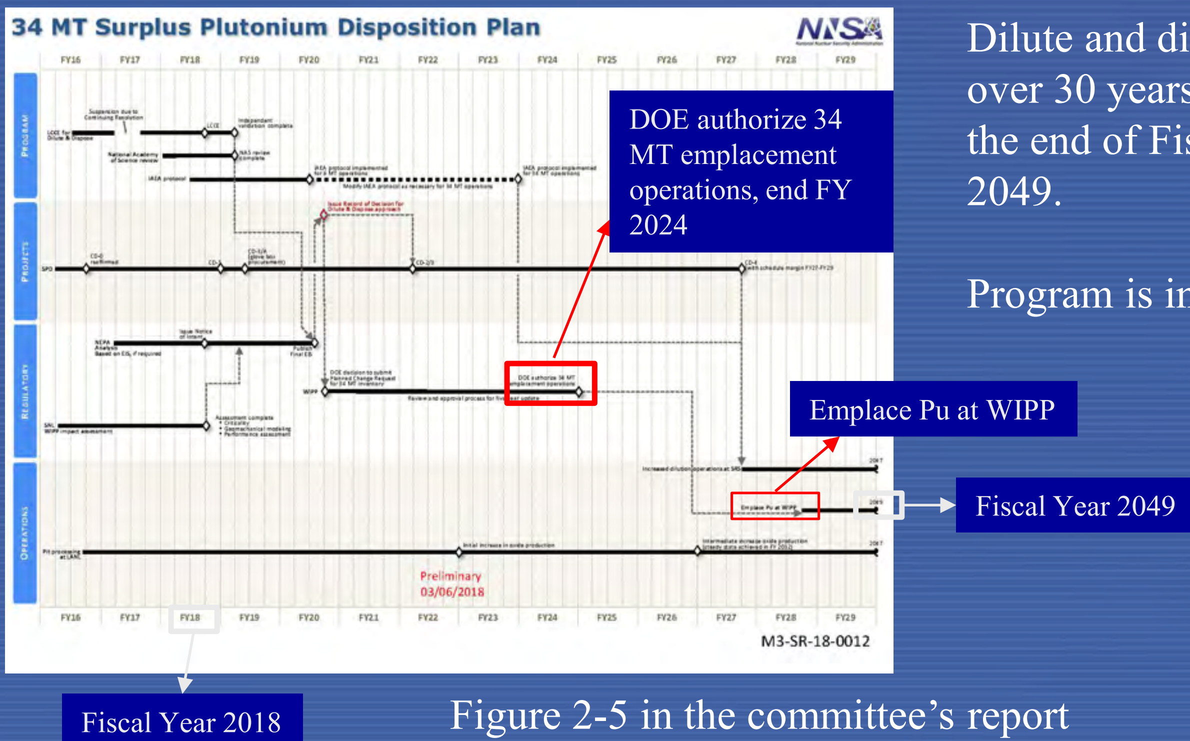


Figure 2-5 in the committee's report

Dilute and dispose program is expected to last over 30 years with emplacement beginning at the end of Fiscal Year 2024 and ending in 2049.

Program is in planning and design stages.

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Interim Report: Status

- Limited availability of publicly releasable data and information to the committee, expected to be released by end of 2018

- High-level review of conceptual plans:
  - Proposed process
  - Current capacity at WIPP
  - Requirements of the PMDA

- Specific tasks not yet addressed:
  - Transportation safety, security, and regulatory compliance
  - WIPP pre- and post-closure safety performance

Findings, Conclusions, Recommendations

- Advice provided as:
  - Findings - statements of fact based on gathered evidence,
  - Conclusions – judgments based on findings and/or evidence
  - Recommendations – proposed actions
- Total: Seven findings, two conclusions, four recommendations.
- Questions posed to DOE for additional evidence.

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Conclusion 1

- The dilute and dispose process has been demonstrated at a small scale by DOE-EM as it begins to process 6 MT of surplus plutonium, a quantity separate from the 34 MT associated with the Plutonium Management and Disposition Agreement (PMDA).

- The committee agrees with earlier assessments that the technical complexity of the dilute and dispose process is lower than that of the construction of a MOX fuel option. Due to lack of information, the committee makes no judgment in this interim report on the DOE's ability and the associated risks of scaling up the current infrastructure and processes to address the 34 MT.

- The committee has, however, identified several barriers that will need to be addressed by DOE-NNSA and others before the dilute and dispose conceptual plans can be implemented to support U.S. commitments under the PMDA.

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Finding 1

- DOE-NNSA's dilute and dispose option, if implemented, is likely to face several challenges during its inception and lifetime of over three decades. These include
  - potential changes to the intended purpose, size, operations, and lifetime of WIPP;
  - the lack of availability of other suitable repositories for disposing of diluted plutonium (i.e., Yucca Mountain or elsewhere);
  - state, tribal, and local acceptance of diluted and packaged plutonium; transportation, and permanent disposal operations;
  - changes in U.S. nuclear weapons programs (e.g., new pit production and associated waste streams); and
  - funding availability.

- These challenges could lead to technological and/or programmatic changes to the current conceptual plans in order to achieve the DOE-NNSA's mission to dispose of 34 MT of surplus plutonium in an efficient, safe, and secure manner.

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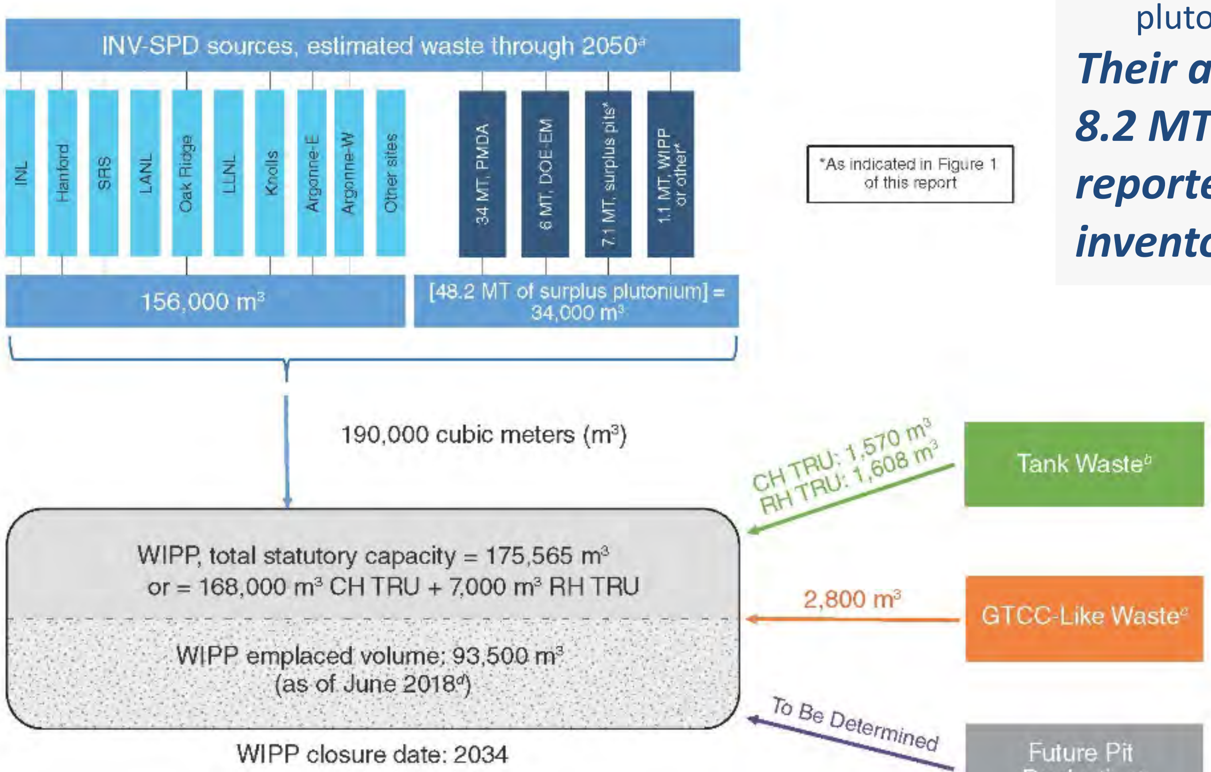
Finding 2

- The committee identified the following three barriers to implementation of DOE-NNSA's current conceptual plans:
  - Insufficient current statutory and current physical capacity within WIPP for disposal of 34 MT of diluted plutonium throughout the lifetime of the dilute and dispose project.
    - (PRE VoR Permit Change)
  - Unclear strategy for development of the National Environmental Policy Act (NEPA) environmental impact statement for disposing of 34 MT of surplus plutonium in WIPP using the dilute and dispose process.
  - Lack of Russian Federation approval for dispositioning 34 MT of surplus plutonium using the dilute and dispose process to meet the requirements of the PMDA.

Insufficient Capacity

exceeds WIPP's current legislated capacity by over 20,400 m³



The 2017 Government Accountability Office (GAO) report:

- WIPP would reach current available physical capacity by 2026 and that an additional two panels would be needed to accommodate future TRU waste.
- an additional one-and-a-half rooms would be needed to emplace 34 MT of diluted surplus plutonium.

Their assessment did not include the 8.2 MT (from the 42.2 MT total) reported in the 2017 special inventory report.

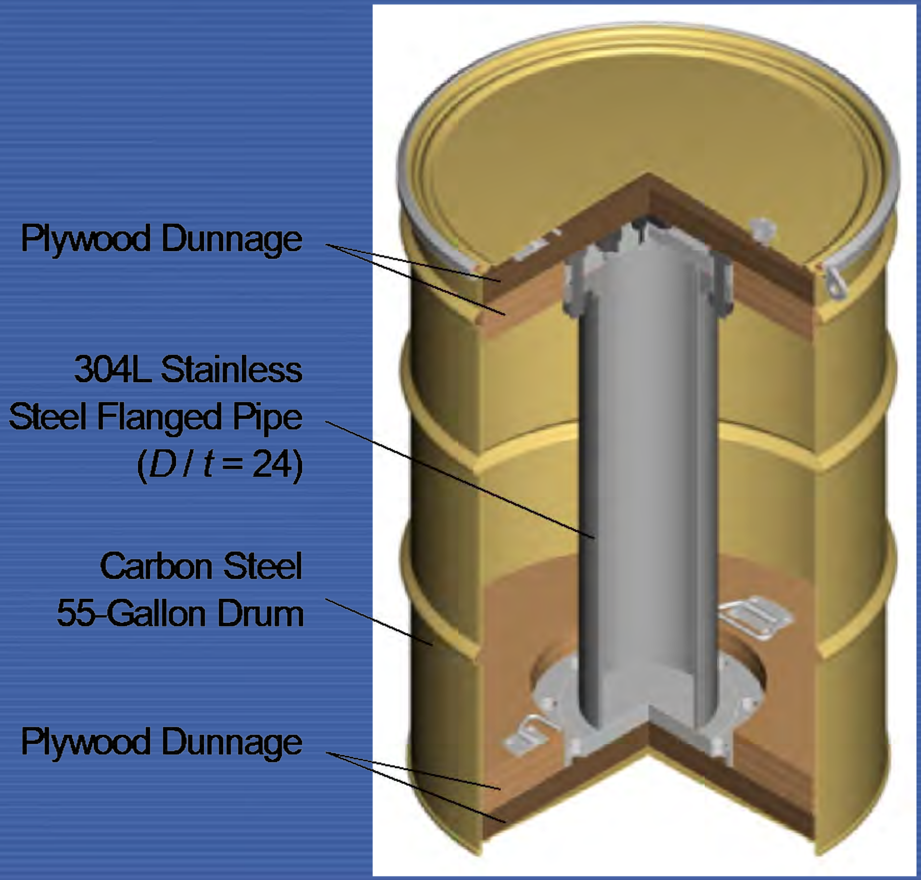
WIPP Volume Capacity--Current and Projected Volumes

TRU Waste Inventories	Current Permit—Calculates Volume of Outer Container Cubic meters (m^3)	Permit Modification--Changes Volume of Record to Inner Container (m^3)	Notes
TRU Waste Already Emplaced at WIPP	93,500	~-30%	WDS data through mid-June
"WIPP-Bound" Best Estimates **	~78K	~-15%	Data cutoff 12/31/16; Includes 6 metric tons (MT) of surplus Pu~5K m^3; Source: DOE/TRU-17-3425
SubTotal: Already Emplaced + WIPP-Bound	~172K		
UNSUBSCRIBED CAPACITY	~4K	>40K	Volume below WIPP LWA Limit of 175,565 m^3
"Potential Inventory" Estimates**	~19K		Data cutoff 12/31/16; Source: DOE/TRU-17-3425
Total Emplaced, WIPP-Bound, and Potential Waste**	~191K	~150K	191K – 40K = ~150K

** Estimates will vary as estimates are updated and waste is packaged.

- Definitions:
- WIPP-Bound – this is waste already in storage or projected to be generated in the future and is expected to meet the WIPP waste acceptance criteria, currently totaling approximately 78,000 m^3;
- Potential Waste – this is waste that may be intended for WIPP but requires resolution of a regulatory or other constraint before it may be considered, currently totaling approximately 19,000 m^3; and

Criticality Control Overpack
Criticality Control Container



.216 m3

Photo
(lid and upper dunnage removed)

.0128 m3

LWA vs VoR: -94%

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Surplus Pu in Context

- Container volume as of May 27, 2019
  - TMW Total Volume (m^3): 95,929
  - LWA Total Volume (m^3): 67,889
  - 176,560 CH Containers
  - 12,453 Shipments (713 RH) (14,923,888 loaded miles)

- 48.2 MT Surplus Pu
  - TMW Total Volume (m^3): 34,705
  - LWA Total Volume (m^3): 2,056
  - ~ 160,666 Containers
  - ~ 3825 Shipments (~ 5,741,822 loaded miles)

Recommendation 1

- The remaining statutory capacity as defined in the Waste Isolation Pilot Land Withdrawal Act (P.L. 102-579, as amended by P.L. 104-201; LWA) and New Mexico Environment Department (NMED) permit at WIPP should be treated as a valuable and limited resource by DOE. DOE-EM and the Carlsbad Field Office should modify their current emplacement planning process to allow for guaranteed long-term allocation of disposal capacity for waste streams of highest priority to DOE.

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Finding 3 and Finding 4

- **Finding 3**: Shifting the plutonium disposition program of record to the dilute and dispose option will require detailed discussions between DOE and the states of New Mexico and South Carolina. Accommodating 34 MT of diluted plutonium and other planned and/or potential future DOE waste streams in WIPP will necessitate changes to state permits and possibly legislation requiring state cooperation, including public participation.
- **Finding 4**: DOE will need to determine which laws, regulations, and orders are applicable to the proposed dilute and dispose process and develop and implement a strategy to work with regulators to obtain the necessary changes.

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Recommendation 2

- DOE-NNSA should engage New Mexico and South Carolina as well as their congressional delegations prior to the public engagement required by the National Environmental Policy Act process to assess prospects for successfully amending the existing legal agreements to allow for the dilution and packaging of 34 MT of surplus plutonium at the Savannah River Site and its disposal in WIPP.

Finding 5

- The dilute and dispose option for surplus plutonium disposition is neither recognized nor approved by the existing PMDA. Irradiated MOX fuel containing the surplus plutonium is the currently approved disposition option for plutonium within the PMDA and is an option that is consistent with the standard established with commercial spent fuel (i.e., that the plutonium would be as inaccessible for recovery for reuse in weapons by the host state as if it were in spent fuel, or the “spent fuel standard”).
- Disposition options that use chemical barriers alone, such as dilution or combining plutonium with other elements, do not meet this standard. The physical barrier of deep geologic disposal is offered by the DOENNSA as a necessary barrier to meet the intent of the PMDA. However, emplacement of diluted plutonium in WIPP remains recoverable by United States.

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Finding 6

- Based on limited information regarding the NEPA strategy for the dilute and dispose program and the fact that DOE-NNSA’s dilute and dispose plans derive from a similar program managed by DOE-EM to dilute and dispose of 6 MT of surplus plutonium, the committee finds that a full programmatic environmental impact statement (PEIS) of the dilute and dispose option, encompassing all sites, transportation, and activities involved in the dilute and dispose process rather than a supplemental EIS would help ensure the proper scope and scale of the proposed change.
- As much as 42.2 MT of surplus plutonium is being considered for disposal at WIPP, including 34 MT related to the PMDA. This represents the majority of the United States’ declared excess plutonium and its processing would stress the sites, transportation, and activities well beyond the current disposition plans for 6 MT.

Finding 7

- DOE-NNSA does not have a well developed public outreach plan for the host sites for processes or for the transportation corridor states and tribes (i.e., the current plan is to follow public input requirements defined by NEPA) for the dilute and dispose program.

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Conclusion 2

- Public trust will need to be developed and maintained throughout the lifetime of the dilute and dispose program as several permit modifications and potential changes to legislation will be required. These changes will require ensuring the regulators and the public of the safety and security of the DOE plans.

- This is particularly challenging for the dilute and dispose program due to several factors:
  - classification of aspects of the planning (constituents of the adulterant, processing steps, security and safeguards assessments);
  - early stage of program development with changes likely to occur as more information is known; and
  - potential impacts that cross many States and DOE sites.

Recommendation 3

- If the dilute and dispose option becomes the program of record, the committee strongly suggests that DOE consider re-initiating the Environmental Evaluation Group, as an independent technical review organization that can represent the concerns of the state of New Mexico, throughout the lifetime of the dilute and dispose program. Members of the technical review organization would need to be technically qualified to address the health and safety issues and a subset would need to have clearances or access authorizations that will allow thorough review of classified plans as they evolve and provide assessments of the dilute and dispose process.

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Recommendation 4

- In addition to and separate from the independent review organization representing the State of New Mexico described in Recommendation 3, periodic classified reviews for Congress by a team of independent technical experts should be required until classified aspects of the dilute and dispose plan, including the safety and security plans, are completed and implemented. Since DOE's plans and decisions are expected to mature and evolve, these independent reviews would provide a mechanism to review classified aspects of the program and would improve public trust in those decisions.

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Follow-up Questions for DOE

- ***WIPP Disposal Capacity:*** Does DOE-NNSA agree that WIPP's current statutory and physical disposal capacity is a barrier to implementation of the dilute and dispose process for dispositioning 34 MT of surplus plutonium? If not, what data and analyses are DOE-NNSA using to support its alternative conclusion? If so, what are DOE-NNSA and the larger DOE planning or doing to ensure that there is available repository space to dispose of all 34 MT of diluted surplus plutonium and to avoid surface storage of diluted plutonium? What, if any, legal or legislative changes are required to ensure the availability of disposal space in WIPP for disposing of 34 MT of surplus plutonium? If WIPP becomes temporarily unavailable due to an unforeseen closure, what are the plans for the dilute and dispose program? How does the conceptual plan change if permit modifications (i.e., changes to the calculation of the volume of record, physical expansion of WIPP, or life extension of WIPP) are not approved?
- ***Environmental Impact Statements***: How many and what kinds of environmental impact statements are currently associated with the dilute and dispose program? Which ones will need to be updated? And how will they be updated (i.e., supplemental EIS versus programmatic EIS)? What are the timeframes for completing these updates? Regardless of the type of EIS prepared, what are DOE-NNSA's plans to incorporate transportation safety and security risks into the NEPA process?
- ***WIPP Compliance***: Will the disposal of 34 MT of diluted plutonium in WIPP require changes to WIPP's Provisional Compliance Recertification Application or to the U.S. Environmental Protection Agency certification of WIPP? If so, what changes will be required, and how difficult (time, costs) will those changes be to implement? What is the timeframe for starting the application process?

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Next Steps and Final Report

- Essentially all documents from DOE now received
- One last face-to-face meeting after documents received
- Develop final report, current goal is summer 2019

- Final report will review those documents at a high-level to confirm that DOE’s plans are feasible but will not perform technical review and validation of the analysis and assessments in the planning documents (i.e., criticality assessment, performance assessment)

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THANK YOU

Download the Interim Report, *Disposal of Surplus Plutonium at the Waste Isolation Pilot Plant,* at:

http://www.nationalacademies.org/

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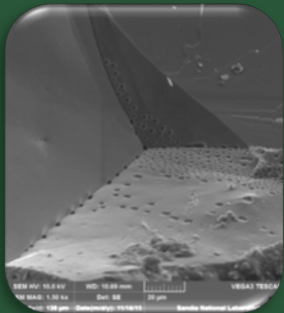
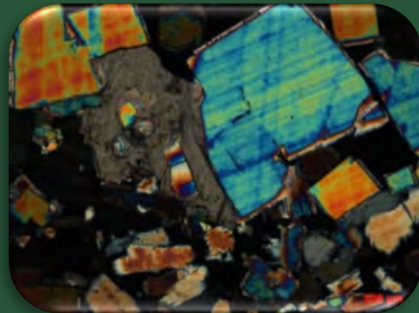

Waste Package Requirements and Design Approaches in the US

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Rapid City, SD, United States
May 28-30, 2019

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NOTICES

This is a technical presentation that does not take into account the contractual limitations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). Under the provisions of the Standard Contract, DOE does not consider spent nuclear fuel in canisters to be an acceptable waste form, absent a mutually agreed-to contract amendment. To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract provisions prevail.

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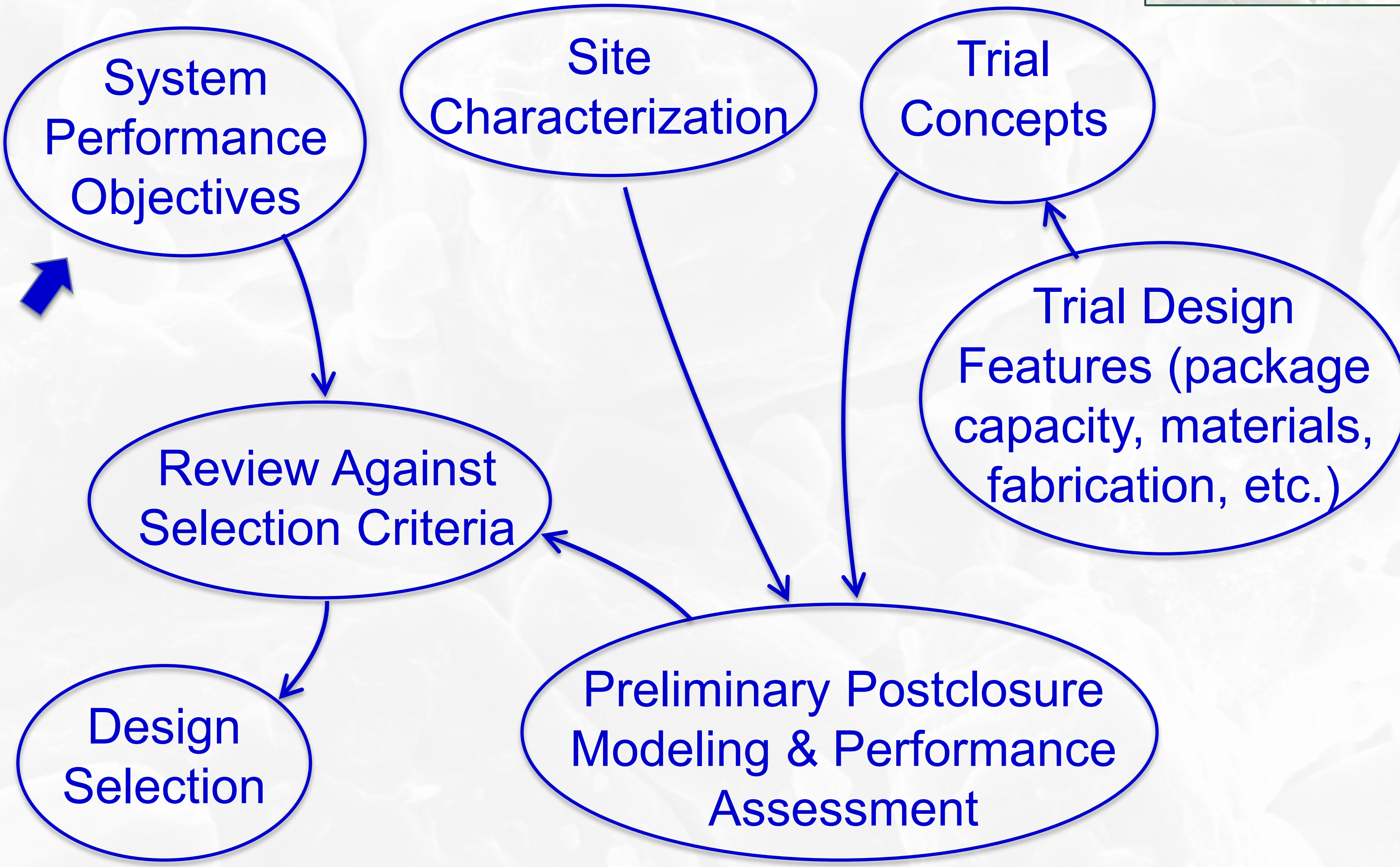
Outline

Spent light-water reactor fuel (UOX)

- Design process, a system-level exercise
- Objectives/requirements hierarchy
- Functional analysis
- Overpack vs. canister performance allocation
- Yucca Mountain overpack and TAD canister
- Survey of overpack materials
- Standardized canister specification development in the U.S., for multi-media
- Postclosure criticality control

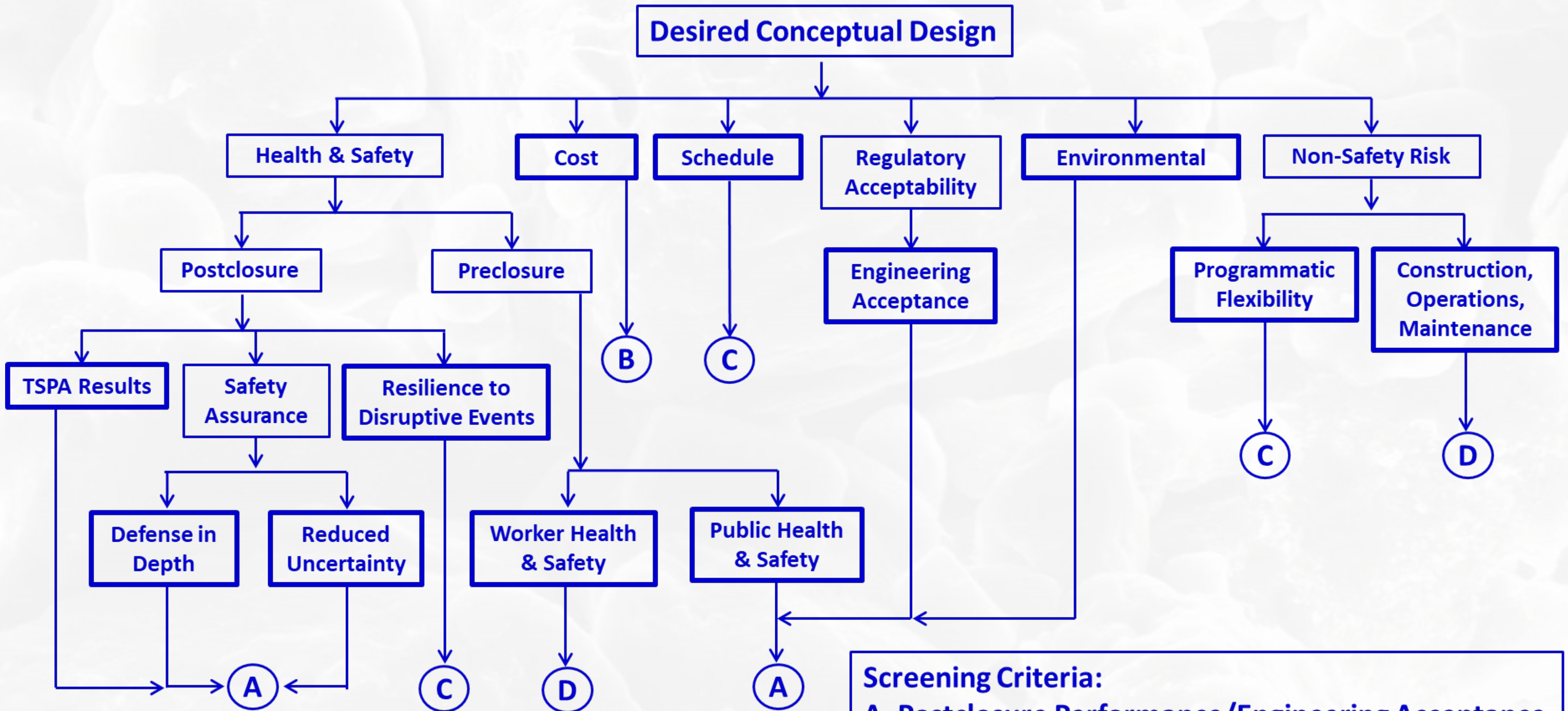
Conceptual Design Selection

A System-Level, Iterative, Risk-Informed Process



Objectives Hierarchy

YM LA Design Selection Study



Bold signifies fundamental objectives

Screening Criteria:

A. Postclosure Performance/Engineering Acceptance
B. Cost/Schedule
C. Flexibility for Expansion and Other Changes
D. Construction/Operations/Maintenance Feasibility

Based on Figure 3-3 of CRWMS M&O 1999. *License Application Design Selection Report*. B00000000-01717-4600-00123 REV 01 ICN 01. Office of Civilian Radioactive Waste Management, U.S. Department of Energy.

Functional Analysis, System-Level

- Engineered barrier requirements evolve, e.g.,
  - 10CFR60 – "…substantially complete" EBS containment for ~10^3 yr
  - 10CFR63 – Risk-informed system performance assessment
- Identify applicable performance requirements, e.g.,
  - Barriers important to waste isolation § 63.21(c)
  - Preclosure safety § 63.112
  - FEPs analysis and other PA requirements § 63.114
  - Multiple barrier strategy § 63.115
- Allocate functions and identify barriers, e.g.,
  - Repository handling (overpack)
  - Disposal containment (overpack)
  - Heat dissipation to protect fuel cladding (canister)
  - Postclosure criticality control (canister)
- Correlate requirements, design features and controlling parameters, and analysis parameters
- Verify by analysis (preclosure safety, postclosure PA)

Performance Allocation to SNF Canister vs. Disposal Overpack

- **Disposal canisters** are not relied on for postclosure waste isolation performance, and do not generally have requirements related to disposal environments.*
- **Disposal overpacks** will provide postclosure containment, with medium-specific requirements.

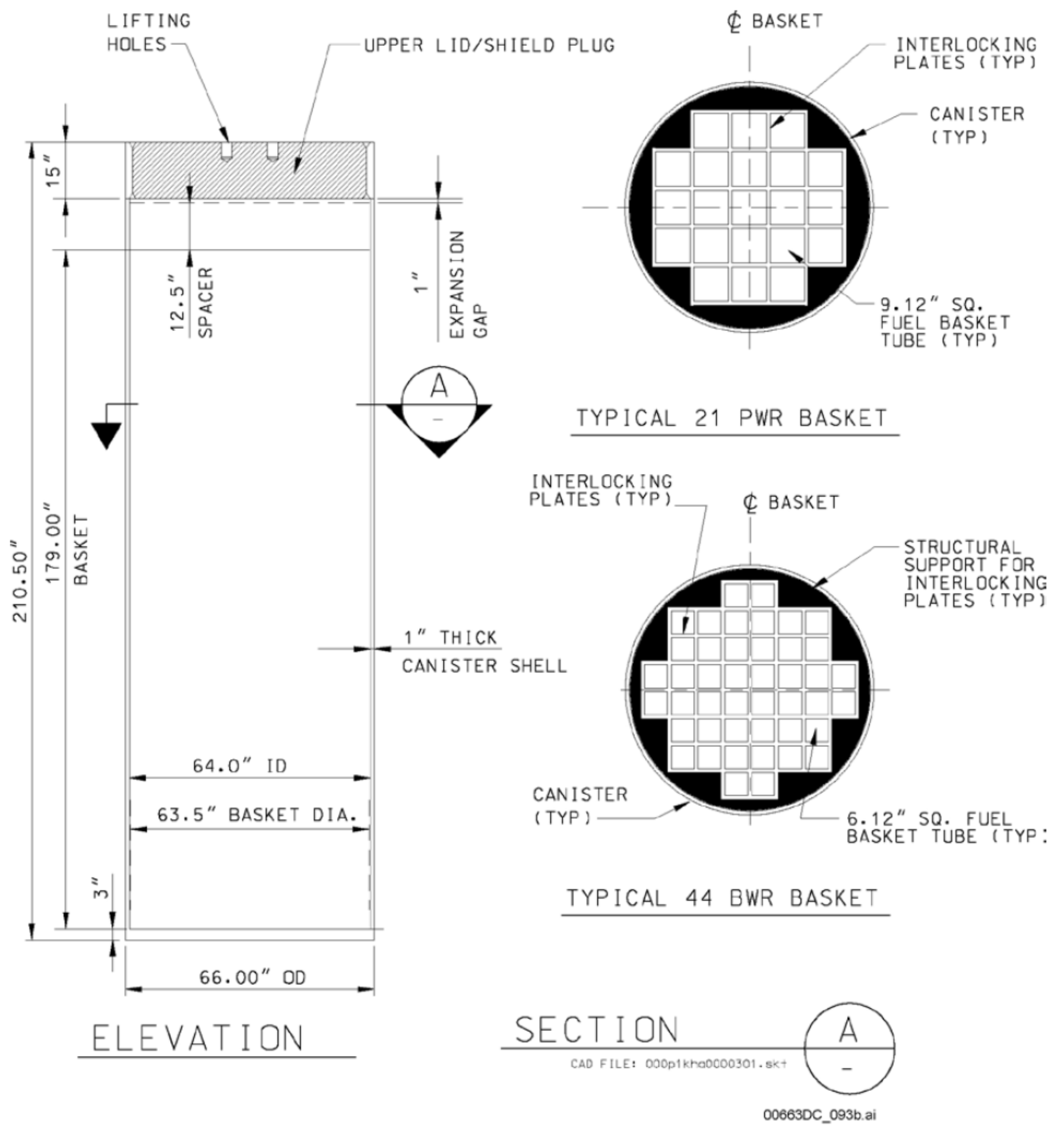
∴ Separate requirements for disposal canisters (generic) vs. disposal overpacks (medium-specific)

* **Exception and design challenge**: Disposal of large canisters in all media except salt, may involve postclosure criticality control measures that are not provided for storage and transportation, and are medium-specific.

YM TAD Canister

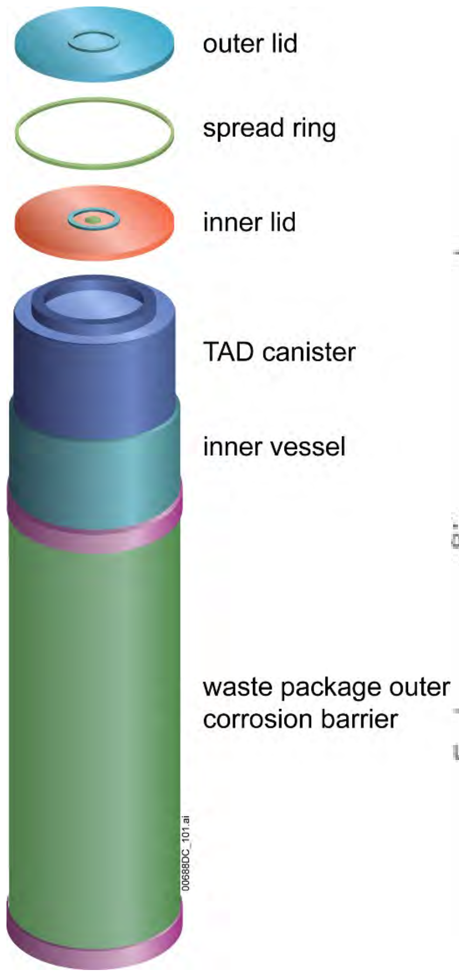
(Performance Specification)

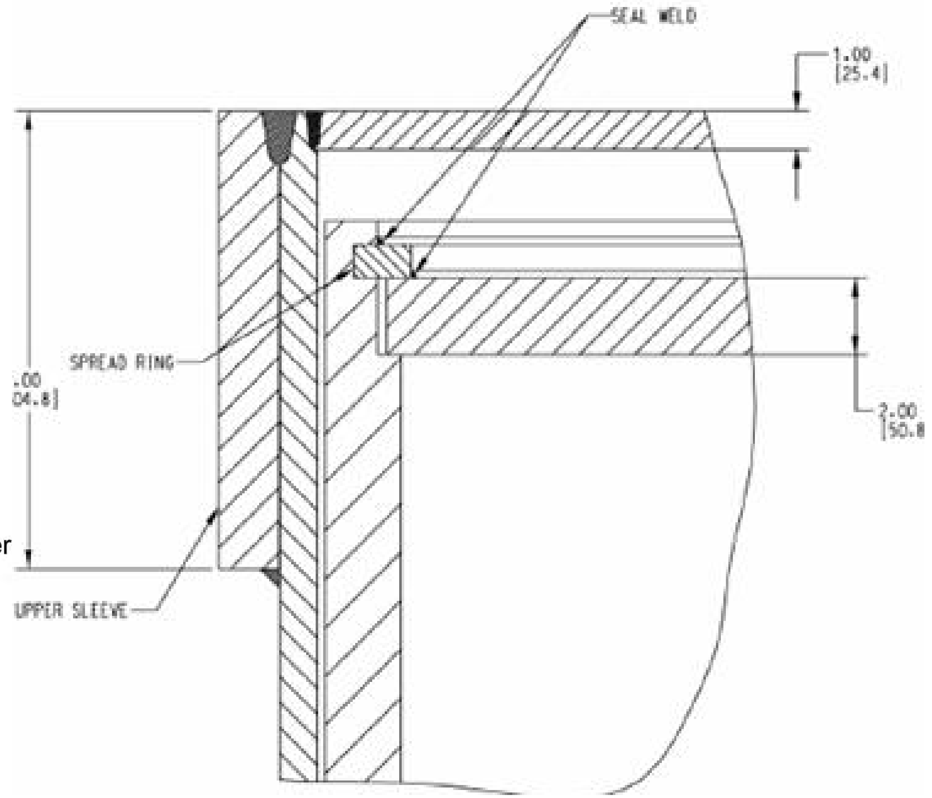
- Capacity: 21-PWR/ 44-BWR
- Weld-sealed
- Material: SS316 (Nuclear grade)
- Fabrication: cold-formed shell and basket, welded
- Basket detail: (TBD)
- Absorber plates: 11-mm borated SS304B4 (powder metallurgy grade)



YM LA Design: Disposal Overpack Concept

- Unsaturated, oxidizing disposal environment
- Corrosion-resistant (Alloy-22 and SS316)
- Annealed, with stress mitigation of final closure welds





“Generic” Overpack Material Selection:
Corrosion Types and Rates (1/2)

- **Steel or Cast Iron for “Corrosion Allowance”**
  - General corrosion rate $\propto$ to O_2 fugacity e.g., $r = f_{O2} \times 100$ µm/yr [A]
  - Never slower than ~1 µm/yr in water:

$$3Fe(0) + 4H_2O \rightarrow Fe_3O_4 + 4H_2\uparrow$$

  - Not sensitive to localized corrosion (possible galvanic attack)
- **Copper in Anoxic Aqueous Environments**
  - Chloride and sulfide sensitive
  - Otherwise corrosion is very slow in reducing conditions except [B] if

$$f_{H2} < 0.001: \qquad 2Cu(0) + H_2O \rightarrow Cu_2O + H_2\uparrow$$

- **Stainless Steels**
  - General corrosion similar to low alloy steel but much slower
  - SS316 and duplex grades are more resistant than SS304
  - Subject to localized corrosion and stress corrosion cracking

[A] Jovancicevic, V. and Bockris, J.O’M. 1986. *Journal of the Electrochemical Society, 133, (9),* 1797-1807.
[B] Hultqvist et al. 2009. *Catalysis Letters, 132, (3-4), 311-316.* Also *135, (3-4), 165-167.*

“Generic” Overpack Material Selection:
Corrosion Types and Rates (2/2)

- **Ni-Cr-Mo Alloys**
  - Hastelloys (e.g., C-4, C-22, etc.; Haynes International)
  - Passive mixed oxide layer ∴ subject to localized corrosion esp. in oxidizing waters
- **Titanium Alloys**
  - Passive TiO_2 layer (probably too noble for localized corrosion)
- **Coatings**
  - Plasma spray
  - Cold spray, amorphous metals [A]

[A] J. Blink, et al. 2007. “Applications in the Nuclear Industry for Thermal Spray Amorphous Metal and Ceramic Coatings.” *Materials Science & Technology 2007 Conference and Exhibition*, Detroit, MI, USA. September 16-20, 2007.

Standardized Canister Studies (U.S.)

Mission: Safe and feasible storage, transport, and disposal of 100,000+ MTU commercial spent fuel.

Goal to exclude postclosure criticality on low probability, and not to design a canister that sustains criticality events.

Yucca Mountain specific (unsaturated):

Round 1: Multi-Purpose Canister Concept (1995)

Round 2: Transport-Aging-Disposal (TAD) Canister for the Yucca Mountain License Application (2008)*

Generic multi-media (clay/shale, crystalline, salt,* unsaturated):

Round 3: Standardized TAD Study (2015)*

Round 4: "TAD+" Study (in process, re-evaluated readiness for disposal in multiple media, 2019)*

* Uses borated SS304B4 as neutron absorber plate material.

TAD+ Study Objectives (2019)

- Use previous studies and recent R&D to update specifications for a **21-PWR/44-BWR multi-media, multi-purpose canister**
- Technical readiness evaluations → 4 disposal environments:
  - Clay/shale
  - Salt
  - Saturated crystalline
  - Unsaturated media (e.g., tuff, granite, alluvium)
- Identify R&D activities that could support implementation and/or improve the TAD+ concept

TAD+ (2019) Study Results: Summary of Specifications

- General (13 specs)
- Structural (3 specs)
- Thermal (5 specs)
- Dose and shielding (3 specs)
- Criticality (2 specs)
- Confinement and containment (5 specs)
- Operations (5 specs)
- Materials (6 specs)

Technical Readiness for Each Specification: Evaluation Categories

- **Category A:** An *engineering solution is evident* or there exists *evidence in the international literature*
- **Category B:** Technically feasible for the generic environment *but requires study* beyond the current literature
- **Category C:** Demonstrating technical feasibility for the generic environment *requires resolution of significant technical challenges*

- **180 evaluations for TAD+ concept:** 45 criteria × 4 media
  - 164 Category A (resolved)
  - 13 Category B (study required)
  - 3 Category C (significant challenges)

Technical Evaluation Results
(21-PWR/44-BWR with borated SS304B4 absorber plates)

- 13 Category B evaluations (study required)
  - **Clay/Shale**: **Thermal** aspects (meeting near-field temperature limits with 150-year aging)
  - **Clay/Shale** and **Salt**: **Underground transport** aspects (shaft/ramp transport and underground handling/transport)
  - **Clay/Shale** and **Saturated Crystalline**: **Postclosure criticality** aspects (neutron absorber corrosion)
- 3 Category C evaluations (significant challenges)
  - **Saturated Crystalline**: **Thermal** aspects (maintaining clay buffer temperature limits with 150-year aging)

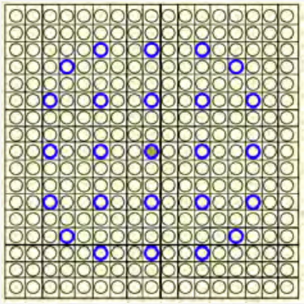
Postclosure SNF Criticality Control Options

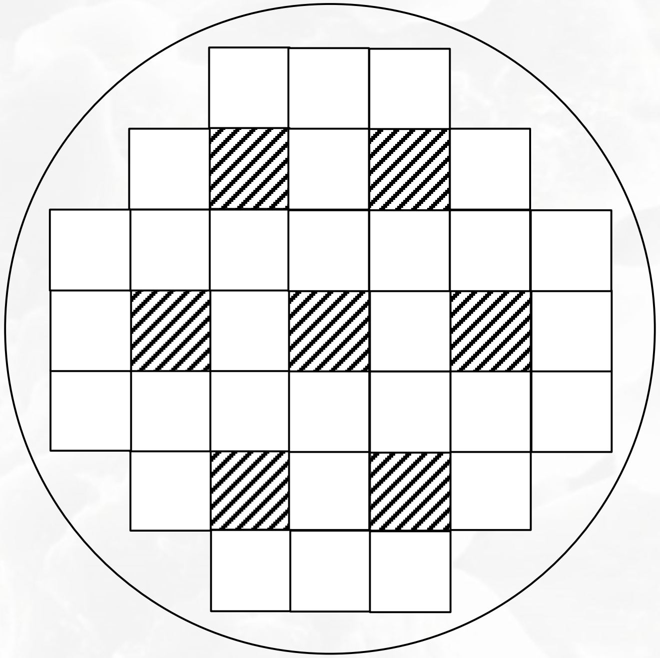
Problem Statement: Dry storage/transportation canisters use aluminum-based neutron absorbers that corrode in ground water. Borated stainless steel may corrode too rapidly in some environments. What other options for postclosure criticality control are available?

- **Site selection**
  - Groundwater availability and composition (e.g., chloride brine)
- **Engineering: as-loaded reactivity margin**
  - 3-D; axial burnup profiles (more difficult to characterize for BWRs)
  - Optimize fuel loading for reactivity (plus thermal and gamma dose)
- **Engineering: moderator exclusion**
  - Package integrity (super-overpack?)
- **Engineering: moderator displacement**
  - Solid fillers (e.g., glass beads, steel shot)
  - Injectable fillers (e.g., cement, molten materials)
- **Engineering: control "features"** (e.g., control rods in PWR fuel)

Potential Criticality Control R&D to Support TAD+ Concept

- Calculate fuel loading maps
  - Thermal + external radiation + reactivity
- Disposal control rod assemblies (DCRAs)
- Corrosion testing
  - Borated stainless-steels
  - Ni-Cr-Mo-Gd
  - Ceramics
- Injectable filler R&D



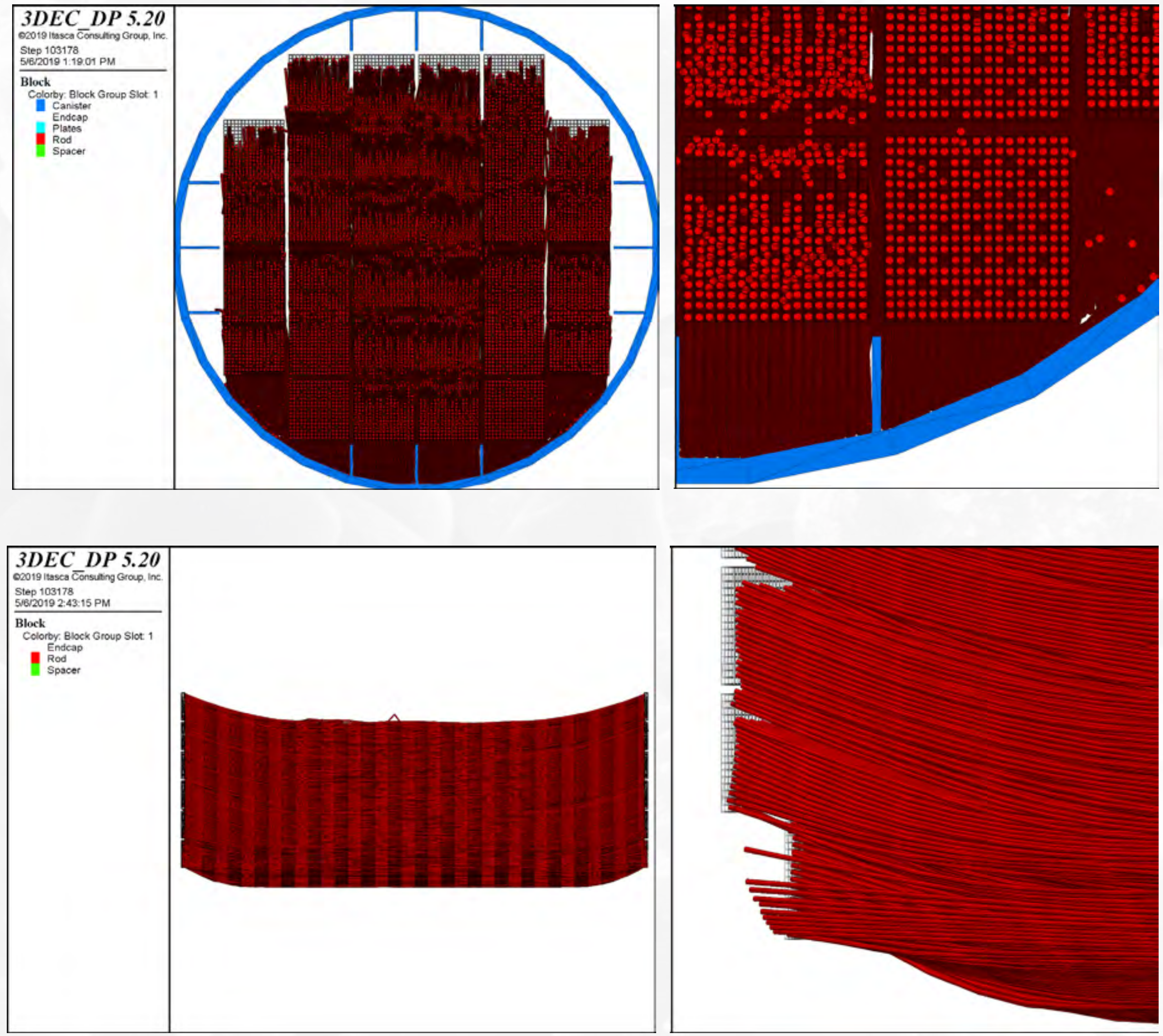


Disposal Control Rod Concept: 3DEC Model for Fuel/Basket Degradation

Hypothesis: Zircaloy-clad disposal control rods deform and degrade with the fuel rods, maintaining criticality control as fuel consolidates

Simulation with PWR Fuel Assembly Nozzles Intact, Basket Plates and Spacer Grids Corroded (DRAFT)

Figure credit: Varun et al. 2019, Itasca Consulting Group, presented at DOE/SFWD Working Group.



Summary

Waste Package Requirements and Design Approaches in the U.S.

- Conceptual design is a system-level process
- Provision for innovation and trial features/alternatives
- Example: YM License Application Design Study
- Functional analysis and requirements allocation
- Example: YM TAD canister and disposal overpack
- Standardized multi-media canister studies in the U.S.
- TAD+ (2019) study technical evaluations
- DCRAs and other R&D needs

QUESTIONS?

BACKUP SLIDES

Overpack Requirements

- Containment
  - Preclosure operations + resistance to off-normal events
  - Long-term waste isolation (site specific)
    - Corrosion
    - Disruptive events
- Safety of workers and the public
  - Handling
  - Shielding
- Reliability
  - Stress relief
  - Manufacture (inspection, rework)
  - “Early failure” characteristics
- Engineering feasibility

Canister Requirements

- Containment
  - Safe preclosure operations
  - Transportation requirements (including criticality control)
- Safety of workers and the public
  - Handling for storage and transportation
- Heat dissipation
- Postclosure criticality control
- Engineering feasibility

Material Selection (1/2)

- Canisters for Handling and Storage
  - Stainless steel (e.g., inhibit corrosion and fuel pool contamination)
  - Cast iron or low-alloy steel (e.g., with coatings, or for dry handling)
- Salt
  - Low-alloy steel or cast iron
  - Stainless steel (inner vessel)
- Crystalline
  - Copper & cast iron
  - Low-alloy steel
  - Titanium & stainless steel
- Clay/Shale
  - Low-alloy steel (overpack)
  - Stainless steel (e.g., HLW pour canisters)
- Unsaturated Hard Rock
  - Corrosion resistant, oxidizing conditions (e.g., Hastelloys, titanium)

Alloy ≡ solid solution, mixture of solid solution phases, or "intermetallic."

Material Selection (2/2)

- Disposal Overpack Materials
  - Corrosion Resistant ($10^5 \rightarrow 10^6$ + yr)
    - Nickel-based alloys (e.g.., Hastelloy® 825, C-4, C-22, etc. from Haynes)
    - Titanium
    - Copper (reducing environments)
  - Corrosion Allowance ($10^3 \rightarrow 10^4$ + yr)
    - Low-alloy steel
    - Stainless steel
  - Coatings
    - Plasma spray, cold spray, amorphous metals, plating
- Canister Materials
- Neutron Absorber Materials
    - Matrix (aluminum, stainless steel) + Absorber (boron, rare earths)
- Performance Measures
  - Containment, mechanical and/or chemical lifetimes
  - Compatibility with storage/handling systems
  - Cost, availability, handling constraints, attractiveness, etc.

Specification Areas (1/4)

- General (13 specs)

1	Storage and transportation
2, 3, 4	Shape and dimensions, loaded weight, capacity
5	Submerged opening
6, 7	Waste characteristics, waste source
8	Edge curvature & protuberances
9, 10	Orientation during S&T, and at the repository
11	Canister design lifetime
12	Canister environmental conditions
13	TAD WP spacer (to allow a range of canister lengths to be compatible with a single WP length)

Specification Areas (2/4)

- Structural (3 specs)

1, 2	Canister leakage and cladding temperature due to seismic, and due to environmental conditions
3	Canister bottom shape

- Thermal (5 specs)

1, 2	Cladding temperature prior to disposal during normal operations, and during off-normal conditions
3	Cladding temperature during an engulfing fire
4	Passive cooling of the canister
5	Cladding temperature limit and thermal conditions in the repository

Specification Areas (3/4)

- Dose and shielding (3 specs)

1, 2	Dose rate limits: average and maximum
3	Surface contamination limits

- Criticality (2 specs)

1	Storage and transportation
2	Postclosure

- Confinement and containment (5 specs)

1	Closure weld qualification or leak testing
2	Helium gas
3	ASME Boiler & Pressure Vessel Code
4	Draining, drying, and backfilling
5	Leakage rate and cladding temperature following a drop

Specification Areas (4/4)

- Operations (5 specs)

1	Underwater handling
2	Lid centering and seating
3	Canister lifting using the lid
4	Empty canister lifting
5	ALARA principle during canister draining, drying, and backfilling

- Materials (6 specs)

1, 2	Materials: Required and prohibited
3	Pool water
4	Corrosion
5	Weld stress relief
6	Markings

Operational Safety: WIPP Lessons Learned

Rey Carrasco
NWP -WIPP

Background

- The Waste Isolation Pilot Plant (WIPP), located in New Mexico began construction in the early 1980's

- Receipt and disposal of Contact Handled (CH) waste began in March 1999

- Receipt and disposal of Remote Handled (RH) waste began in January 2007

- Between March 1999 and February 2014, WIPP safely and compliantly:

  Received 11, 894 shipments and disposed the waste in the u/g,

  90,627 cubic meters of CH TRU waste,

  357 cubic meters of RH TRU waste

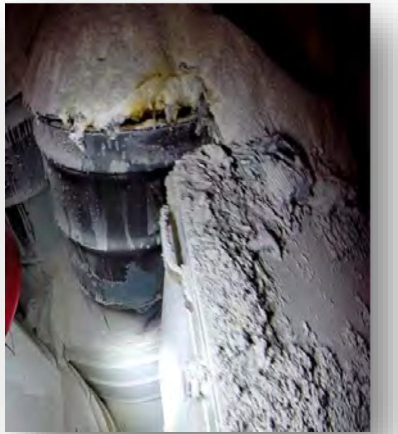
- In February 2014, WIPP operations were paused when a fire and a radiological event occurred in the underground.

Fire Event

- February 5, 2014 a fire occurred in the u/g involving a salt haul truck
- 86 workers in the u/g at the time of the fire were safely evacuated
- Investigated by both DOE and NWP
- DOE Accident Investigation Report issued on March 13, 2015

Radiological Event

- February 14, 2014 an exothermic reaction involving the mixture of the organic materials (absorbent and/or neutralizer) and nitrate salts occurred inside a drum.
  - Pressurization of the drum, failure of the drum locking ring, and displacement of the drum lid
  - TRU waste propelled from the drum up into the polypropylene magnesium oxide (MgO) super sacks on top of the containers and onto adjacent waste containers.
  - Radiological Continuous Air Monitor (CAM) alarm received; ventilation interlocked to filtration mode
  - Small amount of leakage bypassed the HEPA filters and released into the atmosphere
  - DOE Accident Investigation Report Phase I (response to the event) – issued on April 22, 2014
  - DOE Accident Investigation Report Phase II (cause of the event) – issued on April 16, 2015



Lessons Learned

– **Nuclear Facility vs Mine Culture**
  - Although WIPP is a nuclear facility, there was a mining culture in place vs a nuclear culture
  - Difference in expectations between waste handling and non-waste handling vehicles (combustible buildup, manual vs auto fire detection/suppression)

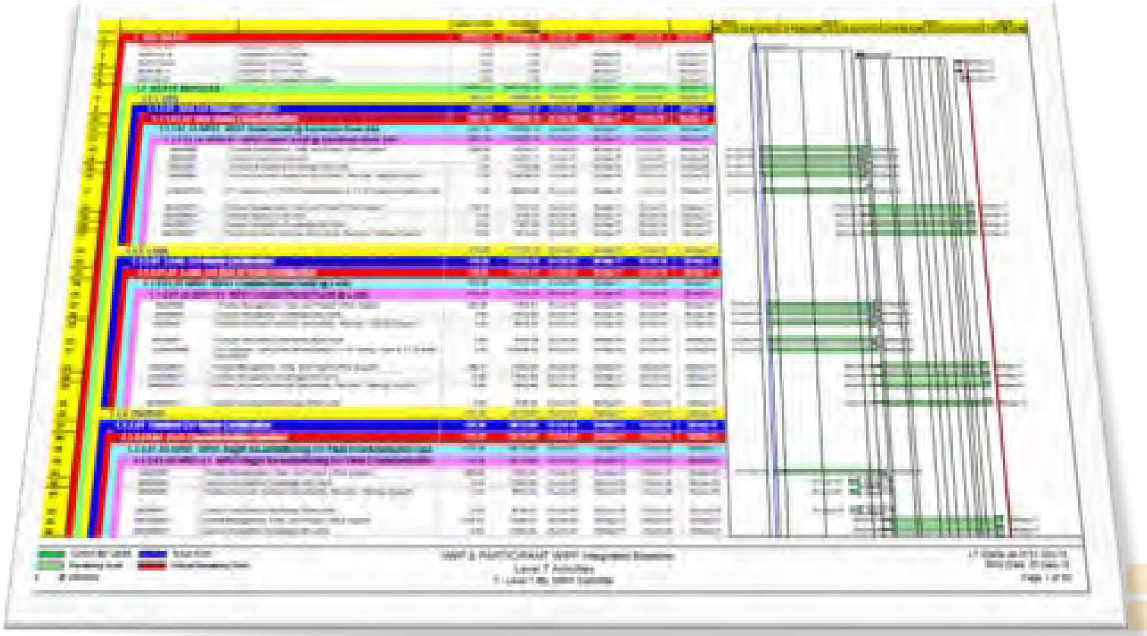
– **Operability and recognition of impaired critical safety equipment**
  - Fire protection program not adequately implemented at the WIPP facility
  - No controls or programs in place for control of combustible materials or maintaining of fire protection support systems
  - Maintenance program not effectively implemented
    - Combustible buildup on salt haul truck; chaining open ventilation doors; inoperable ventilation fans; inoperable mine phones, obscured evacuation reflectors, disabling of auto fire suppressions system; no overall method to understand status and impact of impaired mine safety related equipment
  - Mindset of production over maintenance based on complex wide priorities to accelerate shipments from generator sites in support of individual site milestones and regulatory agreements

Lessons Learned

- **Training and drill programs**
  - Emergency management/preparedness and response programs not effectively implemented
  - Limited drills, inadequate donning of self-rescuers or SCSRs during training or drills, or hands on training with portable fire extinguishers
  - Inconsistencies between u/g fire response procedures and drills/training (shifting ventilation during evacuation)
- **Expectations and capabilities of the Facility Shift Manager to manage all aspects of an emergency or abnormal event**
  - CMR response (evaluation and protective actions) was less than adequate
  - Identified problems with communications and alarms during the fire/evacuation delaying egress
- **National TRU Program not robust enough to identify incompatible waste**
- **Communications to the community and regulatory stakeholders was not timely**
  - Ensures trust is maintained rather than rebuilding that trust

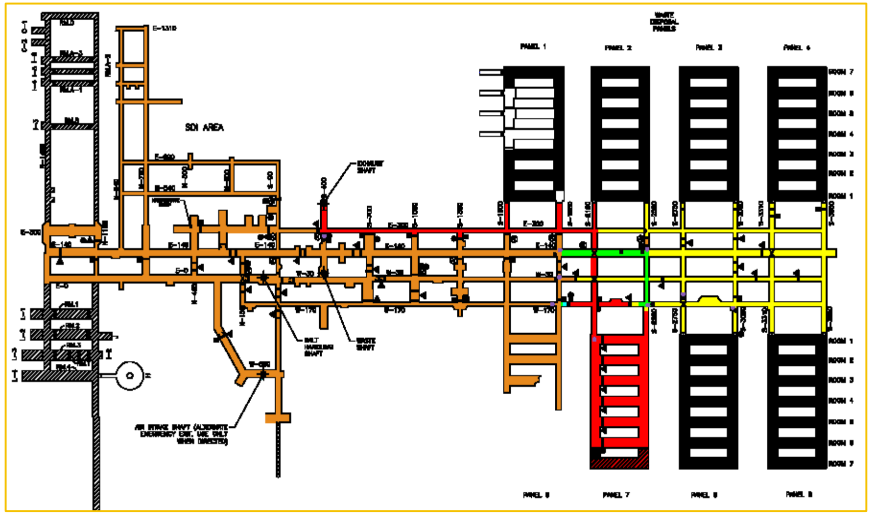
WIPP Recovery Managed as a Project

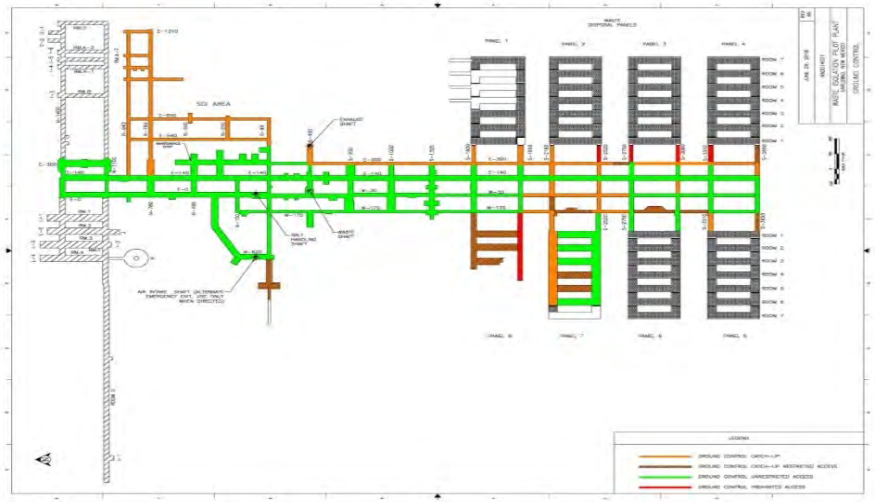
- Baseline established
- Scope, schedule, cost and risks reflected in the recovery baseline
- Primavera detailed schedule developed
- Progress tracked in Plan of the Day and Plan of the Week meetings
- Critical Path calculated on weekly basis



Radiological and Ground Control Recovery

- Radiological release event in February 2014
  - Prevented underground access for several months; required “catch-up” bolting in areas that had not been maintained during that period
  - Created radiologically contaminated areas – complicating all operations including bolting and other ground control





Facility/Equipment Improvements

- New Emergency Operating Center (EOC)
- Remodeled training facility
- U/G Ventilation fan reliability improvements
- Hybrid bolters
- Maintenance backlog reduction
- Interim Ventilation System

New Emergency Operations Center

Combustible Control Zone

Program Improvements

- Fire Protection Program Plan
- DSA Revision 5 Implemented (STD 3009-2014)
- Increased training for fire response and 10X increase in drills

New Equipment

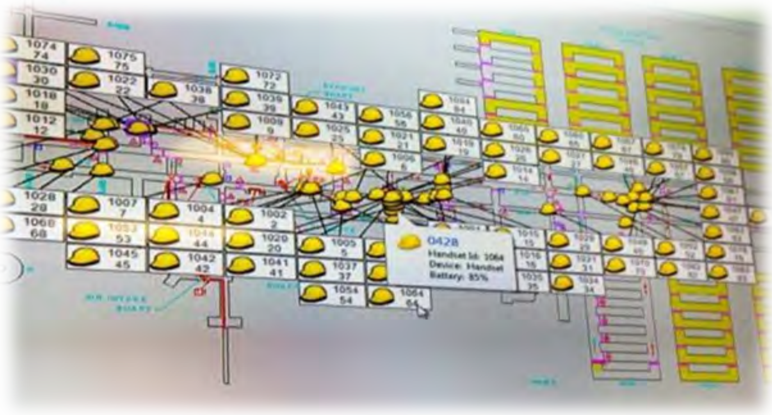
Hybrid Bolting Machine

Enhanced Underground Safety

- New underground notification system
- U/G combustible reduction
- U/G localized fire suppression systems
- Vehicle auto fire suppression systems
- Improved mine stability and ground control

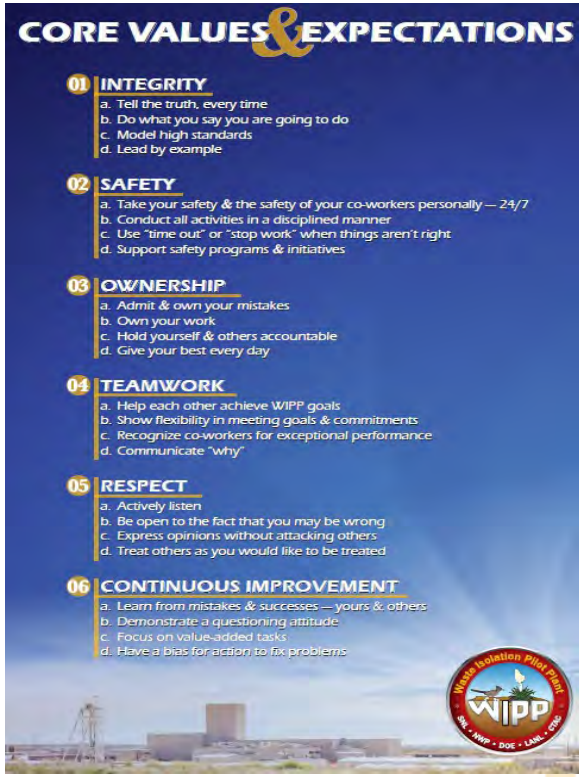
Aggressive Culture Change

- Leadership Academy
- Leaders Forum
- Focus on Values, Expectations, and Standards



U/G Notification System

Vehicle Fire Suppression



Ventilation

- **Phase I - Interim Ventilation System**
  - Two HEPA skids and fan units
    - 114,000 cfm of airflow
  - Doubled the existing 60k cfm capacity
  - Ensured adequate air flow at the waste face for resumption of waste emplacement
  - Increased airflow for ground control and maintenance operations
- **Phase II – Supplemental Ventilation**
  - Reconfiguring mine circuits and additional fans
    - 180,000 cfm airflow
- **Phase III – Permanent Ventilation System**
  - Design and construct a new (permanent) ventilation system
    - Capable to provide 420,000 cfm

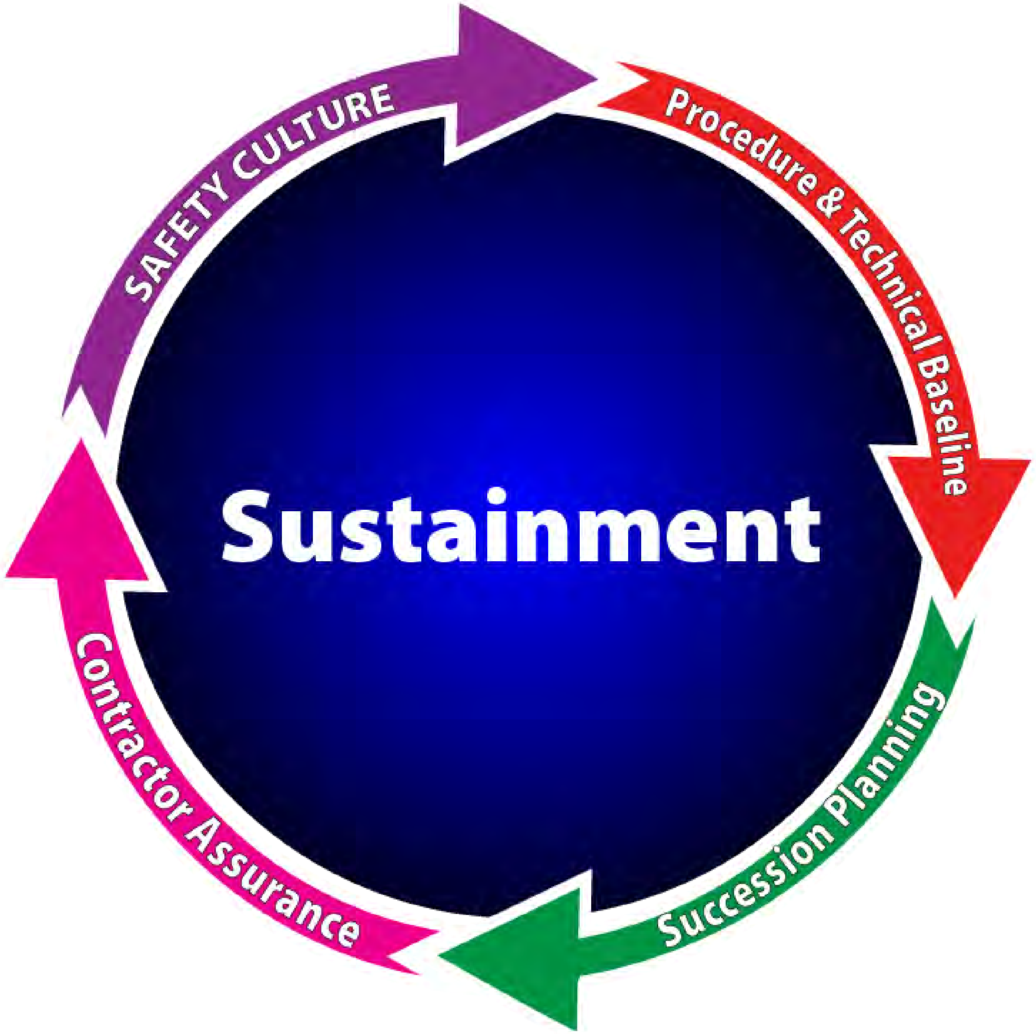
National TRU Program

- Re-Certification of Generator Sites
- Specific requirements for Previously Certified Waste
  - Chemical Compatibility Evaluation
  - Enhanced Acceptable Knowledge
  - Evaluation of oxidizing chemicals (Basis of Knowledge)
- Generator Site Technical Reviews
- Initial Shipping Schedule Established

Resumption of Waste Emplacement

- Contractor and DOE ORRs completed in December
  - Prestart Findings Closed
- WIPP Site approved to emplace Waste in Waste Handling Building
- First waste disposed of on January 4, 2017
- Night and day difference between today vs. where we were in 2014

Keys to Sustainment



sus·tain *(sə-stān′)*
To keep in existence; maintain, continue, or prolong: sustain an effort.

MSA Noteworthy Practices

- *Methods to enhance safety Culture*
- *Fact finding process*

Safety Culture

- Values and Expectations
- Shared Goals
- Leadership Academy
- Leaders Forum
- WIPP Fundamentals Handbook
- Time Out/Stop Work
  - Time out of the day
- Critique/Fact Finding Process
- Lessons Learned Process
- Positive Reinforcement
  - Everyday Hero's
  - Breakfast/lunch celebrations
- Management Field Observations
- Barrier Busters
- Union leadership meetings

CORE VALUES & EXPECTATIONS

01 INTEGRITY
a. Tell the truth, every time
b. Do what you say you are going to do
c. Model high standards
d. Lead by example

02 SAFETY
a. Take your safety & the safety of your co-workers personally — 24/7
b. Conduct all activities in a disciplined manner
c. Use "time out" or "stop work" when things aren't right
d. Support safety programs & initiatives

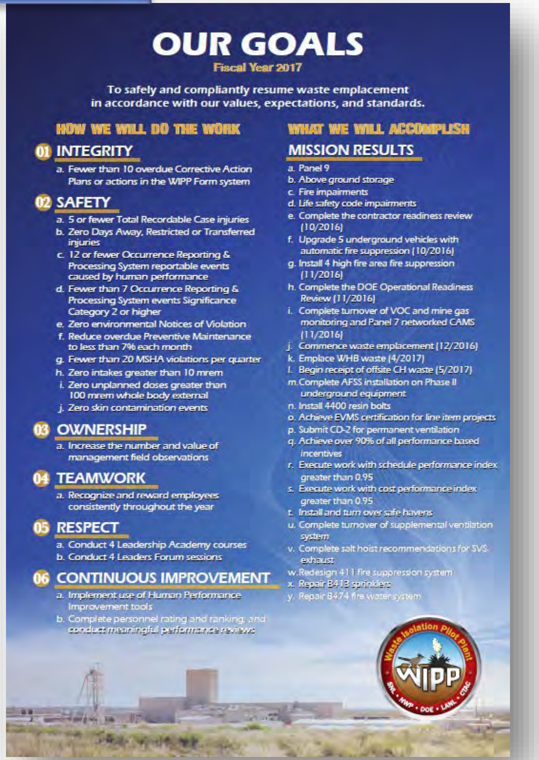
03 OWNERSHIP
a. Admit & own your mistakes
b. Own your work
c. Hold yourself & others accountable
d. Give your best every day

04 TEAMWORK
a. Help each other achieve WIPP goals
b. Show flexibility in meeting goals & commitments
c. Recognize co-workers for exceptional performance
d. Communicate "why"

05 RESPECT
a. Actively listen
b. Be open to the fact that you may be wrong
c. Express opinions without attacking others
d. Treat others as you would like to be treated

06 CONTINUOUS IMPROVEMENT
a. Learn from mistakes & successes — yours & others
b. Demonstrate a questioning attitude
c. Focus on value-added tasks
d. Have a bias for action to fix problems

Waste Isolation Pilot Plant
WIPP
SNL • NWP • DOE • LANL • CTAC



OUR GOALS

Fiscal Year 2017

To safely and compliantly resume waste emplacement in accordance with our values, expectations, and standards.

HOW WE WILL DO THE WORK

01 INTEGRITY
a. Fewer than 10 overdue Corrective Action Plans or actions in the WIPP Form system

02 SAFETY
a. 5 or fewer Total Recordable Case injuries
b. Zero Days Away, Restricted or Transferred injuries
c. 12 or fewer Occurrence Reporting & Processing System reportable events caused by human performance
d. Fewer than 7 Occurrence Reporting & Processing System events Significance Category 2 or higher
e. Zero environmental Notices of Violation
f. Reduce overdue Preventive Maintenance to less than 7% each month
g. Fewer than 20 MSHA violations per quarter
h. Zero intakes greater than 10 mrem
i. Zero unplanned doses greater than 100 mrem whole body external
j. Zero skin contamination events

03 OWNERSHIP
a. Increase the number and value of management field observations

04 TEAMWORK
a. Recognize and reward employees consistently throughout the year

05 RESPECT
a. Conduct 4 Leadership Academy courses
b. Conduct 4 Leaders Forum sessions

06 CONTINUOUS IMPROVEMENT
a. Implement use of Human Performance Improvement tools
b. Complete personnel rating and ranking, and conduct meaningful performance reviews

WHAT WE WILL ACCOMPLISH

MISSION RESULTS
a. Panel 9
b. Above ground storage
c. Fire impairments
d. Life safety code impairments
e. Complete the contractor readiness review (10/2016)
f. Upgrade 5 underground vehicles with automatic fire suppression (10/2016)
g. Install 4 high fire area fire suppression (11/2016)
h. Complete the DOE Operational Readiness Review (11/2016)
i. Complete turnover of VOC and mine gas monitoring and Panel 7 networked CAMS (11/2016)
j. Commence waste emplacement (12/2016)
k. Emplace WHB waste (4/2017)
l. Begin receipt of offsite CH waste (5/2017)
m. Complete AFSS installation on Phase II underground equipment
n. Install 4400 resin bolts
o. Achieve EVMS certification for line item projects
p. Submit CD-2 for permanent ventilation
q. Achieve over 90% of all performance based incentives
r. Execute work with schedule performance index greater than 0.95
s. Execute work with cost performance index greater than 0.95
t. Install and turn over safe havens
u. Complete turnover of supplemental ventilation system
v. Complete salt hoist recommendations for SVS exhaust
w. Redesign 411 fire suppression system
x. Repair B413 sprinklers
y. Repair B474 fire water system

Waste Isolation Pilot Plant
WIPP
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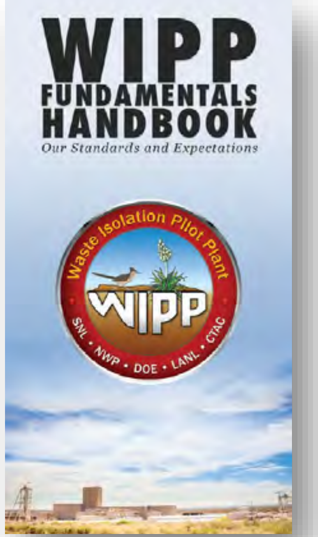


Procedure and Technical Baseline

- **Documented Safety Analysis Rev 5b**
  - TSR
  - Key Elements
- **Safety Management Programs**
  - Radiation Protection
  - The Initial Testing, In Service Inspection, and Maintenance
  - Emergency Preparedness Program
  - Waste Acceptance Criteria Compliance Program
  - Operational Safety
  - Procedures and Training
- **Implementing procedures**

Succession Planning

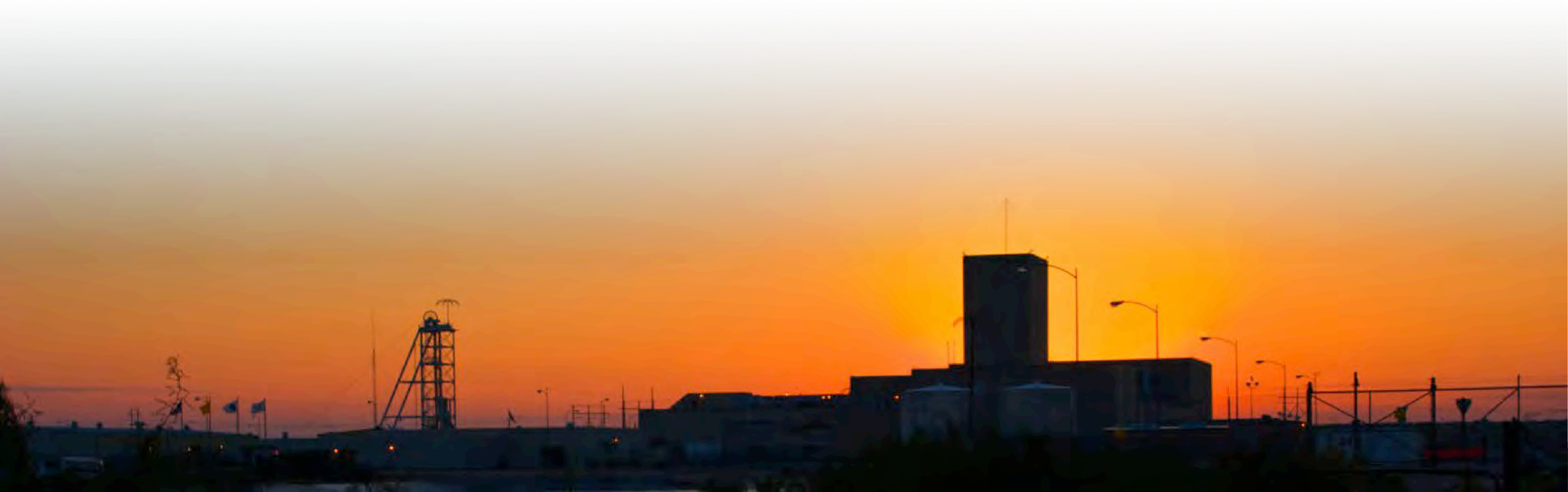
- **Selection based on**
  - – Expertise in the function
  - – Breadth of experience
  - – Past performance

Contractor Assurance

- Self Assessment
- Independent Assessment
- Corrective Action Program and Analysis
- Benchmarking

Sustainment

- All of these things work together to make sure that WIPP continues to improve



WIPP Panel Closure Program

Rey Carrasco
NWP - WIPP

Scope of Presentation

- Panel Closure System Background
- Design Review Guidelines
- HWDF Panel Closure System Design Criteria
- Panel Closure System Design Alternatives

Design Review Guidelines

- Design Review per WP 09-CN3018
- List of Alternatives
- HWDF Performance Specifications
- Additional Schedule and Cost Considerations
- Judge and Rank Alternatives to Assist in final selection

HWDF Criteria

The panel closure system is designed to meet the following requirements that were established by the DOE for the design to comply with 20.4.1.500 NMAC (incorporating 40 CFR §264.601(a)):

- the panel closure system shall perform its intended functions under loads generated by creep closure of the tunnels Waste Isolation Pilot Plant
- the nominal operational life of the closure system is 35 years
- the panel closure system may require minimal maintenance per 20.4.1.500 NMAC (incorporating 40 CFR 264.111)
- materials shall be compatible with their emplacement environment and function

Operational Criteria

- PCS Design shall Limit VOCs Migration
- Flow of VOCs through the Disturbed Rock Zone (DRZ)
- Shall Consider Methane Gas Explosion
- 35 Year Design Life
- Occasional As Opposed to Routine Maintenance
- Address Most Severe Ground Conditions

Design Criteria

- PCS Performs Intended Function Under Creep Closure Loads
- Treat Closure Surfaces

Safety Criteria

- Class III B Using Standard Construction Methods
- Structural Analysis Based Upon WIPP Data

Structural/Material Criteria

- Selected Materials Compatible with Underground Environment
- Thermal Cracking for Concrete Components
- PCS Sustains Pressure and Temperature Loads from a Methane Explosion

Construction Criteria

- Conventional Mining Practices
- QA/QC Program for Material Properties
- Consideration of Available Underground Services

Should We Design for Restricted Flow?

- Uncertainty in Source Term of VOCs
- Uncertainty in Molar Gas Generation Rates
- Uncertainty in VOCs Flow Through Large Scale Seal Components
- Uncertainty in Volumetric Closure Rates
- HWDF VOCs Limits Must Be Achieved in Real Time or WIPP Operations Could Be Shut Down for Violation of the RCRA Permit

Should We Design for Restricted Flow?

- Flow Restriction Would Allow Time to Evaluate VOCs Flow Trends and Take Remedial Action Without Shutting Down WIPP Operations
- Barriers for Protection of Underground Personnel Should be of "Substantial Construction"

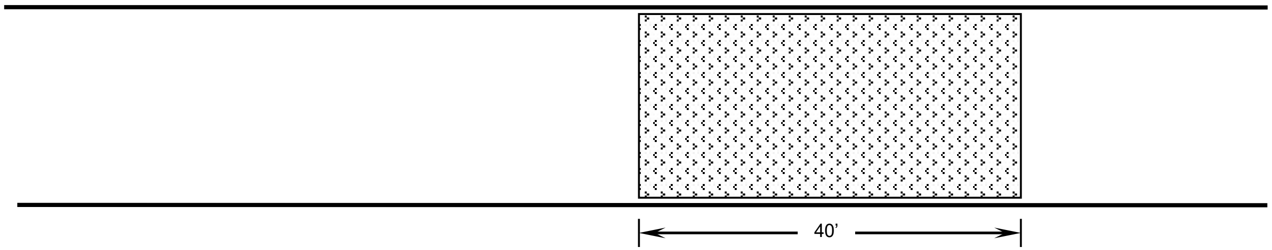
Evaluation of Design Alternatives

- Estimated Effective Intrinsic Permeability and Conductance
- Estimated Costs
- Weights Established for the Broad Categories
- Alternatives Worksheet to Score from 1 to 10 for each of the HWDF Design Criteria

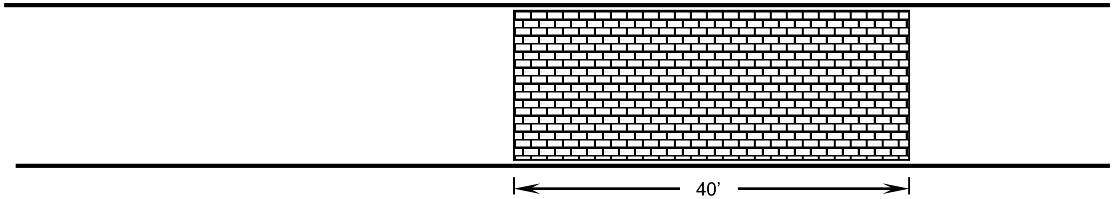
List of Alternatives

- Simple Operational Alternatives
- Original Options A through D
- Monoliths of Various Materials
- Block Wall Options
- Backfills
- Combination of Block Walls and Backfills

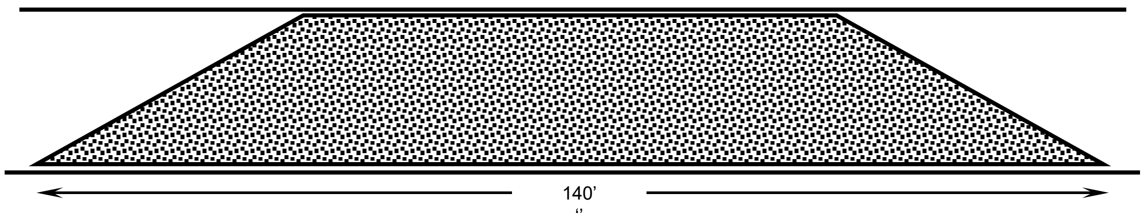
Option 9 Concrete Monolith



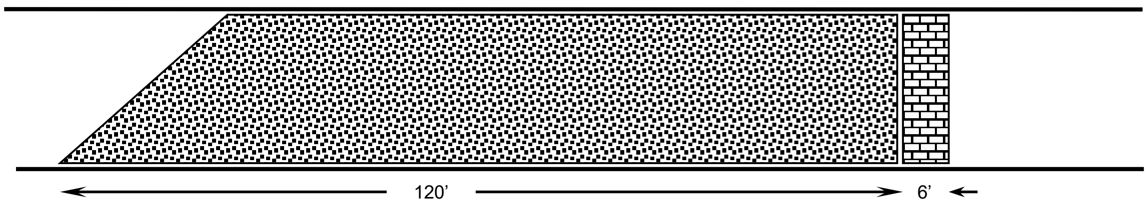
Option 10 Block Wall



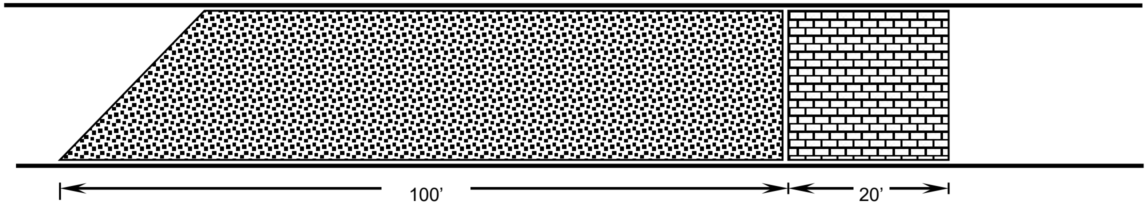
Option 11 Granular Material



Design Combinations

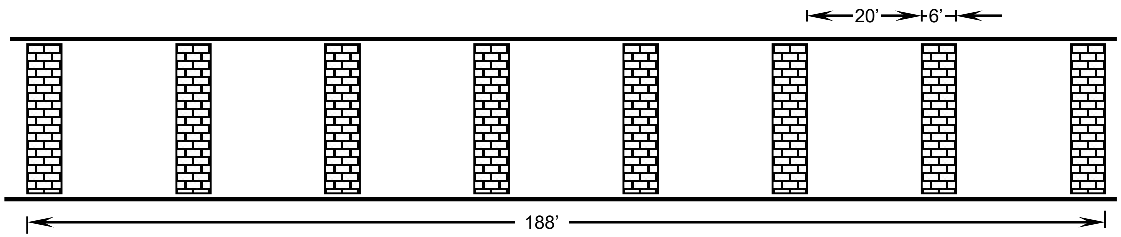


Option 12

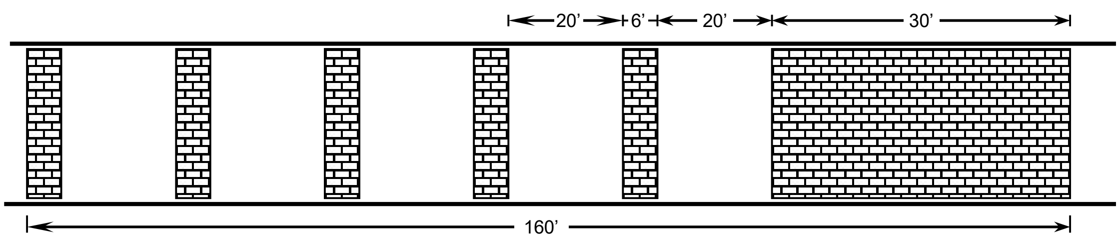


Option 13

Intermittent Walls

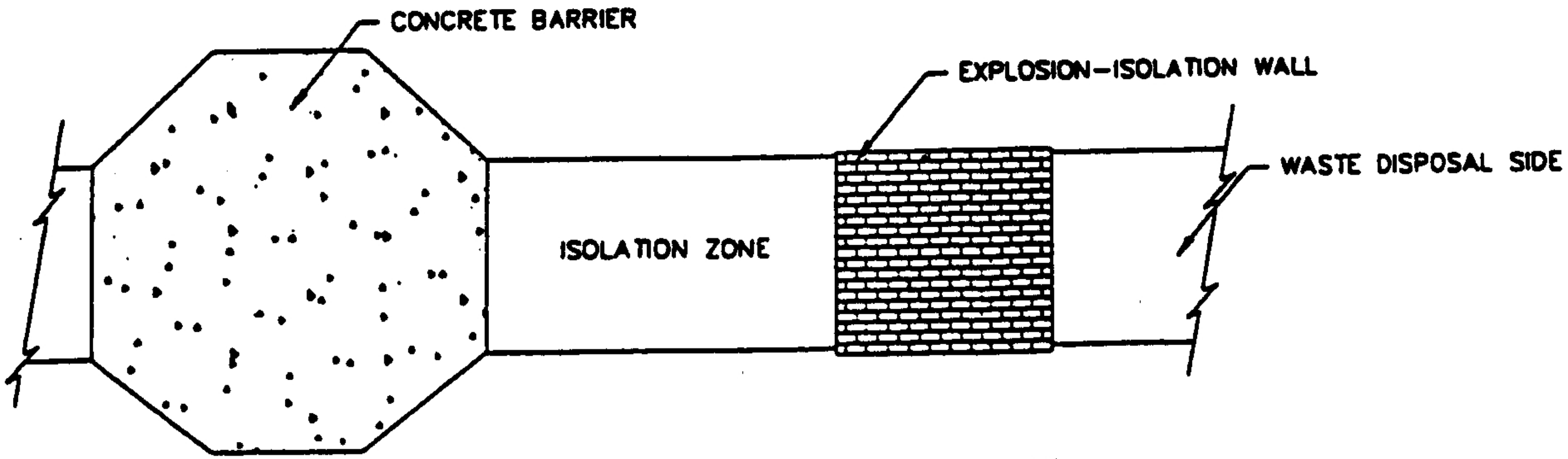


Option 14



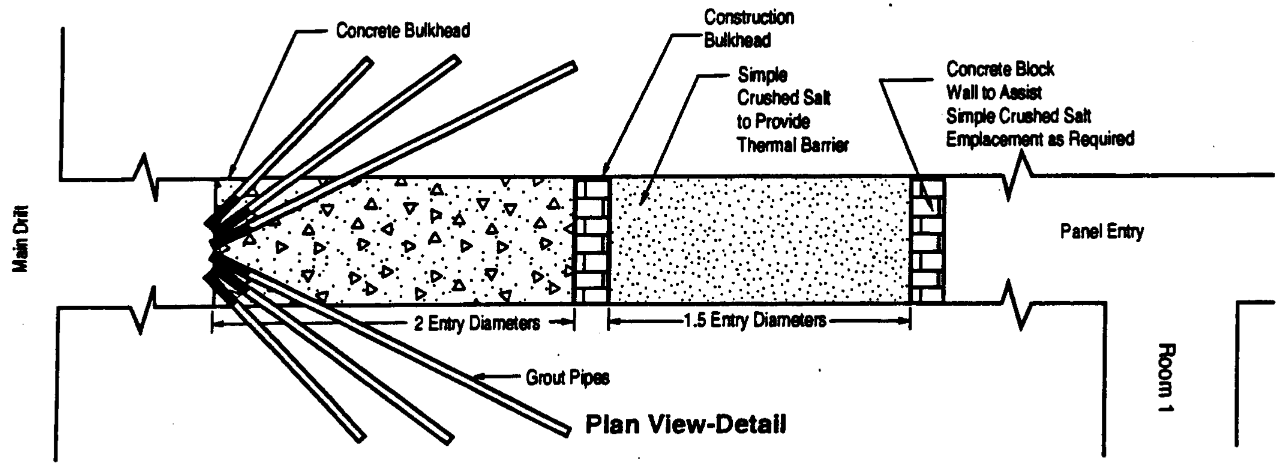
Option 15

EPA Selected Option D



D. CONCRETE BARRIER WITH DRZ REMOVED AND EXPLOSION ISOLATION WALL

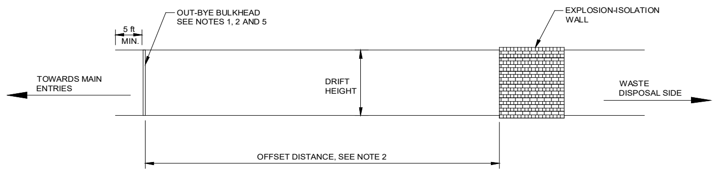
PCS Conceptual Design - 1995



Note that design components will be selected for radiation protection and fire suppression.

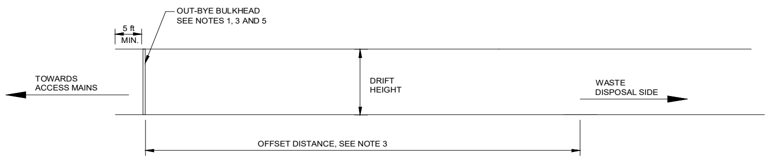
LEGEND

ROM SALT



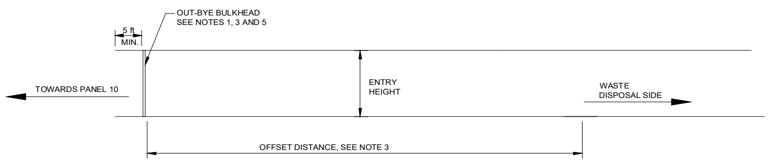
WPC-A FOR PANEL ACCESS DRIFTS WITH EXPLOSION-ISOLATION WALLS - PANELS 1, 2 AND 5

NOT TO SCALE



WPC-A FOR PANEL ACCESS DRIFTS W/OUT EXPLOSION-ISOLATION WALLS - PANELS 3, 4, 6, 7 AND 8

NOT TO SCALE



WPC-A FOR PANEL 9 - WASTE PLACEMENT SOUTH OF S2750

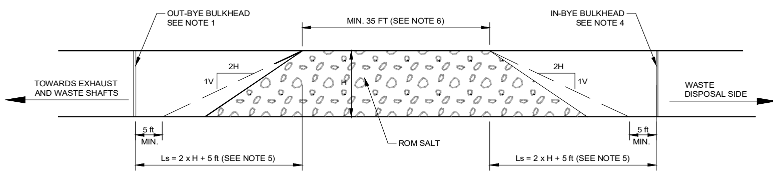
NOT TO SCALE

NOTES

1. RECESS OUT-BYE BULKHEAD MIN. 5 FT FROM INTERSECTION WITH ANOTHER DRIFT OR MAIN ENTRY.
2. OFFSET OUT-BYE BULKHEAD FROM EXPLOSION-ISOLATION WALL. MINIMUM OFFSET DISTANCE IS 2.0 x ACCESS DRIFT HEIGHT.
3. FOR PANELS WITHOUT EXPLOSION-ISOLATION WALLS, OFFSET OUT-BYE BULKHEAD FROM WASTE CONTAINERS. MINIMUM OFFSET DISTANCE IS 22 FT.
4. INSTALL IN-BYE BULKHEAD AT LEAST 22 FT FROM THE NEAREST WASTE CONTAINER.
5. WPC-B BULKHEADS SHOULD BE PLACED AT LEAST 5 FT FROM THE TOE OF ROM SALT (IF APPLICABLE) ASSUMING ROM SALT END SLOPES OF 2H:1V.
6. MINIMUM LENGTH OF WPC-B ROM SALT IS A FUNCTION OF THE MAIN ENTRY WIDTH AS FOLLOWS:

MINIMUM ROM SALT LENGTH - EXLUDING END SLOPES

ENTRY WIDTH (ft)	MIN. ROM SALT LENGTH (ft)
14	35
16	40
20	50
25	65



WPC-B FOR PANEL 10 - WASTE PLACEMENT SOUTH OF S1600

NOT TO SCALE

CLIENT
NUCLEAR WASTE PARTNERSHIP LLC

PROJECT
WIPP CLOSURE
GEO-MECHANICAL COMPLIANCE

CONSULTANT
Golder Associates

YYYY-MM-DD	2016-07-18
PREPARED	GG
DESIGN	GG
REVIEW	WTT
APPROVED	WTT

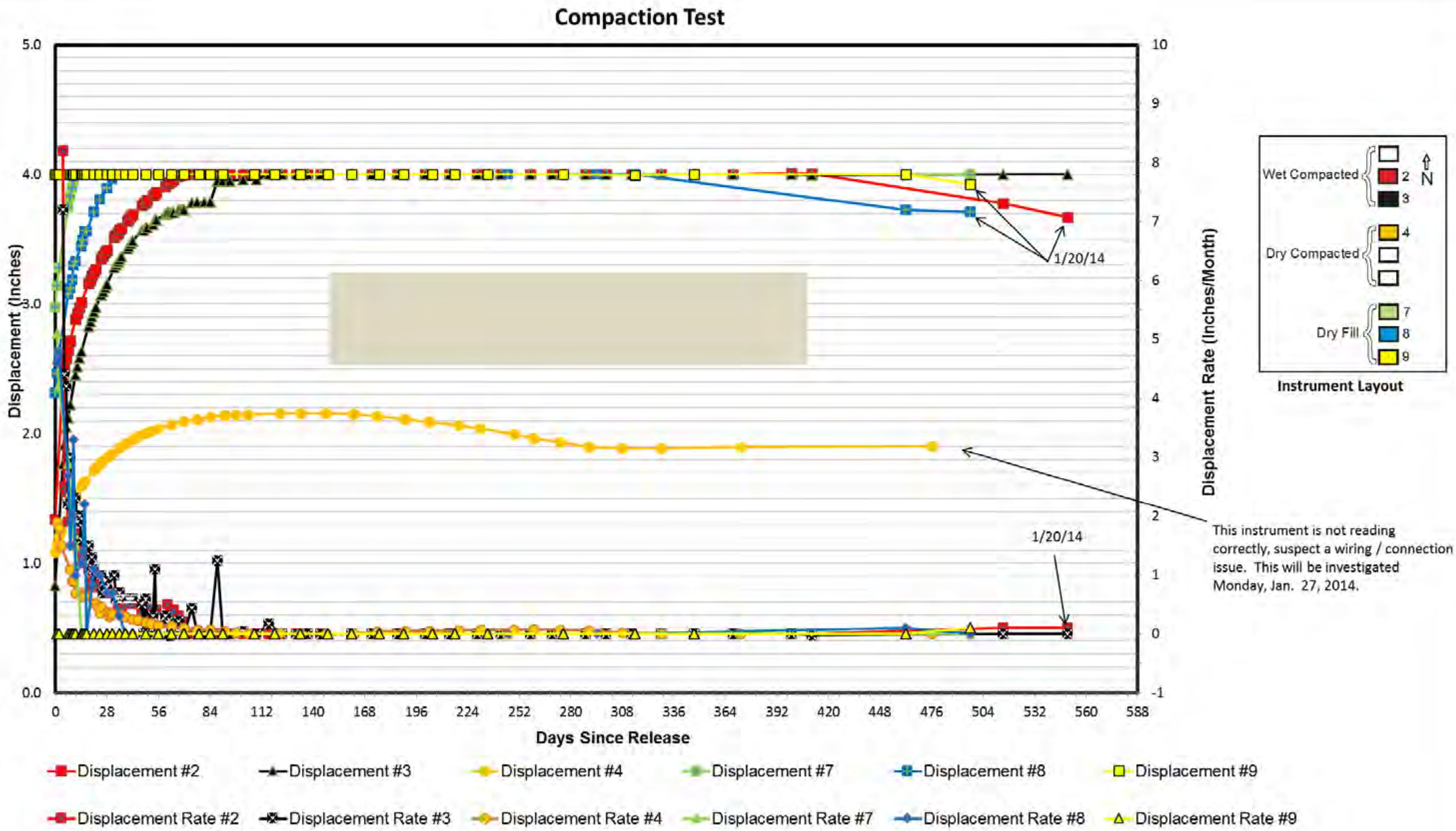
TITLE
WPC DETAILS
BULKHEAD AND ROM SALT LOCATIONS

PROJECT No.	CONTROL	Rev.	FIGURE
063-2213NEW		----	4

Path: --- | File Name: FIG4-WPC-Detail-BulkheadRomROMLocations-07-18-2016.dwg

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET SIZE HAS BEEN MODIFIED FROM: ANSI B

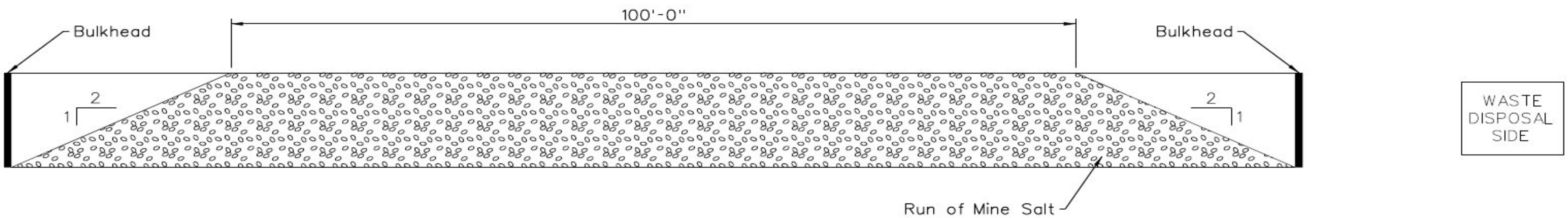

RD7
800-899-VOLVO
WACKER NEUSON


Compaction Test
Displacement (Inches)
Displacement Rate (Inches/Month)
Days Since Release
1/20/14
1/20/14
This instrument is not reading correctly, suspect a wiring / connection issue. This will be investigated Monday, Jan. 27, 2014.
Wet Compacted
Dry Compacted
Dry Fill
N
Instrument Layout
Displacement #2
Displacement #3
Displacement #4
Displacement #7
Displacement #8
Displacement #9
Displacement Rate #2
Displacement Rate #3
Displacement Rate #4
Displacement Rate #7
Displacement Rate #8
Displacement Rate #9

EPA Approved Panel Closure System

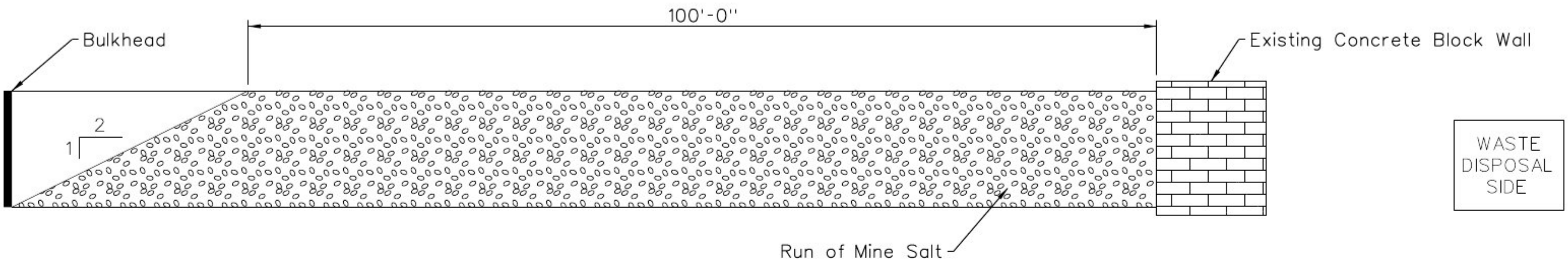
- Approved by EPA in October 2014
  - Minimum 100 feet of run-of-mine salt between steel bulkheads
  - Minimum 100 feet of run-of-mine salt between steel bulkheads and explosion-isolation walls

EPA Approved Panel Closure System Between Panels 9 and 10 and in Access Drifts to Panels 3, 4, 5, 6 and 7



1. Salt Zone 100'-0" minimum length.
2. Salt layers can be inclined within specifications.
3. Detailed design drawings are presented in Appendix D.
4. The ROM salt shall be placed to fill up to the back.
5. ROM salt is a porous salt in the loose state derived from underground mining operations at WIPP.

EPA Approved Panel Closure System Panels 1, 2 and 5



1. Salt Zone 100'-0'' minimum length.
2. Salt layers can be inclined within specifications.
3. Detailed design drawings are presented in Appendix D.
4. The ROM salt shall be placed to fill up to the back.
5. ROM salt is a porous salt in the loose state derived from underground mining operations at WIPP.

TYPICAL INTAKE/EXHAUST DRIFT

Conclusions

- Presentation of the Design Review Guidelines
- Presentation of the HWDF Panel Closure System Design Criteria
- Presentation of Panel Closure System Conceptual Design Alternatives
- Evaluation of Conceptual Design Alternatives
- *Selection of a Single Conceptual Design by a Broad Consensus That Achieves the HWDF Criteria at Lowest Cost and Least Impact on Operations*